BC Clean Air Research Fund

Final Report

A new approach to modelling smoke plume rise for BC wildfires

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Prof. Roland Stull
604-822-5901, FAX: 604-822-6088, rstull@eoas.ubc.ca

Nadya Moisseeva, PhD Candidate
nmoisseeva@eos.ubc.ca

Dr. Rosie Howard
rhoward@eoas.ubc.ca

Department of Earth, Ocean and Atmospheric Sciences
University of British Columbia
2020-2207 Main Mall
Vancouver, BC, V6T 1Z4

Final report written by Nadya Moisseeva.

PROJECT OVERVIEW

Abstract

This work aims to better describe wildfire smoke-plume rise to enable the BlueSky Modeling Framework (BSF) to make more accurate smoke-concentration (PM2.5) forecasts.

In the first activities, Howard and Stull replaced an older inappropriate smoke-stack description of plume rise with a model called VIPER (Vertical Injection of Particulates Emitted from Wildfires). VIPER uses the large-scale heat released from the fire to turbulently mix the smoke upward into a deep mixed-layer of air.

While VIPER is a step in the right direction, recent observations suggest that smoke rise might be a hybrid of smoke-stack and mixed-layer behaviors. Namely, smoke-stack behavior is seen near the ground driving the formation of a horizontal reverse flow ahead of the fireline, and mixed-layer behavior of the smoky air is seen at higher altitudes.

This observation motived Nadya Moisseeva to develop a hybrid model — the second stage of this work. Because of the paucity of quality-controlled observation data, she is running Weather Research and Forecasting Spread Fire Model (WRF-SFIRE) as a large eddy simulation (LES) to produce rich synthetic data to simulate plume dynamics of a real prescribed fire. Via sensitivity studies, she found that fire heat flux, horizontal wind and stability profiles dominate the plume dynamics. Her research parameterizes plume kinematics by modelling the depth of the reverse flow using fire heat output (fuel conditions) and meteorological predictors (stability and wind).

Our next research will focus on evaluating the VIPER and hybrid parameterizations using independent LES case studies, and finally incorporating these approaches into BlueSky.

FINANCIAL OVERVIEW

Revenue Description

Table 1 Projected Total Project Revenue (cash and in-kind)

Organization	2016/17		2017/18		Total
	Cash	In-kind	Cash	In-kind	
BC CLEAR - Fraser Basin Council	20,000				20,000
UBC Stull's grants and contracts already on hand	25,121	12,500	12,900	2,500	53,021
Natural Resources Canada (Kerry Anderson)				10,000	10,000
Environment Canada (Al Pankratz)		20,000			20,000
UBC Faculty of Graduate Studies	500				500
UBC EOAS Travel Fund	600				600
TOTAL	46,221	32,500	12,900	12,500	104,121

Table 2 Actual Revenue for the full-year Reporting Period (cash and in-kind)

Organization	2016/17		2017/18		Total
	Cash	In-kind	Cash	In-kind	
BC CLEAR - Fraser Basin Council	20,000				20,000
UBC Stull's grants and contracts already on hand	26,897	12,500	**	**	39,397
Natural Resources Canada (Kerry Anderson)				**	**
Environment Canada (Al Pankratz)		20,000			20,000
CatIQ Canadian Catastrophe Conference Scholarship	1,000				1,000
TOTAL	47,897	22,500	**	**	80,397

Note: Please attach copies of letters or agreements confirming additional funds.

Nadya Moisseeva's salary is paid from a combination of CLEAR and NSERC grants.*
Rosie Howard's salary is paid from a combination of CLEAR and Mitacs grants.*
**Moisseeva received a 3-year NSERC scholarship starting 1 May 2016.*
Stull is in the 5th year of his 5-year NSERC-Discovery grant, which ends 31 Mar 2017.
Stull has two active Mitacs cluster grants, one of which continues through 2020.
I have these funds on hand, and agree to use them to help support the salaries of Rosie Howard and Nadya Moisseeva for this CLEAR project.
*** Values will be determined at the end of the next fiscal year. At present (March 2017), there is no reason to suspect that they will differ from the projected budget.*

Please explain revenue discrepancies (if any)

The original Project Revenue included $1100 of travel funding from UBC Faculty of Graduate Studies and UBC EOAS Travel Fund. The costs were instead covered by a $1000 scholarship received from the CatIQ Canadian Catastrophe Conference (C4 2017, see supporting email attached).

