Smoke forecasts from wildland fires for Canada

The BlueSky – Canada project

Kerry Anderson
Natural Resources Canada

Prepared By:
Natural Resources Canada
5320 122 Street Northwest
Edmonton, Alberta T6H 3S5
Project Sponsor: Mike Norton
DRDC Project Number: CSSP-2013-CP-1019
Technical Authority: Philip Dawe, Portfolio Manager, DRDC – Centre for Security Science

Contract Report
DRDC-RDDC-2016-C179
March 2016

Smoke forecasts from wildland fires for Canada

The BlueSky - Canada project

Kerry Anderson
Natural Resources Canada

Natural Resources Canada   Ressources naturelles Canada

Defence Research and Development Canada

Contractor Report
March 2016

Scientific Authority
Philip Dawe, MEng., PEng., DRDC CSS

Abstract

In 2007, an inter-agency partnership began the development of a system to forecast the spread of smoke from wildfires in Western Canada based on the US Forest Service BlueSky framework. In 2010 the Western Canada BlueSky system became a reality and smoke forecasts were produced throughout the wildfire season. The system is currently run at the University of British Columbia. It couples information on wildfire hot spots observed by satellite, forest fuel loads compiled by the Northern Forestry Research Center, algorithms to predict smoke emissions and plume rise, weather forecast data produced by a high-resolution numerical weather model (WRF3) and smoke dispersion modeling using the Hybrid Single Particle Lagrangian Integrated Trajectory model HYSPLIT.

The current system, BlueSky - Canada, provides smoke forecasts for all of Canada south of the Arctic Ocean. Forecasts are produced four times a day in order to use the latest hotspot detection information. The system is able to handle thousands of fires and properly processes the fire information, transport and dispersion in concert with the weather forecasts. Space-time paired comparisons to fine particulate matter 2.5 microns in diameter or less ($PM_{2.5}$) monitoring data show errors in the details of the magnitude and timing of events, although qualitative comparisons between the forecast smoke patterns and actual impacted areas using MODIS images indicate reasonable agreement in situations involving extensive smoke from large fire complexes. During the fire season (April 1 to September 30), the BlueSky – Canada smoke forecasting system can be viewed at the website www.FireSmoke.ca.

The system was developed through the collaborative efforts of the following partners: British Columbia Ministry of Environment, British Columbia Ministry of Forests, Lands and Natural Resource Operations, Alberta Department of Environment and Sustainable Resource Development, Manitoba Health, Ontario Ministry of Natural Resources, Natural Resources Canada, Environment Canada, University of British Columbia and the United States Forest Service. In addition to the above partners, this work is supported by the Canadian Safety and Security Program managed by Defence Research and Development Canada's Centre for Security Science.

This page intentionally left blank.

This page intentionally left blank.

Table of contents

Abstract……..i
Table of contents iv
List of figures vi
List of tables vii
Acknowledgements viii
1. Introduction..1
1.1 Background 1
1.2 Objective...2
1.3 Impact...2
1.4 Scope..3
2. Methods 4
2.1 BlueSky – Canada Smoke Forecasting System...4
2.1.1 Fire Detections 4
2.1.2 Emissions...5
2.1.3 Meteorology...6
2.1.4 Dispersion..6
2.2 BlueSky - Canada Playground 6
2.3 Canadian Forest Fire Emissions Prediction System 7
2.3.1 Fire Growth..7
2.3.2 Energy Balance 8
2.3.3 Plume Rise...8
2.3.4 Emissions...9
2.4 Outreach 11
2.5 National Smoke Forum 12
2.6 Publications...12
3. Results 13
3.1 BlueSky – Canada..13
3.1.1 The 2013 Fire Season...13
3.1.2 The 2014 FireSeason 15
3.1.3 The 2015 FireSeason 16
3.1.4 Performance and Validation 19
3.2 BlueSky – Canada Playground...21
3.3 Canadian Forest Fire Emissions Prediction System 22
3.3.1 Fire-growth 22
3.3.2 Energy Balance 22
3.3.3 Plume Rise..23
3.3.4 Emissions..24

3.4 Outreach..24
3.4.1 User Group Meetings 24
3.4.2 Webinars and Presentations 25
3.5 National Smoke Forum 26
3.6 Publications 26
3.6.1 Journal Publications 26
3.6.2 Conference Proceedings and Posters 28
3.6.3 Newsletters 28
4. DISCUSSION AND CONCLUSIONS...29
5. REFERENCES...31

List of figures

Figure 1. Elliptical fire-growth used in the CFFEPS model, The rate of spread from time t1 to t2 is used to calculate the forward spread distance. The grey area represents the area burned between times t1 to t2. 8

Figure 2. Orientation of 12 and 4 km WRF domains used for the 2013 fire season (a larger 36 km grid is also run, but is not plotted). 14

Figure 3. Orientation 12 and 4 km grid-spacing WRF domains for Blue-Sky West (top) and BlueSky-East (bottom) in 2014. These meteorological runs were initialized from the 00 UTC and 18 UTC NAM respectively (a larger 36 km grid is not shown). 16

Figure 4. WRF 12 and 4 km BlueSky operational domains for the 2015 fire season: West (top), as initialized from the 00 UTC North American Mesoscale (NAM) model; East (bottom), as initialized by the 18 UTC NAM model. The 12 km Canada-wide domains are identical, thus improving redundancy/reliability. 17

Figure 5. TERRA satellite image of northern central Canada from 23 July 2014. 20

Figure 6. TERRA satellite image (in gray) of northern central Canada overlaid with BlueSky column-integrated output (colours) for 23 July 2014. 21

Figure 7. Screen shot of BlueSky - Canada Playground Interface 22

Figure 8. Histogram of correlation coefficients for the Alberta plume study by predictive model and by observation period. The average values are the average of the results less the surface to 850 hpa results. 23

Figure 9. Scatter plot of predicted versus observed plumes from the Alberta plume study. Thermodynamic model predictions based on the surface to 500 hpa lapse rate are shown in blue, Briggs model prediction shown in red. "Predicted equals observed" is shown as a black dashed line. Observed plume heights are limited to daily observations closest to 17:00 LST. 24

List of tables

Table 1. Area per hotspot (hectares) 5
Table 2. Bulk densities (gm/cm^3) of surface fuels per fuel type. 10
Table 3. Reduction factors per fuel type 11
Table 4. Emission factors (g/kg) of pollutants. 11
Table 5. Operational reliability of BlueSky during the 2013 fire season. 15
Table 6. Operational reliability of BlueSky during the 2014 fire season. 16
Table 7. Meteorology and emissions used to create four BlueSky smoke forecasts each day. 18
Table 8. Operational reliability of BlueSky during the 2015 fire season. 19

Acknowledgements

The project has had, over the years, many contributors. Some have been part of the core team, as included in the Program Charter, while others have contributed through participation in advisory roles or as financial supporters as provincial/territorial representatives. The list includes

- David Lyder (Alberta Environment)
- Philip Dawe (Defence Research and Development Canada, Centre for Security Science)
- Steve Sakiyama, Cindy Walsh, Warren McCormick (British Columbia Ministry of Environment)
- Didier Davignon, Al Pankratz, Radenko Pavlovic (Environment and Climate Change Canada)
- Jeff Eyamie (Health Canada)
- Kerry Anderson, Peter Englefield, Brian Simpson (Natural Resources Canada)
- Frank Dempsey (Ontario Ministry of Environment)
- William Cole (Ontario Ministry of Natural Resources)
- Jed Cochrane, Jonathan Large (Parks Canada)
- Shi Ming Huang (Sonoma Technologies Inc.)
- Rosie Howard, Roland Schigas, Roland Stull (University of British Columbia)
- Narasimhan Larkin, Susan O'Neill (USDA Forest Service)

1. Introduction

Every year Canada typically experiences 8,000 forest fires resulting in dozens of evacuations of communities due to smoke. Health alerts impacting the lives of millions of Canadians are issued each summer indicating the negative health effects of smoke exposure. Industries and tourism are also affected by smoke (McLean et al. 2015; Krstic and Henderson 2015; Gould *et al.* 2013; Beverly and Bothwell 2011). Through the development of a national smoke forecasting system, agencies and the public can be provided with current and forecast smoke conditions and expected exposures to fine particulates ($PM_{2.5}$).

On February 22, 2013, the Canadian Safety and Security Program (CSSP) approved the project entitled smoke forecasts from wildland fires for Canada. This was a three year project, which began on June 1, 2013 and completed on March 31, 2016. This project was aimed at providing smoke forecasts for the Canadian public, using the BlueSky Framework developed by the USDA Forest Service.

BlueSky - Canada is now an operational tool being used in Canada. Run out of the Geophysical Disaster Computational Fluid Dynamics Center of the University of British Columbia's Department of Earth, Ocean and Atmospheric Sciences, BlueSky - Canada provides smoke forecasts for all of Canada south of the Arctic Ocean. Forecasts are produced four times a day using the latest forest fire information. The system is able to handle thousands of fires and process the smoke emissions, transport and dispersion in concert with the weather forecasts.

In addition to BlueSky - Canada, a further result of this project is a national community has developed, the objective of which is to bring together members from a wide variety of interest groups to discuss issues around smoke from wildland fires. The intent of this community is to establish a future direction for smoke forecasting and research in Canada. Through this CSSP-funded project, a National Smoke Forum has been established in association with the Wildland Fire Canada Conference series. The first such forum was held in October 10, 2014 in Halifax, Nova Scotia, while the second is now being planned for October 28, 2016 in Kelowna, British Columbia.

1.1 Background

In 2007, an inter-agency partnership began the development of a system to forecast the spread of smoke from wildfires in Western Canada based on the US Forest Service BlueSky framework. In 2010, the Western Canada BlueSky system became a reality and smoke forecasts were produced throughout the wildfire season. The system was run at the University of British Columbia (UBC) and coupled information on wildfire hot spots observed by satellite, forest fuel loads compiled by Natural Resources Canada (NRCan), algorithms to predict smoke emissions and plume rise, weather forecast data produced by a high-resolution Mesoscale Model 5 (MM5) numerical weather model and smoke dispersion modeling using HYSPLIT. The original forecasts were made available daily through a British Columbia government website (http://www.bcairquality.ca/bluesky/west/), where animations of hourly wildfire smoke in the form of $PM_{2.5}$ ground level concentrations out to 48 hours into the future could be viewed.

In 2013, funding from the Canadian Safety and Security Program (CSSP) provided an opportunity to develop a national system. The intended output was the creation of national smoke forecast products and tools useful for providing information to the public. From this, the BlueSky - Canada smoke forecasting was established. This system now provides smoke forecasts for all of Canada south of the Arctic Ocean. Forecasts are produced four times a day using the latest hotspot detection information. During the fire season (April 1 to September 30), the BlueSky – Canada smoke forecasting system can be viewed at the website www.FireSmoke.ca.