Dr. Rosie Howard received a combination of merit and union-mandated salary increases. These were covered by Prof. Stull's other grants and contracts, resulting in larger numbers in the tables above and below, for cash sources outside of CLEAR.

Expenses Description

Table 3 Projected Expenses for the full-year Reporting Period (cash and in-kind)

Project Costs	**Expenses**		
	All Sources		
	Cash	*In-kind*	*Total*
Salaries and fees	45,121	10,000	55,121
Travel and accommodation	1,100		1,100
Computer Access		5,000	5,000
Fire data and code collab. from other agencies		30,000	30,000
University Indirect Costs of Research (13% for Fraser Basin Council. Higher for other grants and contracts)	(Included in Salaries)		(Included in Salaries)
TOTAL PROJECT COSTS	46,221***	45,000	91,221

Table 4 Actual Expenses for the full-year Reporting Period (cash and in-kind)

Project Costs	**Expenses**		
	All Sources		
	Cash	*In-kind*	*Total*
Salaries and fees	46,897	10,000	56,897
Travel and accommodation	1,000		1,000
Computer Access		5,000	5,000
Fire data and code collab. from other agencies		30,000	30,000
University Indirect Costs of Research (13% for Fraser Basin Council. Higher for other grants and contracts)	(Included in Salaries)		(Included in Salaries)
TOTAL PROJECT COSTS	47,897	45,000	92,897

Please explain expense discrepancies (if any)

1) Travel and salary pay-raise differences were discussed above under "Revenues".

2) Total projected cash expenses listed at ***, plus $12,900 budgeted for the next fiscal year, equal the total $59,121 total cash cost that was in our proposal spreadheet.

RESULTS OVERVIEW

Activity Description

Table 5 Summary of Activities for the Reporting Period

Activity*	Completion Date	Description of Results
(0) Acquisition and set-up of LES model	2016-03-31	See below
(1) LES evaluation	2016-06-30	See below
(2) Set-up and performance of sensitivity tests	2016-12-31	See below
(3) Development of analytical model	Ongoing	See below
(4) Evaluation of analytical model	Ongoing	See below
(5) Refinement of new plume rise theory	Ongoing	See below

*As outlined in the project contribution agreement or contract.

Details of Activities Based on Project Timeline

(0) Acquisition and set-up of LES model

a. *Acquire the latest release of WRF-Fire:*
   Complete
b. *Set-up WRF-FIRE in LES mode on lab computers and clusters:*
   Model configured on local machines, Google Cloud as well as WestGrid cluster
c. *Perform test simulations:*
   Tested standard fire spread scenarios: compared 3 fuel categories for line ignition, tested various ignition conditions (slow and fast initial spread, variable ignition radius), compared 4 different spatial resolutions and time-stepping intervals. Experimented with vertical grid stretching (see Appendix 2 for overview presentation).
d. *Develop output graphics based on test runs:*
   Produced 3D animations using VAPOR visualization software (see Appendix 2 for overview presentation).
e. *Develop evaluation metrics for estimating plume rise:*
   Evaluation to be based on water vapour mixing ratio anomalies produced by WRF-FIRE. Water vapour is used as a surrogate for smoke particulates because LES does not model actual emissions. Water vapour is the primary constituent of forest fire smoke, so its distribution will be representative of real plumes. Full vertical injection profiles will be considered, as such provide valuable input for subsequent dispersion modelling.

(1) LES evaluation

a. *Select case study periods and verification sites*

Identified cases: prescribed research burns from November 2012 at Elgin Airforce Base from RxCADRE 2012 campaign

b. *Acquire observational data for the case studies*
Obtained fuel, surface, fire irradiance, dispersion, and atmospheric sounding data

c. *Perform case study LES simulations*
Developed an idealized domain mimicking large grassland fire from RxCADRE and modelled in high-resolution LES mode

d. *Assess and adjust model performance*
WRF-FIRE handling of ignition and fire spread required significant adjustments.

(2) Set-up and perform sensitivity tests

a. *Develop a set of sensitivity tests required for analytical parameterization of plume rise (wind speed, fire intensity, humidity, environmental sounds)*
A range of sensitivity tests was performed for various wind conditions and stability regimes. Static neutral, unstable turbulent and stable boundary layer conditions with winds ranging from calm to strong were examined.

b. *Calculate metrics for each variable from the output*
Complete

c. *Create output graphics of smoke plume behaviour*
Developed 3D animations of fire and plume behaviour. Produced 2D animations of crosswind average boundary layer response to change in stability and wind conditions (see samples in the attached presentation).