The BlueSky – Canada smoke forecasting system is able to handle thousands of fires and properly process the fire information, transport and dispersion in concert with the weather forecasts. The Weather and Research Forecasting (WRF) model has replaced the MM5 numerical weather model. The weather model component of the BlueSky system is run twice daily over three domains (a national domain plus domains for eastern and western Canada) at 36 and 12 km resolutions with additional 4 km resolutions domains as deemed necessary.

1.2 Objective

The intended output of the project was the creation of national forecast products and tools useful for providing information to the public. These included:

a) BlueSky - Canada: a web-based forecast product available to the public. Integration of this output with Canada's Multi-Agency Situational Awareness System (MASAS) would also be assessed;

b) BlueSky - Canada Playground: an interactive smoke forecast tool used by fire management agencies to predict possible smoke emissions and dispersion from prescribed fire operations;

c) Canadian Forest Fire Emissions Prediction System (CFFEPS): a new module compatible with the Canadian Forest Fire Danger Rating System used to predict smoke plume dynamics and emissions;

d) Webinars and Presentations: an outreach program intended to make agencies aware of the BlueSky - Canada products and provide an opportunity for their feedback;

e) National Forum/Workshop: a scientific exchange with users to be held in conjunction with the Wildland Fire Canada 2014 conference, Halifax, NS, leading to a national standing forum on smoke and air quality;

f) Publications: technical documentation and manuscripts submitted to peer-reviewed journals will be produced from project results.

1.3 Impact

Outputs from BlueSky - Canada were intended to better inform the public, health protection agencies and hospitals, fire management agencies, environment ministries, and other federal and provincial departments Canada-wide by predicting and assessing the risk of smoke from wildland fires up to 48 hours in advance. The system was intended to provide guidance to health agencies to make informed evacuation decisions and provide advance public messages on ways to reduce risk due to smoke exposure related to smoke exposure in order to protect the health and safety of Canadians. The interactive tool was aimed at helping fire managers plan prescribed burning operations to minimize the public's exposure to adverse smoke effects. Scientific and technical knowledge created by a BlueSky system was intended be used by and shared with university researchers and federal departments such as Health Canada, Environment Canada, and Public Safety Canada, which have a national role of informing Canadians on health, environmental hazards, and emergency conditions.

The impact of the BlueSky – Canada system is captured by the overall usage of the product. BlueSky – Canada produced 2119 forecasts of the three fire seasons (2013-2015). The webpage was accessed regularly across Canada with, for example, 451 visits in June 2015. These forecasts have been incorporated into British Columbia's Asthma Monitoring System (BCAMS, McLean et al. 2015) are being evaluated by Manitoba Health's Office of Disaster Management. The BlueSky Canada Playground gained usage over the project from 445 modelled dispersions in the 2013 to 896 in 2015.

1.4 Scope

The scope of this study was to develop and enhance smoke forecasting systems to better predict smoke occurrence for the protection of health and safety of Canadians. This took the form of four main directions of study:

a) Systems Operations focussed on improving the existing system to a timely and reliable forecast product.

b) Research and New Applications focussed on the advancement of knowledge and versatility, thus improving the science behind the forecast and its uses.

c) Performance and Validation focussed on the accuracy of the forecasts in terms of spatial extent and concentrations.

d) Outreach and Engagement focussed on methods of disseminating the product to the public including direct information through health agencies and emergency measures organizations, and through fire management agencies. Also, responding to user needs and feedback was addressed.

2. Methods

The methodology of the project followed the six objectives outlined in the objectives section of the introduction. These included BlueSky - Canada smoke forecasting system, BlueSky - Canada Playground, the Canadian Forest Fire Emissions Prediction System (CFFEPS), Webinars and Presentations, National Forum/Workshop, and Publications.

2.1 BlueSky – Canada Smoke Forecasting System

The BlueSky – Canada smoke forecasting system is a web-based product showing the evolution of smoke from wildland fires over time. The BlueSky - Canada system was adapted from the BlueSky Framework developed by the Air/Fire team from the USDA Forest Service. The original system was developed in 2002 (Larkin *et al.* 2009) for the Pacific Northwest. Since then it has expanded to cover most of the continental US.

The BlueSky Framework uses a modular approach where the user may choose from multiple models. For example, the framework allows users to choose from the Multiscale Model 5 (MM5) or the Weather Research and Forecasting (WRF3) model to predict the meteorology; CONSUME (Prichard *et al.* 2009) or BURNUP for fuel consumption; FEPS (Anderson *et al.* 2004) or BURNUP for emissions; etc. By deciding which models to incorporate into the framework's predictions, the user can configure the framework to produce the best, representative predictions for the forecast region.

At the 2007 Workshop on Wildfire Smoke Forecasting in Edmonton, it was decided to bring the BlueSky Framework to Canada. The Geophysical Disaster Computational Fluid Dynamics Center of the University of British Columbia's (UBC) Department of Earth, Ocean and Atmospheric Sciences was selected as the installation site. During 2008 and 2009, UBC conducted a feasibility study and developed a prototype model for test runs. The first daily BlueSky forecasts for British Columbia and Alberta were produced in August, 2010.

Much of the functionality of BlueSky – Canada is based on fire information collected by NRCan's Canadian Wildland Fire Information System (CWFIS). The CWFIS is a fire information system that monitors fire danger conditions across Canada. Daily noon weather conditions are collected from over 1800 federal and provincial weather stations and are used to calculate daily Canadian Forest Fire Weather Index (FWI) System indices across Canada (Van Wagner 1987). These indices are then used to produce fire weather and fire behaviour maps based on the Canadian Forest Fire Danger Rating System (CFFDRS). The CWFIS also collects and maps satellite-detected hotspots to monitor fire activity, models daily fire growth, maps reported fire locations, provides national situation reports, and hosts a data warehouse of historical fire perimeters for all of Canada. Started in 1995, the CWFIS is now in year–round operation and can be accessed at http://cwfis.cfs.nrcan.gc.ca/.

Integration of BlueSky – Canada output as input into Canada's Multi-Agency Situational Awareness System (MASAS) was implemented at UBC in early 2016.

2.1.1 Fire Detections

Fire detections in the BlueSky – Canada system are collected by NRCan in the form of satellite-detected hotspots from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) and NOAA's Advanced Very High Resolution Radiometer (NOAA/AVHRR) satellite-based detection systems (Anderson *et al.*, 2009). The Canadian Wildland Fire Information System

(CWFIS) collects and processes this satellite-detected fire activity six times daily. Fire weather, fuel consumption and smoke emissions are calculated at each hotspot location, which, in turn, are passed to the BlueSky - Canada smoke forecasting system.

A critical component to calculating fire emissions is the fire size. In the original 2010 implementation of BlueSky in Canada, an assumption of 38.5 hectares consumed per hotspot (350 m burn radius) was used. This value was empirically derived from the national area burned and the number of hotspots observed during the 2010 fire season. In later years, this value was refined by province and fuel type. The most recent values are shown in Table 1, and are based on the 2014 and 2015 fire seasons, using the national area burned and a minimum of 1000 hotspot observations. When applied, average values are used in place of missing data.

Table 1. Area per hotspot (hectares)

	Province/Territory								
	BC	Alberta	Saskatchewan	Manitoba	Ontario	Quebec	NWT	Yukon	Average
Conifer	11.69	31.36	40.76	44.41	45.64	-	26.57	33.35	27.49
Deciduous	9.72	27.56	32.86	-	-	-	20.9	-	20.91
Low vegetation (cropland, tundra, alpine)	-	-	1.11	1.24	-	-	26.91	-	11.42
Mixedwood	16.51	25.63	39.9	-	-	-	25.09	-	32.06
Grass	11.77	31.48	41.59	-	-	-	28.9	-	30.11
Average	11.41	29.63	35.38	18.85		30.7	26.29		26.36

In addition to hotspot information, agency-reported fires and US fires (smoke from which can blow into Canada) were incorporated in the BlueSky - Canada system for the 2014 fire season using the SmartFire2 program. This program combines information from different sources to provide the best estimate of current fire conditions.

2.1.2 Emissions

The smoke emission estimates used by the BlueSky System are generated by the CWFIS. Under the original system, emissions were estimated as a function of the Total Fuel Consumption (TFC in kg/m^2) of the Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992) and the Forest Floor Fuel Consumption (FFFC in kg /m^2, de Groot *et al.*, 2009). The FFFC, which was determined from measurements collected months after a fire, represents the longer duration burning, including both the smoldering and flaming phases, while the flaming phase alone is captured by fuel-consumption measurements of the FBP system, which were generally collected only hours after experimental burns. For the purposes of calculating smoke emissions, it is assumed that the TFC value from the FBP system represents flaming combustion, while the difference between the TFC and the FFFC captures smoldering combustion.

At this stage, the SmartFire2 program, a component of the BlueSky Framework, collects together hotspots and ground report information, clustering them into individual fire events for simulation. Fire emissions are then modelled using the Fire Emissions Prediction System (FEPS, Anderson *et al.* 2004) to determine fire emissions rates and evolution over time.

These calculations are now being replaced by the Canadian Forest Fire Emissions Prediction System (CFFEPS).

2.1.3 Meteorology

BlueSky - Canada uses version 3 of the Weather Research and Forecasting (WRF) model. This is a numerical weather prediction model used to calculate the evolution of the atmosphere in a three-dimensional domain for the next 60 hours. The WRF model requires extensive computing resources, which are available at the University of British Columbia's Geophysical Disaster Computational Fluid Dynamic Centre.

The WRF model is run twice daily to provide weather forecasts for all of Canada. It does so in a nested fashion to increase resolution over points of particular interest or complexity. For 2013, the system was nested down to a 4 km resolution for Western Canada, while a 36 km grid was used to create forecasts for Eastern Canada. Beginning in 2014, WRF was run twice daily, each with a 12 km grid resolution covering most of Canada. Nested inside these forecast domains were high resolution subdomains of 4 km resolution for BC/Alberta and for Ontario/Quebec.

2.1.4 Dispersion

BlueSky uses HYSPLIT (Stein *et al.* 2015) to model smoke dispersion for each detected hotspot. The evolution of particulate concentrations over time is modelled using a series of puffs to represent each plume. Vertical and horizontal dispersion through the model domain is predicted by the mean wind field and a turbulent component. Plume predictions from all detected fires are then combined to present the final forecast shown on the BlueSky - Canada webpage.

The HYSPLIT model is a hybrid between Lagrangian and Eulerian approaches to modelling 3D dispersion. The model provides a number of physical operating parameters such as plume rise, wet-deposition, particle or puff modes, etc. During the project these were tested to determine the best configuration for Canadian forecasts.

2.2 BlueSky - Canada Playground

BlueSky - Canada Playground is an interactive smoke forecast tool used by wildland fire management agencies to predict possible smoke emissions and dispersion from prescribed fire operations. Prescribed burns are intentionally ignited to achieve a specific forest management or land use objective, such as hazard reduction or habitat management. These burns are preplanned under controlled conditions. One desired result is to minimize the impact of smoke on neighbouring populations.

BlueSky - Canada Playground is a tool that fire managers can use to plan their prescribed burns while minimizing the smoke impacts. It is a Canadian implementation of the US Playground system – a computer model framework developed by the U.S. Forest Service. Weather conditions, fuel moisture and forest type are entered through Playground's interactive, web-based input screen. These inputs are passed to the BlueSky - Canada smoke forecasting system, where smoke plumes are modelled and displayed. Playground then predicts the hourly surface smoke concentrations (as $PM_{2.5}$) up to 48 hours into the future. Such a tool is useful for:

- Informing burn decisions – both in planning and implementation phases.

- Developing health and public advisories to appropriate communities about potential smoke impacts from prescribed burns

- Provide a common tool available to Canadian agencies with consistency in methodology, format and content

- Examination of the smoke from a singular prescribed burn or wildfire in the past through its archive ability.

In addition, Playground can be used for wildfires where the transport and dispersion of smoke from a single wildfire of interest can be simulated.

2.3 Canadian Forest Fire Emissions Prediction System

Canadian Forest Fire Emissions Prediction System (CFFEPS) is a new module compatible with the Canadian Forest Fire Danger Rating System (CFFDRS) and is used by the BlueSky - Canada system to predict smoke plume dynamics and emissions. The system consists of an elliptical fire-growth model, an emissions model and a model to predict the penetration height of a smoke plume, based on thermodynamic principles.

As a Canadian model, CFFEPS uses the CFFDRS, including the Canadian Fire Weather Index (FWI) System (Van Wagner 1987) and the Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992). These systems drive the elliptical fire growth model and provide the amount of fuel consumption, which is used for the emissions estimates. The model also uses elements from CONSUME developed by the US Forest Service (Prichard *et al.* 2009) and FEPS (Anderson *et al.* 2004).

2.3.1 Fire Growth

Many of the calculations in the CFFEPS model depend on fire size. To determine this, the model uses a simple elliptical fire growth model to predict the area burned similar to that used in Anderson *et al.* 2009. As shown in Figure 1, the model assumes that a fire grows in an elliptical shape: the stronger the driving wind, the higher the ellipticity. Fuel type and wind direction are held constant.

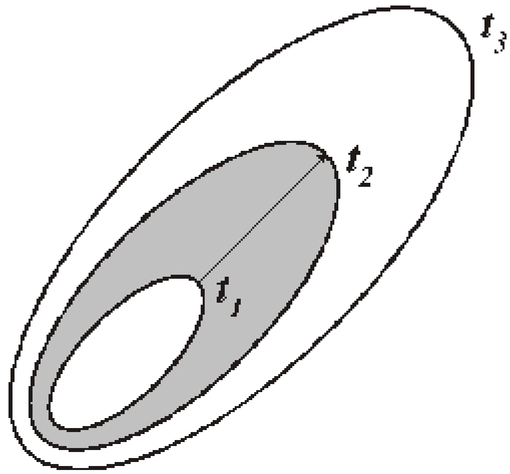

Figure 1.Elliptical fire-growth used in the CFFEPS model, The rate of spread from time t_1 to t_2 is used to calculate the forward spread distance. The grey area represents the area burned between times t_1 to t_2.

The fire-growth model uses components of the CFFDRS to drive it. The fine fuel moisture code (FFMC) is diurnally adjusted over time using the technique developed by Lawson *et al.* (1996). The rate of spread (ROS) is calculated over the course of the day and from this the area growth is determined. The surface and the total fuel consumption (SFC and TFC) are then calculated for the area burned to estimate the amount of smoke emissions.

While a number of sophisticated fire-growth models exist that calculate fire spread over a heterogeneous field of fuels and terrain, this model does not go that far. The data needs of models such as Prometheus (Tymstra*et al.* 2007) and FARSITE (Finney *et al.* 1998) are extensive and outside the present approach used in CFFEPS. Future attempts may be conducted to incorporate such models into CFFEPS, but for now are outside of the present scope of the model.

2.3.2 Energy Balance

To determine the amount of energy involved in plume development, it was necessary to develop an energy balance for a wildland fire. Byram's traditional equation for fire line intensity (Byram 1959) is shown as $I = H\ w\ r$, where I is the fire intensity (kW/m^2), H is the heat of combustion (1.8 x 10^7 J/kg), w is the mass of fuel consumed (kg) and r is the fire's velocity or rate of spread (m/s). Energy entering the plume (J) can be derived from this by replacing rate of spread with area growth (m^2).

It was recognized that not all the energy from the fire enters the plume. A certain amount goes into heating the fuel and evaporating the moisture ahead of the fire, while some is lost into the soil, in incomplete combustion and emitted horizontally behind the fire as radiation The devised energy balance is based on parameters from the CFFDRS.

2.3.3 Plume Rise

Plume rise in the CFFEPS model is based on the thermodynamic plume model developed by Anderson *et al.* (2011). This model predicts the penetration height of a plume based on an amount of energy injected into the atmosphere and a constant environmental lapse rate. The CFFEPS model provides the user with choices for entrainment, the impact of which depends on the fire size. This is calculated from the elliptical fire-growth model previously described.

The thermodynamic model uses the energy and size of the fire as input. The plume height is then equated to the height of a predicted column of air mixed from the environmental lapse rate to a dry adiabatic lapse rate, with the top of the column captured by the height of thermal equilibrium.

To test the model, data from a smoke plume study being conducted by Environment Canada and Alberta Environment and Sustainable Resource Development (AESRD) was used. In this study, smoke plume heights are measured using hand-held inclinometers and photographs taken by wildfire lookout observers.

A new plume-rise model named VIPER (Vertical Injection of Particulates Emitted from WildfiRes) has been developed for future inclusion the BlueSky framework. Written in Python, VIPER employs the theory developed by Stull, which builds on the thermodynamic approach (Anderson*et al.*, 2011). This approach recognizes that the fire is able to thermodynamically model the bottom few kilometers of the atmosphere, rather than behave as an isolated plume rising through an unmodified atmosphere.

2.3.4 Emissions

The CFFEPS model uses fuel consumption as calculated by the FBP system. This includes surface fuel consumption (SFC), crown fuel consumption (CFC) and total fuel consumption (TFC).

Surface fuel consumption (SFC) represents fuel consumption as the fire burns into the forest floor. The bulk density of the forest floor increases with depth, which has an impact on emissions. Table 2 shows the bulk densities used per fuel type. These values are based on the original bulk densities documented in the FBP literature and summarized by Anderson 2000.

Table 2.Bulk densities (gm/cm^3) of surface fuels per fuel type.

	Depth			
Fuel	0-2 cm	2-4 cm	4-6 cm	6-8 cm
C1	0.045	-	-	-
C2	0.019	0.034	0.051	0.056
C3	0.015	0.020	0.032	0.066
C4	0.022	0.029	0.045	0.059
C5	0.093	-	-	-
C6	0.030	0.050	0.050	0.050
C7	0.100	0.100	0.050	-
D1	0.061	-	-	-
M1/2	0.0265	0.071	0.0795	0.082
M3/4	0.041	0.061	0.084	0.112

The three combustion stages are considered to have three duration periods, as shown on Table 3. Flaming combustion is considered to occur instantaneously, with all consumption immediately released into the atmosphere. Smoldering combustion is assumed to last for two hours and residual combustion for six.

Table 3. Reduction factors per fuel type

Fuel	Depth	Flaming (Instantaneous)	Smoldering (2 hours)	Residual (6 hours)
Ground	Litter	0.95	0.05	0
	Upper duff	0.10	0.70	0.20
	Lower duff	0	0.20	0.80
Canopy	-	0.85	0.05	0
Slash	-	0.70	0.15	0.15
Grass	-	0.95	0.05	0

Table 4 describes the emission factors of pollutants used in CFFEPS. These are based on the average emission factors used in CONSUME. Depending on the three stages of combustion, time series of emissions released in the atmosphere are created for each pollutant in accordance with the emission factors and the duration of the combustion stages.

Table 4.Emission factors (g/kg) of pollutants.

	PM	PM_{10}	$PM_{2.5}$	CO	CO_2	CH_4	NMHC
Flaming	11.5	7.5	6.5	45	1261	1.5	2.5
Smoldering	17	12	9.5	104.5	1142.5	5.5	5
Residual	17	12	9.5	104.5	1142.5	5.5	5

2.4 Outreach

An outreach program was planned to make agencies aware of the BlueSky - Canada products and provide an opportunity for their feedback. Annual BlueSky user groups meeting were planned to provide a means of interaction between the BlueSky team and the intended users. These would be open to any interested party and would be held in Edmonton and Vancouver. Conference participation was also expected to serve as a platform to present the project to an audience not familiar with the project. The webinar is a new approach to outreach and the team expected to take advantage of this avenue of communication.

2.5 National Smoke Forum

A National Forum/Workshop was held October 10, 2014 in Halifax, NS. The objective of this meeting was to conduct an information exchange with users of smoke forecasting systems such as BlueSky for Canada, possibly leading to a national standing forum or national coordinating body for smoke and air quality. The meeting was held in conjunction with the Wildland Fire Canada 2014 conference to maximize participation from the fire community as well as to introduce health agencies to the fire community.

2.6 Publications

As part of the project, publications would be produced from project results. These would include technical documentation and manuscripts submitted to peer-reviewed journals.

3. Results

3.1 BlueSky – Canada

The BlueSky – Canada system was run operationally from April 1 to September 30 for the three fire seasons (2013-2015) covered by the project. . Products evolved over that period from daily forecasts for western Canada at 12 km in 2013 to four times daily, national forecasts at 12 km, with twice-daily 4 km forecasts for parts of western and eastern Canada by the end of the project.

3.1.1 The 2013 Fire Season

Version 3.3 of the BlueSky Framework with some individual component upgrades was used to produce the BlueSky – Canada smoke forecasts for 2013. The Weather Research and Forecasting (WRF) model meteorological domain used for the 2013 forecasts is sketched in Figure 2.