(3) Development of the analytical models

VIPER*:*

The VIPER model employs a theory developed by Dr. Roland Stull, which is motivated by Dr. Kerry Anderson's thermodynamic approach to plume-rise modelling (Anderson, 2011). Annie Seagram has been the primary code developer, under the direction of and in collaboration with Dr. Rosie Howard. As VIPER has advanced, several versions have been produced, the most recent of which is in Appendix 6. In this theory, the area between an environmental sounding and a dry adiabat (as found on a thermo-diagram) is integrated, such that the area A [K m], multiplied by air density [kg m^{-3}] and specific heat capacity [J kg^{-1} K^{-1}] is equal to the heat distributed vertically to warm the air to uniform potential temperature, Q_{distr} [J m^{-2}]. The fire provides the heat input into the air Q_{in}: Heat conservation requires that the heat input be distributed into the air; thus, $Q_{distr} = Q_{in}$.

The value of Q_{in} is calculated independently based upon the Canadian Forest Fire Emissions Prediction System (CFFEPs; Anderson, 2015). VIPER need only find the optimal dry adiabat to solve the equation described above. The model algorithm is as follows:

a. An environmental sounding is provided, with the following required variables: height, temperature, mixing ratio.

b. The sounding is piecewise linearly interpolated. The spacing between the interpolated points is determined by the minimum spacing of the heights of the input sounding.
c. Missing meteorological parameters are calculated for the sounding (e.g. density).
d. An initial dry adiabat is generated such that $Q_{distr} > Q_{in}$, and the temperature difference between the temperature of the sounding and the dry adiabat at the surface is ΔT_0.
e. The estimated value of ΔT_0, and thus the resulting dry adiabat, is then adjusted using a bisection algorithm. Once the value of Q_{distr} approaches Q_{in} within a predetermined tolerance level, i.e. $Q_{in} - Q_{distr} < Q_{tolerance}$, the algorithm terminates.
f. The height at which the final dry adiabat and the environmental sounding intersect determines the maximum equilibrium smoke-plume height, and the amount of heating that occurred at each level below that maximum height is proportional to the amount of smoke vertically dispersed to those levels.

Key amendments and improvements to VIPER are summarized below (see Appendix 6 for technical details):

- Wind direction does not affect the plume rise output from VIPER: $s = |U - r|$.
- Local convection created by the fire itself is considered, increasing the heat available from the fire. This decreases in value as the environmental temperature increases.

Hybrid:

Nadya Moisseeva's hybrid model is based on plume kinematics, rather than bulk methods. Using thermodynamic approximations from Dr. Kerry Anderson (NRCan) and Vertical Injection of Particulates Emitted from Wildfires (VIPER) model Moisseeva's approach aims to parameterize near-ground vertical velocities associated with pyro convection. Using ambient atmospheric conditions and assuming mass continuity within each vertical layer of the atmosphere, the model predicts the depth of the near-surface reverse flow formation ahead of the fire. The bottom of the smoke injection layer corresponds to the vertical level at which the reverse flow is fully extinct.

(4) Evaluation of the analytical models

VIPER:

(a) Observational plume-rise data and temperature profile input to VIPER

Fire-spotter smoke-plume rise observations have been collected for 102 wildfires in Alberta, Canada during 2014 and 2015, thanks to Al Pankratz (ECCC). Each observation, measured with an inclinometer, was corrected for observer tower height and earth curvature (Anderson, 2011). Temperature profiles were extracted from the WRF model for the appropriate times and input to VIPER for comparison with these observations.

(b) VIPER evaluation and discussion

VIPER predicts reasonable plume heights between 947.7 m and 3057.1 m, with a standard deviation of 554.4 m (figs. 1 and 2 in Appendix 7). The spread of the observations is larger, between 27.2 m and 4498.6 m, with a standard deviation of 1095.1 m. The root-mean-squared and mean absolute errors of VIPER are 1336.9 m and 1158.0 m, respectively. While these errors seem substantial, they are close to measurement error. The shortest distance between fire observer tower and fire was 12.9 km. Based upon this distance, for an observer error of only 0.5 degrees in elevation angle, the plume height would change by ~100 m. For a distance of 100 km, this error compounds to ~900 m.