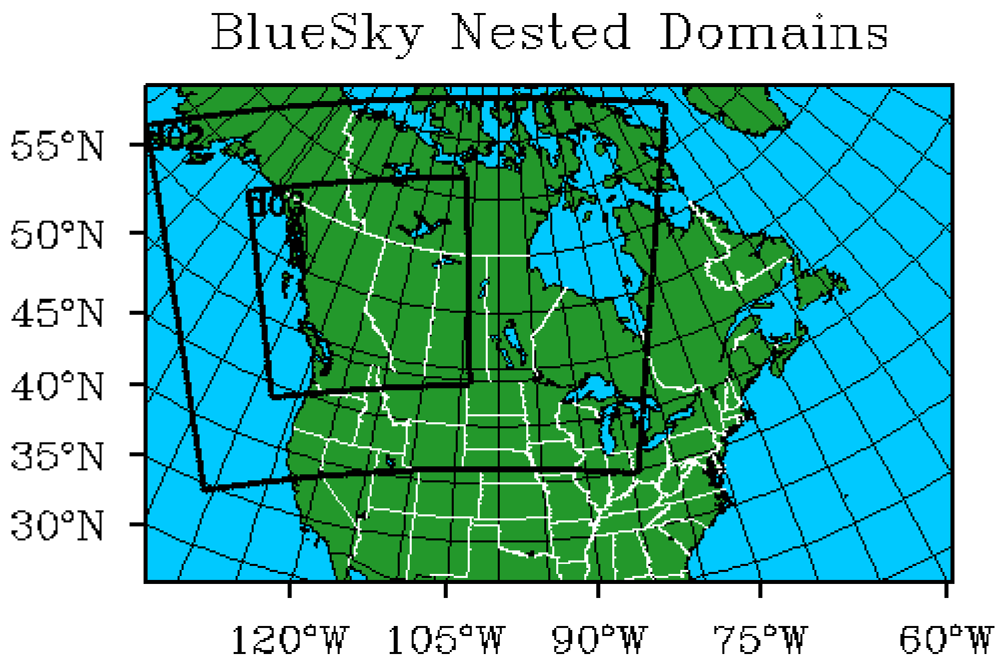

Figure 2. Orientation of 12 and 4 km WRF domains used for the 2013 fire season (a larger 36 km grid is also run, but is not plotted).

The HYSPLIT dispersion model was upgraded from version 4.8 to 4.9; forecasts using 4.9 were produced starting April 23, 2013. Carryover smoke was implemented (initializing HYSPLIT with smoke from the previous forecast) and used in forecasts starting April 23, 2013. HYSPLIT meteorology input was switched from MM5 to WRF3. Twice-daily smoke forecasts for internal evaluation using WRF3 started May 14, 2013; WRF forecast runs were switched to faster cluster nodes June 25, 2013 to meet schedule requirements. Until July 31, 2013, both MM5 and WRF3 smoke forecasts were produced; from August 1, 2013, only the public WRF3 smoke forecasts were produced.

In addition to the twice-daily smoke forecasts for western Canada using a nested 12 & 4 km grid, twice- daily smoke forecasts using a 36 km grid for all provinces east of Manitoba were produced starting May 9, 2013.

Table 5 lists the percentage of smoke forecasts produced by BSC (calculated by counting the number of forecast archive files and dividing by the number of days that forecast was run).

Table 5.Operational reliability of BlueSky during the 2013 fire season.

Domain	Begin	End	Days	00 Forecast	12 Forecast
East (WRF)	May 29	Sep 30	125	95%	88%
West (WRF)	May 14	Sep 30	140	91%	97%
West (MM5)	Apr 01	Jul 31	122	97%	98%

3.1.2 The 2014 FireSeason

During the 2014 fire season, Version 3.5.1 of the BlueSky Framework was used to produce the BlueSky - Canada smoke forecasts from April 1 to October 31, 2014. The WRF model meteorological domain used for the 2014 forecasts is sketched in Figure 3.

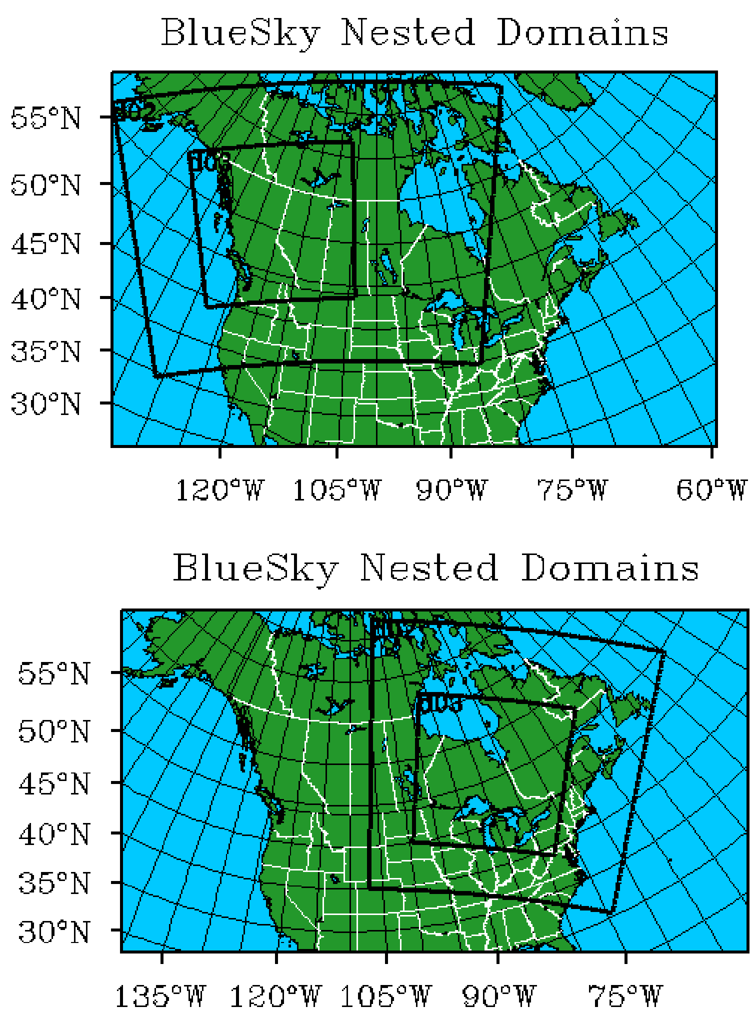

Figure 3. Orientation 12 and 4 km grid-spacing WRF domains for Blue-Sky West (top) and BlueSky-East (bottom) in 2014. These meteorological runs were initialized from the 00 UTC and 18 UTC NAM respectively (a larger 36 km grid is not shown).

The HYSPLIT dispersion model version 7 was used in puff mode. Twice-daily smoke forecasts were run to take advantage of the updated smoke inputs, but using the once/daily 00 UTC WRF meteorology for the West, and the once/daily 18 UTC meteorology for the East.

In addition to the twice-daily smoke forecasts for western Canada using a nested 12 & 4 km grid, twice-daily smoke forecasts using a 36 km grid for all provinces east of Manitoba were produced. Thus, although daily weather forecasts at 12 and 4 km grid spacing for the East domain (Fig. 2) were produced, these fine-resolution forecasts were not used as input to BlueSky. Only the 36 km meteorological forecasts were used in BlueSky East in 2014, same as the 2013 BlueSky set-up.

Table 6 lists the percentage of smoke forecasts produced by BlueSky – Canada (422 forecasts were scheduled for the 211 calendar days):

Table 6. Operational reliability of BlueSky during the 2014 fire season.

Domain	Calendar Days	Forecasts Produced (AM & PM)	Reliability of Produced Forecasts
West	211	398	94%
East	211	399	95%

3.1.3 The 2015 FireSeason

During the 2015 fire season, BlueSky - Canada was run from April 1 to September 30, 2015using the WRF model for the meteorological domains sketched in Figure 1. These did not change during the fire season. Each figure shows a Canada-wide domain run at 12 km grid spacing, and a nested 4 km domain in either the West or east. The identical Canada-wide domains as initialized from the 00 and 18 UTC weather initial conditions provided redundancy to improve operational reliability. Each WRFmodel weather run was used with two different emissions runs, resulting in the four smoke forecasts each day as listed in Table 7.

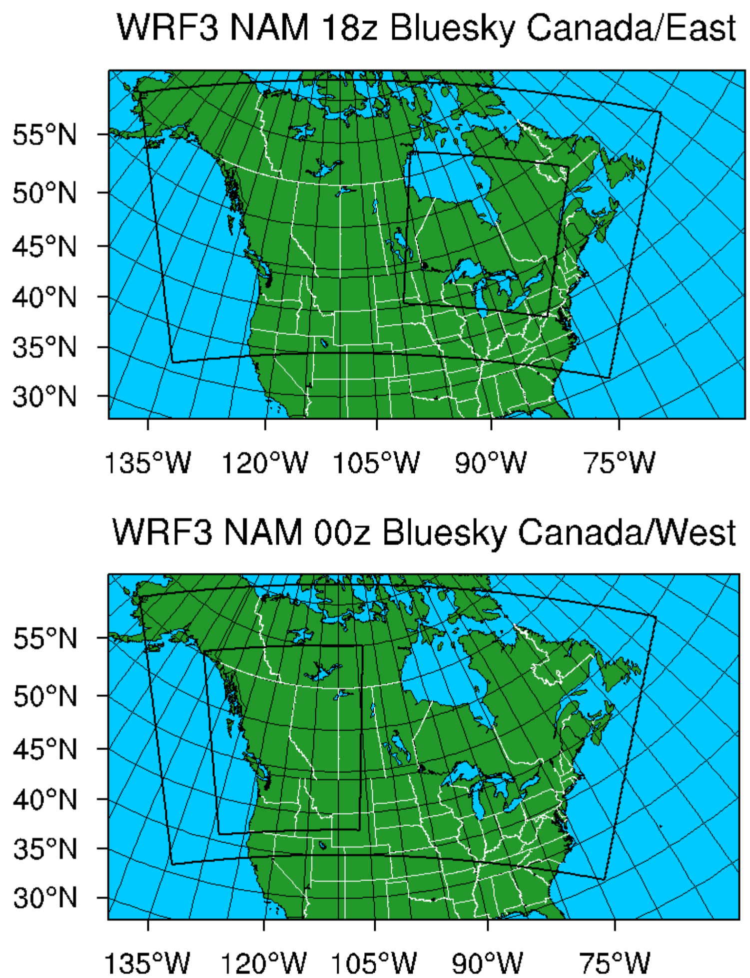

Figure 4. WRF 12 and 4 km BlueSky operational domains for the 2015 fire season: West (top), as initialized from the 00 UTC North American Mesoscale (NAM) model; East (bottom), as initialized by the 18 UTC NAM model. The 12 km Canada-wide domains are identical, thus improving redundancy/reliability.

Table 7. Meteorology and emissions used to create four BlueSky smoke forecasts each day.

Forecast ID	Domain	Meteorology	Emissions
BSC18CA12	Canada	18 UTC(prev. day)	00 UTC (1st)
		12 km grid	12 UTC (2nd)
BSC18EC04	Eastern Canada	18 UTC (prev. day)	00 UTC (1st)
		4 km grid	12 UTC (2nd)
BSC00CA12	Canada	00 UTC	04 UTC (1st)
		12 km grid	16 UTC (2nd)
BSC00WC04	Western Canada	00 UTC	04 UTC (1st)
		4 km grid	16 UTC (2nd)

Table 8 lists the percentage of smoke forecasts produced by BlueSky – Canada (1100 forecasts were scheduled for the 183 calendar days).

Table 8.Operational reliability of BlueSky during the 2015 fire season.

Domain	Period	Calendar Days	Forecasts Produced* (AM & PM)	Reliability of Produced Forecasts
BSC18CA12	AM	183	175	96%
	PM	183	172	94%
BSC18EC04	AM	183	163	89%
	PM	18	164	90%
BSC00CA12	AM	92	89	97%
	PM	92	89	97%
BSC00WC04	AM	92	90	98%
	PM	92	90	98%

* Determined from a count of forecast output files in the archives.

3.1.4 Performance and Validation

Various studies were conducted, comparing BlueSky – Canada smoke forecasts to monitoring ground stations and to satellite imagery. These approaches proved to have their challenges. Space-time paired comparisons to $PM_{2.5}$ monitoring data typically show errors in the details of the magnitude and timing of events. Qualitative comparisons between the forecast smoke patterns and actual impacted areas using MODIS images indicate reasonable agreement in situations involving extensive smoke from large fire complexes.

Comparisons of BlueSky Canada's smoke forecasts to $PM_{2.5}$ monitoring data was conducted for the 2014 fire season. In terms of area burned, this was an extreme year for Canada, the worst since 1998, with 5,126 fires burning over 4.5 million hectares (3.4 million in the NWT alone) (CIFFC 2015).

The first case study was designed to compare forecasted $PM_{2.5}$ concentrations against ground station reports from Yellowknife NWT and Fort Chipewyan AB but a lack of carry-over smoke in the model created unrealistic results. This lead to a decision to include carry-over smoke in future forecasts.

A second more comprehensive study (unpublished) examined BlueSky output against 39 stations in Alberta. This study allowed for testing of some features including carry-over smoke, wet deposition, and particle versus puff mode modes. Again it was found that it is very difficult to produce accurate forecasts for a location very close to many forest fires. It does not take much movement in the atmosphere to displace smoke vertically or horizontally, resulting in poor verification scores. Still the study pointed towards a better selection of parameters driving the BlueSky system.

Qualitative comparison of column-integrated BlueSky smoke forecasts against satellite imagery showed much better comparisons. The BlueSky forecasts currently predict ground concentrations as this has the most impact on public health and safety. On the other hand, it cannot be compared directly with satellite imagery as the smoke may be at higher elevations in the atmosphere. By vertically integrating the smoke forecasted in the model, a product is created that can be used to compare with imagery.

Figures 5 and 6 illustrate a comparison of a column-integrated smoke forecast to a satellite image. Figure 5 shows fires north of Great Slave Lake emitting large amounts of smoke into the atmosphere, which is then carried to the southeast. Figure 6 shows the column-integrated BlueSky smoke forecast for the same period.

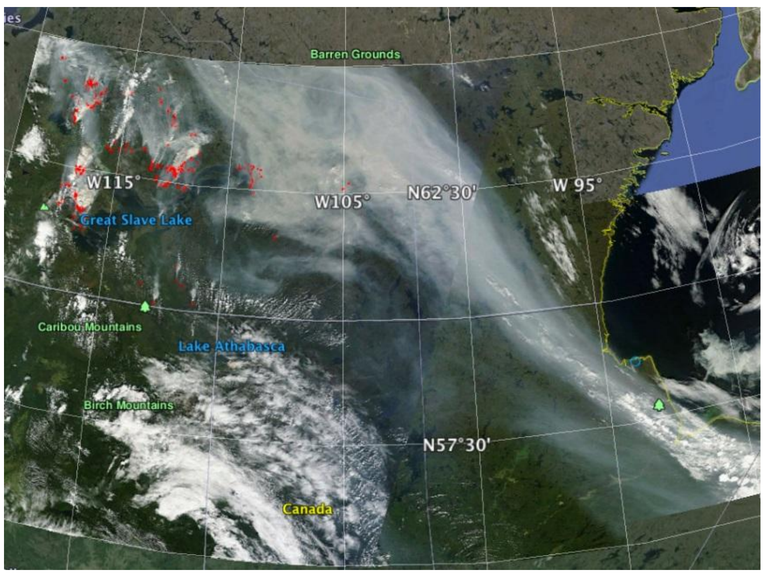

Figure 5.TERRA satellite image of northern central Canada from 23 July 2014.

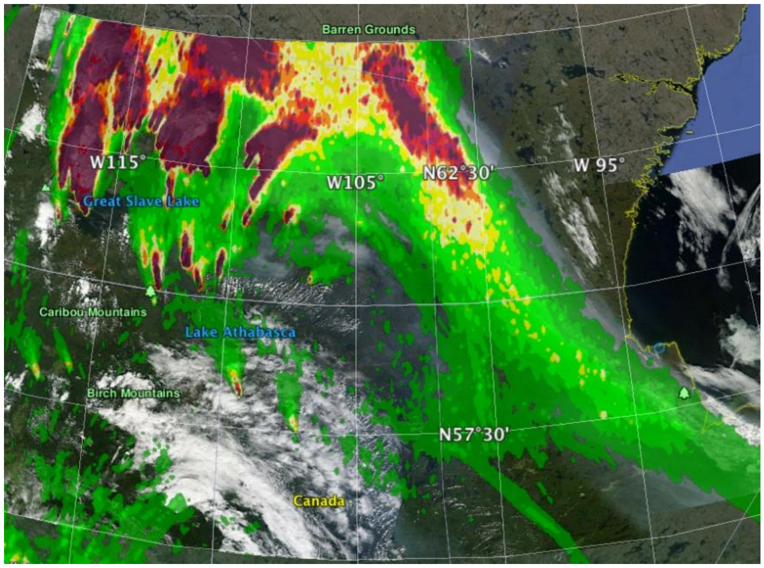

Figure 6. TERRA satellite image (in gray) of northern central Canada overlaid with BlueSky column-integrated output (colours) for 23 July 2014.

Computer code and description of calculations for column-integrated smoke forecasts was provided to UBC BlueSky – Canada operations in August 2015. These files will be implemented in UBC's operational version of the framework by 31 Mar 2016. These new graphics will be an option that users can select on the firesmoke.ca website.

3.2 BlueSky – Canada Playground

The BlueSky – Canada Playground program was operational during the three years covered by the project. Improvements to Canadian BlueSky Playground improvements included development of a user interface compatible with the Canadian Forest Fire Danger Rating System (CFFDRS), and new algorithms for pile burning, diurnal characteristics of burning, and wildland fire conditions.

Figure 7 shows the user interface for the Playground system. After entering the latitude, longitude and the date of the fire, the user selects the most representative fuel type, the fire danger conditions, slope, aspect and wind speed and direction. Fire danger is captured by Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC) and the Drought Code (DC). From these values, the suite of FWI and FBP outputs are calculated and emissions using CONSUME (Prichard *et al.* 2009).

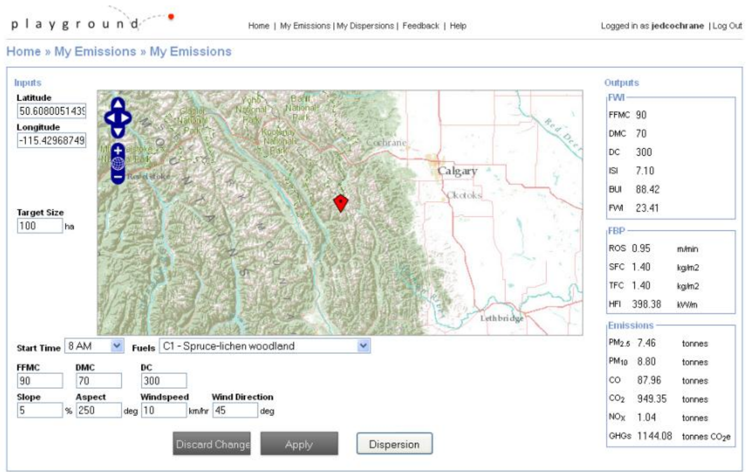

Figure 7. Screen shot of BlueSky - Canada Playground Interface

During 2013, users made 445 dispersion model runs, with the following usage pattern: 293 dispersion model runs prior to the fire season (January to March); 112 dispersion model runs during the fire season; and 40 dispersion model runs after the fire season (October to December).

Records were lost for the number of model runs for 2014.

Users ran 896 Playground smoke-simulation scenarios between April 17 and December 10, 2015, and an additional 56 simulations between January 1 to 25, 2016.

3.3 Canadian Forest Fire Emissions Prediction System

The Canadian Forest Fire Emissions Prediction System (CFFEPS) was developed and implemented in the BlueSky Framework used by the BlueSky – Canada system. This included a method to use CFFDRS products as inputs into the BlueSky – Canada system and Playground. A method to predict plume rise was also integrated into the systems.

To make the program compatible with the BlueSky Framework, three separate programs were designed. The first contained the fire-growth and energy balance calculations; the second conducted the plume rise calculations; the third calculated the emissions. It was decided that the first program would be run by NRCan in Edmonton, leaving the BlueSky to run the plume rise and emissions.

3.3.1 Fire-growth

Elliptical fire-growth used in the CFFEPS model was successfully integrated into the BlueSky - Canada system. Hourly predictions of fire size (in hectares), released energy of the fire (in joules) and values of the flaming, smoldering and residual fuel consumption (measured as fraction of the total fuel consumption) were recorded and passed to the BlueSky framework.

3.3.2 Energy Balance

Constructing an energy balance of a fire turned out to be more problematic than expected. Instead it was decided to inject a fixed amount of the total energy of the fire into the plume. Through adjustment of the correlation scores resulting from the plume rise model described in the next section, it was found that applying 7% of the total energy of the fire to the energy of the plume produced the best results.

3.3.3 Plume Rise

A validation study was conducted using four years of field observations of 85 smoke plumes from 13 fire lookout towers (Anderson *et al.* 2015) from 2010 to 2013. As shown in Figure 8, results indicate a correlation between predicted and observed plume heights with r^2 values ranging from 0.459 to 0.812. The accuracy of the observations may be an issue and thus the true performance of the thermodynamic approach presented may vary from the results shown.

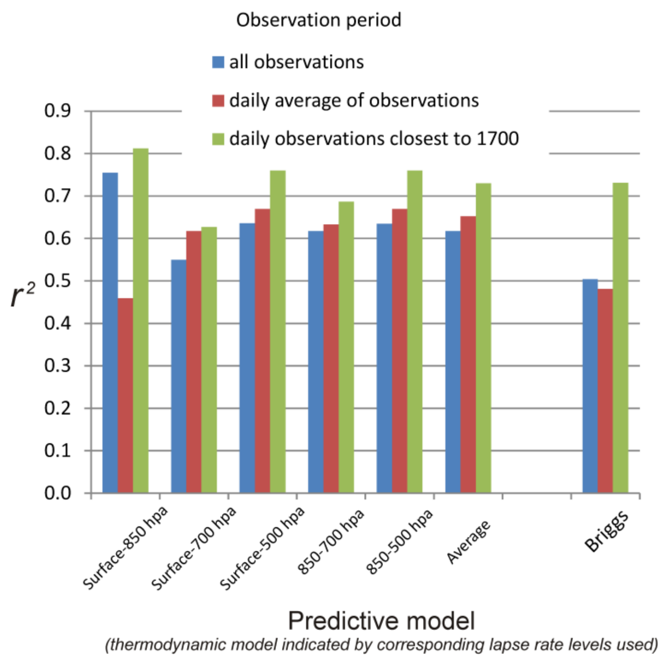

Figure 8. Histogram of correlation coefficients for the Alberta plume study by predictive model and by observation period. The average values are the average of the results less the surface to 850 hpa results.

Predicted plume heights utilizing the thermodynamic approach were compared to those predicted by the Briggs model (currently used in the BlueSky modelling framework), and to the mixing layer height. The latter produced no correlation. Figure 8 shows the Briggs model produced weaker but comparable correlations with the r^2 values range from 0.481 to 0.731, but the dichotomous range and extreme predictions, as shown in Figure 9, weakened the predictive skill of this model compared to the thermodynamic approach.

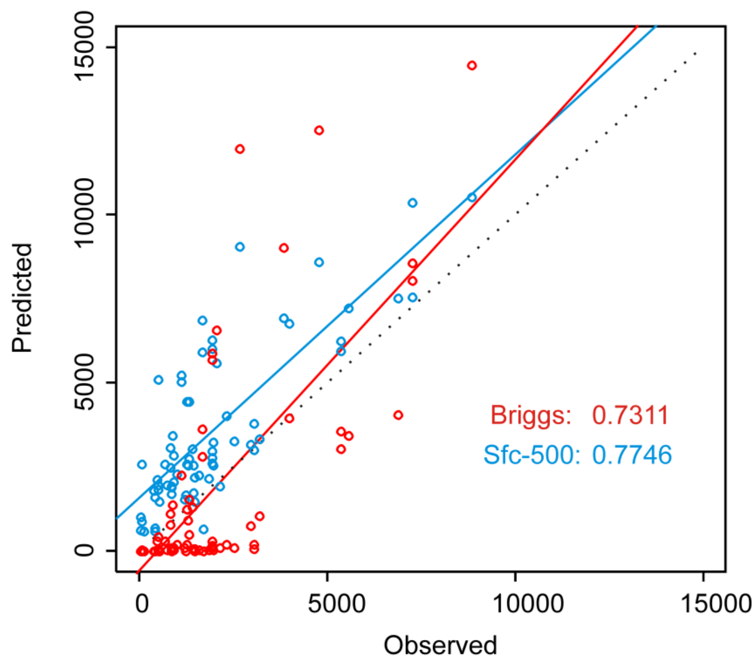

Figure 9. Scatter plot of predicted versus observed plumes from the Alberta plume study. Thermodynamic model predictions based on the surface to 500 hpa lapse rate are shown in blue, Briggs model prediction shown in red. "Predicted equals observed" is shown as a black dashed line. Observed plume heights are limited to daily observations closest to 17:00 LST.

3.3.4 Emissions

The CFFEPS model has been setup to follow the emissions factors used in CONSUME. The model reads in emissions factors, as shown in Table 4, and applies them to determine the emissions rates, evolution and chemical speciation. This information is stored in an ASCII file, allowing for future emissions factors to be easily incorporated into the CFFEPS emissions calculations.

3.4 Outreach

An outreach program was conducted with the intent of making agencies aware of the BlueSky – Canada products and of providing an opportunity for their feedback. Five user-group meetings were held: three in Edmonton and two in Vancouver. Three webinars, six presentations and three posters were presented at various conferences in Canada and the US.

3.4.1 User Group Meetings

During the project, five user group meetings were held. These were aimed at providing outreach and interaction to current and potential users. At each meeting, BlueSky team members gave presentations on the BlueSky – Canada project. The meetings held were as follows:

- On May 24, 2013, an initial meeting of the team was held at UBC. In attendance were BlueSky team members, researchers from the USFS Air Fire Team and staff from Sonoma Technologies Inc.

- A BlueSky Smoke Forecasting Team Meeting was held February 18-20, 2014, at NRCan's Northern Forestry Centre in Edmonton, AB. Attendance included the BlueSky team, Philip Dawe from DRDC CSS, staff from Environment Canada's Canadian Meteorological Centre, and staff from the Alberta Environment and Sustainable Resources.

- An Alberta Smoke Users meeting was held in Edmonton, June 19, 2015. The intent of this meeting was to collect the various federal and provincial agencies in the capital region. In attendance were representatives from Alberta Environment and Sustainable Resource Management, Alberta Health and the Alberta Emergency Management Agency; federal attendees were from Natural Resources Canada and Environment Canada.

- A BlueSky Smoke Forecasting Team Meeting was held in Vancouver October 18-19, 2015. Attendees included BlueSky team members and people from USFS Air Fire Team, Canadian Meteorological Centre and Sonoma Technologies Inc.

- A meeting of Federal departments involved in the production or use of smoke forecasts was held in Edmonton March 29, 2016. The intent of this meeting was to make the various federal departments aware of BlueSky – Canada products and encourage closer collaboration in future years.

3.4.2 Webinars and Presentations

The following webinars were held during the three year period. These presentations helped to promote the project to a wide audience – approximately 300 for the Canadian Institute of Forestry (CIF) lecture series and 200 for the Canadian Interagency Forest Fire Centre (CIFFC) national conversations.

- Anderson K., Cochrane, J. Pankratz, A., Sakiyama, S., Stull, R. "BlueSky Smoke Forecasts for Canada" at the Canadian Institute of Forestry Lecture Series, Edmonton, AB, January 22, 2014.

- Anderson K., Cochrane, J. Pankratz, A., Sakiyama, S., Stull, R. "The BlueSky - Canada Wildland Fire Smoke Forecasting System" for the Canadian Interagency Forest Fire Centre (CIFFC) National Conversation series, April 15, 2014.

- Yao, A "Forest fire smoke and respiratory health in British Columbia" at the BC Lung Association Webinar June 2, 2015, Vancouver, BC

The following presentations were given at conferences on the project during the three year period. Conference presentations typically reached 50 to 100 people.

- Anderson, K. "The Canadian Forest Fire Emissions Prediction System" at 10th Symposium. on Fire and Forest Meteorology, Oct 15-17, 2013. Bowling Green, KY.

- Anderson K.; Cochrane, J.; Pankratz, A.; Sakiyama, S.; Stull, R. "Smoke Forecasts from Wildland Fires for Canada" at the International Smoke Symposium, Oct 21-24, 2013. Washington, DC.

- Henderson, S. "Forest fire smoke exposure and cardiorespiratory mortality in BC, Canada from 2003-2012" at the International Association of Wildland Fire Conference April 20, 2015, Boise, ID

- Henderson, S. "Use of MODIS data to assess atmospheric aerosol before, during, and after community evacuations related to wildfire smoke" at the International Association of Wildland Fire Conference April 20, 2015, Boise, ID

- Anderson, K.; Pankratz, A.; Mooney, C.; Fleetham, K. "An Alberta Plume Study and Comparison to Predictive Models"at 11th Symposium on Fire and Forest Meteorology, May 5-7, 2015. Minneapolis, MN.

- Henderson, S. "Extreme summer weather and respiratory health" at the Asthma Society Clearing the Air Summit May 5, 2015, Toronto, ON

3.5 National Smoke Forum

A National Forum/Workshop was held in Halifax, Nova Scotia on October 10, 2014 in association with the Wildland Fire Canada conference. The Forum was an opportunity to discuss the importance of wildfire smoke, review the current technology and tools that help inform decision making, discuss the policies and issues related to smoke impacts, and suggest plans for projects and organizations to address smoke issues in the future. Sixteen speakers (including two from the US) attended. Attendance at the meeting was 43 with another 40 connecting remotely. A proceeding of the workshop was produced. The National Smoke Forum was held in conjunction with the Wildland Fire Canada Conference, to promote attendance from the fire community.

3.6 Publications

Thirteen publications (4 refereed journal publications; 1 extended abstract; 1 conference proceeding; 7 newsletter articles), and various internal documents and technical documentation were produced from for this project.

3.6.1 Journal Publications

In "*An Evaluation of the British Columbia Asthma Monitoring System (BCAMS) and $PM_{2.5}$ Exposure Metrics During the 2014 Forest Fire Season*" (McLean *et al.* 2015), the BCAMS was evaluated by relating excursions for asthma-related physician visits and dispensations of the reliever medication salbutamol sulfate toc corresponding smoke exposures. Results showed that most excursions (57-71%) were assigned to measured or modeled $PM_{2.5}$ concentrations of 10 $\mu g/m^3$ or higher. Of the smoky days, 55.8% and 69.8% were associated with at least one excursion for physician visits and salbutamol dispensations, respectively. In conclusion, the BCAMS performed well, alerting most often when measures of smoke exposure were relatively high.

In "*Use of MODIS data to assess atmospheric aerosol before, during, and after community evacuations related to wildfire smoke*" (Krstic and Henderson, 2015), a retrospective assessment of 41 smoke-related evacuations in Canada between 2000 and 2007 was conducted using smoke and cloud data from the Terra MODIS. Daily mean aerosol optical depth (AOD) measurements were used to represent smoke levels in the area surrounding each evacuation site. Time series of these data were plotted for the four days prior to evacuation, the evacuation date, and the four days following the evacuation. Daily AOD values were scaled using the daily cloud mask to crudely account for the fact that heavy aerosol can be classified as cloud. Time series plots and the percentage differences between pre- and post-evacuation AOD were used to contextualize each evacuation. Out of 41 cases, approximately half met each of the criteria used to assess public health protection, namely: (1) post-evacuation AOD values over the risk threshold for sensitive populations; (2) peak AOD exposures occurring post-evacuation; and (3) mean AOD higher post-evacuation than pre-evacuation. Some evacuations did not meet any of these criteria. Although evacuation decisions would never be made in the absence of situational intelligence, it was concluded that systematic use of objective and readily available remote sensing data can help to retrospectively evaluate smoke-related evacuations, and may be useful for prospective, real-time application with further development.

In "*Impact of Fine Particulate Matter ($PM_{2.5}$) Exposure During Wildfires on Cardiovascular Health Outcomes*" (Haikerwal et al. 2015), the associations of out-of-hospital cardiac arrests, IHD, acute myocardial infarction, and angina (hospital admissions and emergency department attendance) with $PM_{2.5}$ concentrations were examined during the 2006–2007 wildfires in Victoria, Australia, using a time-stratified case-crossover study design. Health data were obtained from comprehensive health-based administrative registries for the study period (December 2006 to January 2007). Modeled and validated air exposure data from wildfire smoke emissions (daily average $PM_{2.5}$, temperature, relative humidity) were also estimated for this period. There were 457 out-of-hospital cardiac arrests, 2106 emergency department visits, and 3274 hospital admissions for IHD. After adjusting for temperature and relative humidity, an increase in interquartile range of 9.04 lg/m^3 in $PM_{2.5}$ over 2 days moving average (lag 0-1) was associated with a 6.98% (95% CI 1.03% to 13.29%) increase in risk of out-of-hospital cardiac arrests, with strong association shown by men (9.05%,95%CI 1.63% to 17.02%) and by older adults (aged ≥65 years) (7.25%, 95% CI 0.24% to 14.75%). Increase in risk was (2.07%, 95% CI 0.09% to 4.09%) for IHD-related emergency department attendance and (1.86%, 95% CI: 0.35% to 3.4%) for IHD-related hospital admissions at lag 2 days, with strong associations shown by women (3.21%, 95% CI 0.81% to 5.67%) and by older adults (2.41%, 95% CI 0.82% to 5.67%). The conclusion of the report was that $PM_{2.5}$ exposure was associated with increased risk of out-of-hospital cardiac arrests and IHD during the 2006–2007 wildfires in Victoria. This evidence indicates that $PM_{2.5}$ may act as a triggering factor for acute coronary events during wildfire episodes.

In "*The FireWork Air Quality Forecast System with Near-Real-Time Biomass Burning Emissions: Recent Developments and Evaluation of Performance for the 2015 North American Wildfire Season*" (Pavlovic*et al.*, in press), Environment and Climate Change Canada's FireWork air quality (AQ) forecast system was documented and evaluated. Many of the components designed for BlueSky Canada, were shared with the ECCC team, including the near-real-time biomass burning emissions based on the Canadian Wildland Fire Information System (CWFIS). In this study, the capability of the system was demonstrated by analyzing two forecast periods in 2015 (June 2-July 15, and August 15-31) when fire activity was high, and observed fire smoke impacted areas in western Canada and the western U.S. Modelled $PM_{2.5}$ surface concentrations were compared with surface measurements and benchmarked with results from the operational RAQDPS, which did not consider near-real-time biomass burning emissions. Model performance statistics showed that FireWork outperformed RAQDPS with improvements in forecasted hourly $PM_{2.5}$ across the region; the results were especially significant for stations near the path of fire plume trajectories. Although the hourly $PM_{2.5}$ concentrations predicted by FireWork still displayed bias for areas with active fires for these two periods (Mean Bias of 7.3 μg m-3 and 3.1 μg m 3), it showed better forecast skill than the RAQDPS (MB of 11.7 μg m-3 and -5.8 μg m 3) and demonstrated a greater ability to capture temporal variability of episodic $PM_{2.5}$ events (correlation coefficient values of 0.50 and 0.69 for FireWork compared to 0.03 and 0.11 for RAQDPS). A categorical forecast comparison based on an hourly $PM_{2.5}$ threshold of 30 μg m-3 also showed improved scores for probability of detection (POD), critical success index (CSI) and false alarm rate (FAR).

3.6.2 Conference Proceedings and Posters

During the project, the following posters were presented:

- Anderson, K. "The Canadian Forest Fire Emissions Prediction System" at National Smoke Forum, October 10, 2014, Halifax, NS.

- Howard, R.; Seagram, A.; Stull, R. "A Model for the Vertical Spread of Forest Fire Smoke within the Initial Smoke Plume , at the Canadian Meteorological and Oceanographic Society's 49th Congress, May 31 - June 4, 2015

During the project, the following extended abstract was presented:

- Anderson, K.; Pankratz, A.; Mooney, C.; Fleetham, K. 2015. An Alberta Plume Study and Comparison to Predictive Models. In 11th Symp. on Fire and Forest Meteorology, May 5-7, 2015. Minneapolis, MN. Am. Meteorol. Soc., Boston, MS. 11 pp.

These helped to capture the current work and promote the project to the international scientific community.

3.6.3 Newsletters

A four-part article on the BlueSky - Canada project was presented in the 2013 issue the Canadian Smoke Newsletter (Al Pankratz, editor). For the first article in the series, Sakiyama provided a historical perspective of the project, describing its roots in the 2007 meeting in Edmonton to the present. Anderson then described the funding of the project by the Canadian Safety and Security Program. Schigas and Stull described the operations of the BlueSky - Canada system at UBC, while Cochrane described the BlueSky - Canada playground.

Anderson wrote an article entitled "Where there's fire, there's smoke" for the Canadian Safety and Security Project Connect newsletter (Fall 2014). In the article, Anderson described the BlueSky - Canada project, including the forecasting system and the Playground.

As part of a CSSP contract, Stocks wrote an article entitled "Towards Establishing a National Forum on Smoke Forecasting in Canada" for the 2014 issue the Canadian Smoke Newsletter (Al Pankratz, editor).

Sakiyama*et al.* wrote "A Report on the Halifax National Smoke Forum, October 14, 2014" for the 2015 issue the Canadian Smoke Newsletter (Al Pankratz, editor).

4. DISCUSSION AND CONCLUSIONS

BlueSky - Canada is now an operational tool being used in Canada. Run out of the Geophysical Disaster Computational Fluid Dynamics Center of the University of British Columbia's Department of Earth, Ocean and Atmospheric Sciences, BlueSky - Canada provides smoke forecasts for all of Canada south of the Arctic Ocean. Smoke dispersion forecasts are produced four times a day using the latest wildland fire information. The system is able to handle thousands of fires and process the smoke emissions, transport and dispersion in concert with the weather forecasts.

The six objectives of the project included BlueSky - Canada smoke forecasting system, BlueSky - Canada Playground, the Canadian Forest Fire Emissions Prediction System (CFFEPS), Webinars and Presentations, National Forum/Workshop, and Publications.

- The BlueSky - Canada smoke forecasting system successfully ran for the three fire seasons of the project. The project started with a 12 km western domain extending from BC to western Ontario with a 4 km resolution grid for BC and Alberta. The system was expanded to include eastern Canada on May 29, 2013 at 36 km resolution, which was reduced to 12 km beginning in 2014. For the 2015 fire season, a 12-km national grid was created to cover all of Canada with east and west domains embedded in the national grid. Forecasts were originally produced daily, but this was increased to four times a day for 2014.

- The BlueSky - Canada Playground program was introduced with the project. Based on the USFS program, the Canadian version was modified substantively to use input from the Canadian Forest Fire Danger Rating System. This created a powerful tool that has proven to be quite useful for Canadian fire management agencies.

- The Canadian Forest Fire Emissions Prediction System (CFFEPS) was developed and implemented in the BlueSky Framework used by the BlueSky – Canada system. This included a method to use CFFDRS products as inputs into the BlueSky – Canada system and Playground. A method to predict plume rise was also integrated into the systems.

- An outreach program was conducted with the intent of making agencies aware of the BlueSky – Canada products and of providing an opportunity for their feedback. Five user-group meetings were held: three in Edmonton and two in Vancouver. Three webinars, six presentations and three posters were presented at various conferences in Canada and the US.

- A National Forum/Workshop was held in Halifax, Nova Scotia on October 10, 2014 in association with the Wildland Fire Canada conference. The Forum was an opportunity to discuss the importance of wildfire smoke, review the current technology and tools that help inform decision making, discuss the policies and issues related to smoke impacts, and suggest plans for projects and organizations to address smoke issues in the future. Sixteen speakers (including two from the US) attended. Attendance at the meeting was 43 with another 40 connecting remotely. A proceeding of the workshop was produced.

- Four journal publications, 3 poster and extended abstracts and 6 newsletter articles were published as part of this project. More manuscripts are in preparation for the 2016 Canadian Wildland Fire and Smoke Newsletter.

In addition to BlueSky - Canada, a further result of this project was that a national community has developed, the objective of which is to bring together members of a wide variety of interest groups to discuss issues around smoke from wildland fires. In the future, this community will establish a future direction for smoke forecasting and research in Canada.

Through this CSSP-funded project, a National Smoke Forum series was established in association with the Wildland Fire Canada Conferences. The first such forum was held in October 10, 2014 in Halifax, Nova Scotia, while the second is now being planned for October 28, 2016 in Kelowna, British Columbia.

The project was an opportunity to conduct interdepartmental collaboration. This included cooperation between federal departments (Natural Resources Canada, Environment Canada, Parks Canada and Department of National Defense), provincial agencies (British Columbia Ministry of Environment) and academia (University of British Columbia). Further collaboration outside of the core project team included various departments from Alberta, Saskatchewan, Manitoba and Ontario. All in all, this project was an example of how government departments can work together towards a common goal. Many of the initial trials and disagreements were successfully resolved.

5. REFERENCES

Anderson, G. K., D. V. Sandberg, and R. A. Norheim, 2004. Fire Emission Production Simulator (FEPS) User's Guide.*USDA Forest Service* , 99 pp.

Anderson, K.R., 2000. Incorporating smoldering into fire growth modelling.Pages 31-36 *in* 3rd Symp.on Fire and Forest Meteorology, Jan. 9-14, 2000, Long Beach, CA. Am. Meteorol. Soc., Boston, MS.

Anderson, K.R., P. Englefield, J.M. Little, and G. Reuter, 2009.An approach to operational forest fire growth predictions for Canada, *Int. J. Wildland Fire*,**18**, 893-905.doi:10.1071/WF08046.

Anderson, K.R., Pankratz, A., and Mooney, C, 2011. A thermodynamic approach to estimating smoke plume heights. *In* 9th Symp.on Fire and Forest Meteorology, Oct 18-20, 2011. Palm Springs, CA. Am. Meteorol. Soc., Boston, MS. 7 pp.

Anderson, K.R., Pankratz, A., Mooney, C., and Fleetham, K. 2015. An Alberta Plume Study and Comparison to Predictive Models.*In* 11th Symp.on Fire and Forest Meteorology, May 5-7, 2015. Minneapolis, MN. Am. Meteorol. Soc., Boston, MS.11 pp.

Beverly, J.L., and Bothwell, P. 2011. Wildfire evacuations in Canada 1980–2007. Natural Hazards, 59, 571–596.

Byram, G.M. 1959. Combustion of forest fuels. Pages 61-89 in K.P. Davis, ed, Forest Fire: control and use. McGraw-Hill Book Co., New York.

CIFFC [Canadian Interageny Forest Fire Centre]. 2015. Canada Report 2014. Canadian Interagency Forest Fire Centre, Winnipeg, Manitoba, Canada. de Groot W.J., J.M. Pritchard, T.J. Lynham, 2009. Forest floor fuel consumption and carbon emissions in Canadian boreal forest fires.*Canadian Journal of Forest Research* 39, 367–382.

Finney MA, 1998. FARSITE: Fire area simulator – model development and evaluation. Res. Pap. RMRS-RP-4. USDA For. Serv., Rocky Mt. Res. Stn. Ogden, UT.

Forestry Canada Fire Danger Group, 1992. Development and structure of the Canadian Forest Fire Behavior Prediction System, Science and Sustainable Development Directorate, Information Report ST-X-3, Vol. 3. Forestry Canada, Science and Sustainable Development Directorate.

Gould, J.S., Patriquin, M.N., Wang, S., McFarlane, B.L., & Wotton, B.M. 2013. Economic evaluation of research to improve the Canadian forest fire danger rating system. Forestry, 86(3), 317–329.

Haikerwal, A., Akram, M., Del Monaco, A., Smith, K., Sim, M.R., Meyer, M., Tonkin, A.M., Abramson, M.J. and Dennekamp, M., 2015.Impact of fine particulate matter (PM2. 5) exposure during wildfires on cardiovascular health outcomes.Journal of the American Heart Association, 4(7), p.e001653.

Krstic, N.; Henderson, S.B. 2015. Use of MODIS data to assess atmospheric aerosol before, during, and after community evacuations related to wildfire smoke. Remote Sensing of Environment 166, 1-7.

Larkin, N.K., O'Neill S.M., Solomon R., Krull C., Raffuse S., Rorig M., Peterson J., Ferguson S.A., 2009. The BlueSky smoke modeling framework.*International Journal of Wildland Fire,* 18, 906-920.

Lawson B.L., Armitage O.B., Hoskins W.D., 1996. Diurnal variations in the fine fuel moisture code: tables and computer source code. Canadian Forest Service, Forest Resource Development Agreement Report 245. Canadian Forest Service: Victoria, BC.

McLean, K.E.; Yao, J.; Henderson, S.B. 2015. An Evaluation of the British Columbia Asthma Monitoring System (BCAMS) and PM2.5 Exposure Metrics during the 2014 Forest Fire Season. Int. J. Environ. Res. Public Health 2015, 12, 6710-6724; doi:10.3390/ijerph120606710

Pavlovic, R.; Chen, J.; Anderson, K.; Moran, M.D., Beaulieu, P.A.; Davignon, D; Cousineeau, S. (in press) The FireWork Air Quality Forecast System with Near-Real-Time Biomass Burning Emissions: Recent Developments and Evaluation of Performance for the 2015 North American Wildfire Season (accepted by Journal of Air and Waste Management Association)

Prichard S.J., Ottmar R.D, and Anderson, G.K, 2009. Consume 3.0 User's Guide Pacific Northwest Research Station, Pacific Wildland Fire Sciences Laboratory, USDA Forest Service. 233 pp.

Stein A.F., Draxler R.R., Rolph G.D., Stunder B.J.B., Cohen M.D. and Ngan F., 2015 NOAA's HYSPLIT atmospheric transport and dispersion modeling system. *Bulletin of the American Meteorological Society* 96(12), 2059-2077.

Tymstra C, Flannigan MD, Armitage OB, Logan K, 2007. Impact of climate change on area burned in Alberta's boreal forest. *International Journal of Wildland Fire* 16(2):153-160.

Van Wagner C.E., 1987. Development and structure of the Canadian Forest Fire Weather Index System. Canadian Forestry Service, Forestry Technology Report 35. Ottawa, ON. 36 pp.

5.1 Publications

Anderson, K. 2013. Canadian Safety and Security Program Project Charter. 2013 Smoke forecasts from wildland fires for Canada. CSSP-2013-CP-1019.Version 1.7a. 11 pp

Anderson, K. 2013. BlueSky - Canada Part 2 - 2013 CSSP Project. The Canadian Smoke Newsletter 2013, 27-28.

Anderson, K. 2014. Development and Structure of the Canadian Forest Fire Emissions Prediction System (Internal report).19 pp.

Anderson, K. 2014. Where there's fire, there's smoke. Canadian Safety and Security Project Connect Fall 2014, 4: 5-6.

Anderson, K.; Dawe, P.; Mintz, R. 2014. Canadian Safety and Security Program Project Charter. 2014 Smoke forecasts from wildland fires for Canada. CSSP-2013-CP-1019.Version 2.0.11 pp.

Anderson, K.; Pankratz, A.; Mooney, C.; Fleetham, K. 2015. An Alberta Plume Study and Comparison to Predictive Models. In 11th Symp.on Fire and Forest Meteorology, May 5-7, 2015. Minneapolis, MN. Am. Meteorol. Soc., Boston, MS.11 pp.

Cochrane, J. 2013. BlueSky - Canada Part 4 - playground: a tool to inform prescribed burn decisions (the Canadian version). The Canadian Smoke Newsletter 2013, 33-34.

Haikerwal, A., Akram, M., Del Monaco, A., Smith, K., Sim, M.R., Meyer, M., Tonkin, A.M., Abramson, M.J. and Dennekamp, M., 2015.Impact of fine particulate matter (PM2. 5) exposure during wildfires on cardiovascular health outcomes.Journal of the American Heart Association, 4(7), p.e001653.

Krstic, N.; Henderson, S.B. 2015. Use of MODIS data to assess atmospheric aerosol before, during, and after community evacuations related to wildfire smoke. Remote Sensing of Environment 166, 1-7.

McLean, K.E.; Yao, J.; Henderson, S.B. 2015. An Evaluation of the British Columbia Asthma Monitoring System (BCAMS) and $PM_{2.5}$ Exposure Metrics during the 2014 Forest Fire Season. Int. J. Environ. Res. Public Health 2015, 12, 6710-6724; doi:10.3390/ijerph120606710

Pavlovic, R.; Chen, J.; Anderson, K.; Moran, M.D., Beaulieu, P.A.; Davignon, D; Cousineeau, S. (in press) The FireWork Air Quality Forecast System with Near-Real-Time Biomass Burning Emissions: Recent Developments and Evaluation of Performance for the 2015 North American Wildfire Season (accepted by Journal of Air and Waste Management Association)

Sakiyama, S.; Pankratz, A.; Simpson, B.; Anderson, K. "A Report on the Halifax National Smoke Forum, October 14, 2014." Canadian Smoke Newsletter 2014, 2-8.

Schigas, R and Stull, R. 2013. BlueSky - Canada Part 3 - BlueSky - Canada wildfire smoke: status at UBC. The Canadian Smoke Newsletter 2013, 29-32.

Stock, B.J. 2014. Towards Establishing a National Forum on Smoke Forecasting in Canada. The Canadian Smoke Newsletter 2014, 4-9.

5.2 Presentations

Anderson K., Cochrane, J. Pankratz, A., Sakiyama, S., Stull, R. "BlueSky Smoke Forecasts for Canada" at the Canadian Institute of Forestry Lecture Series, Edmonton, AB, January 22, 2014.

Anderson K., Cochrane, J. Pankratz, A., Sakiyama, S., Stull, R. "The BlueSky - Canada Wildland Fire Smoke Forecasting System" for the Canadian Interagency Forest Fire Centre (CIFFC) National Conversation series, April 15, 2014.

Anderson K.; Cochrane, J.; Pankratz, A.; Sakiyama, S.; Stull, R. "Smoke Forecasts from Wildland Fires for Canada" at Canada - US Smoke Forecasting Meeting, May 24, 2013, Vancouver, BC.

Anderson, K. "The Canadian Forest Fire Emissions Prediction System" at 10th Symp. on Fire and Forest Meteorology, Oct 15-17, 2013. Bowling Green, KY.

Anderson K.; Cochrane, J.; Pankratz, A.; Sakiyama, S.; Stull, R. "Smoke Forecasts from Wildland Fires for Canada" at the International Smoke Symposium, Oct 21-24, 2013. Washington, DC.

Anderson, K. "The Canadian Forest Fire Emissions Prediction System" at BlueSky Smoke Forecasting Team Meeting, Feb 18-20, 2014. Edmonton, AB.

Sakiyama, S.; Anderson K.; Cochrane, J.; Lyder, D.; Pankratz, A.; Stull, R.; Schigas, R. "BlueSky Team Meeting" at BlueSky Smoke Forecasting Team Meeting, Feb 18-20, 2014. Edmonton, AB.

Anderson K.; Cochrane, J.; Pankratz, A.; Sakiyama, S.; Stull, R. "Smoke Forecasts from Wildland Fires for Canada" at National Smoke Forum, October 10, 2014, Halifax, NS.

National Smoke Forum Proceedings, October 10, 2014, Marriott Harbourfront Hotel, Halifax, Nova Scotia, Canada. (in preparation) 25 pp.

Henderson, S. "Forest fire smoke exposure and cardiorespiratory mortality in BC, Canada from 2003-2012" at the International Association of Wildland Fire Conference April 20, 2015, Boise, ID

Henderson, S. "Use of MODIS data to assess atmospheric aerosol before, during, and after community evacuations related to wildfire smoke" at the International Association of Wildland Fire Conference April 20, 2015, Boise, ID

Henderson, S. "Extreme summer weather and respiratory health" at the Asthma Society Clearing the Air Summit May 5, 2015, Toronto, ON

Yao, A "Forest fire smoke and respiratory health in British Columbia" at the BC Lung Association Webinar June 2, 2015, Vancouver, BC

5.3 Posters

Anderson, K. "The Canadian Forest Fire Emissions Prediction System" at National Smoke Forum, October 10, 2014, Halifax, NS.

Thi, A.; Lyder, D. Improvements to the 2012 Evaluation of the Western Canadian BlueSky Smoke Forecasting System at National Smoke Forum, October 10, 2014, Halifax, NS.

Howard, R.; Seagram, A.; Stull, R. "A Model for the Vertical Spread of Forest Fire Smoke within the Initial Smoke Plume , at the Canadian Meteorological and Oceanographic Society's

49th Congress, May 31 - June 4, 2015