Discrepancy between modelled and observed plume heights can also be attributed to errors in the WRF input temperature profiles. Forecast profiles are much smoother than their observed counterparts, so the "missing" differences, which represent energy, will accumulate for larger plume heights, i.e. a larger area on the thermo-diagram. Future work will compare VIPER output using observed temperature soundings within a radius of influence (yet to be determined) of observed plume heights, e.g. from Edmonton Stony Plain, in an attempt to quantify the portion of error introduced by using WRF model profiles.

Hybrid*:*

(a) Select independent case studies to test the new plume rise theory

Using RxCADRE 2012 data, we have identified two fires with differing energy levels and fuel types. A small grassland fire (S5) and a large forested lot burn (L2F) allow to test the plume model at the low and high ends of the energy spectrum, respectively. Both burn experiments were conducted in November 2012 at the Elgin Air Force Base.

(b) Perform LES simulation of the identified case studies to predict plume rise.

L2F fire simulations were performed in collaboration with US Forest Service (USFS). S5 simulation is in preparation.

(c) Use the analytical model to predict plume rise for the same cases

Ongoing.

(d) Compare LES and analytical results

Ongoing.

(e) Produce journal submission and/or conference abstract submission based on new plume rise theory

Paper draft on using LES for modelling wildfire plumes is in preparation for submission to International Journal of Wildland Fire.

(5) Refinement of new plume rise theories

VIPER*:*

(a) Potential model improvements based upon current evaluation

Since the distribution of plume heights is different for observed and modelled (fig. 2, Appendix 7), there are likely physical processes missing from the

VIPER theory, causing the model to not capture the full range of plume heights. For example, atmospheric moisture has not been included. Further research is being carried out to extend the theory so VIPER can predict the low and high plume heights that are currently missing. Nadya Moisseeva's research also applies here.

(b) Potential bias-correction when using forecast instead of observed input temperature soundings

It may be possible to estimate a bias (weather-condition dependent or other) between modelled and observed soundings and the resulting plume height. Although this is clearly an oversimplification of the physical differences between the profiles, nonetheless, it may be a practical solution.

(c) Fire growth behaviour

VIPER relies upon the fire growth model designed by Kerry Anderson (part of CFFEPs) to give the appropriate parameters as input to VIPER, specifically fire-front velocity and area growth. CFFEPs contains many approximations so these parameters are also a source of error, however it helps to produce a large dataset suitable for analysis and is currently our only source for this kind of data.

Hybrid*:*

(a) Adjust model parameters based on (4).
Not started.
(b) Quantify uncertainty / establish error margins.
Not started.
(d) Perform additional LES simulations, as needed.
Not started.
(e) Refine the theory as needed.
Not started.
(f) AMS conference presentation.
Complete (see Deliverable C and Appendix 3).

Please explain activity discrepancies (if any)

VIPER:

Development and testing of VIPER has depended strongly upon the input of Kerry Anderson and development of his fire growth behaviour model. Dr. Anderson frequently updates and debugs this large piece of modular code, and in turn we must rerun VIPER every time a new version is received (once every few months). Compiling the fire growth code can sometimes take multiple days or weeks due to computer platform differences.

Hybrid:

The original approach to WRF-FIRE model evaluation was based on the use of an observational dataset of inclinometer plume rise height measurements made by fire spotters in fire lookout towers. Because of large errors associated with such observations, we also hoped to incorporate satellite data, where available. We have extracted all orbits from Multi-angle Imagining SpectroRadiometer (MISR) coinciding with our inclinometer observations and used an existing reconstruction algorithm to extract plume rise heights. This required manual digitization of satellite plumes for each individual fire, as well as substantial data transfers to obtain all the necessary orbit information. The process was both labour- and computationally- intensive, but essential for quality control.

The results of the cross-evaluation suggested little agreement between inclinometer and satellite data. This presented a substantial obstacle to both WRF-FIRE evaluation and model development. Alternative sources of observational data had to be considered, introducing a delay into the original timeline. The final approach was based on data collected during the research fires as part of the RxCADRE 2012 campaign, as outlined above.

Our observations-driven work on evaluating the ability of WRF-FIRE to capture plume dispersion appears to be the first of its kind. To our knowledge, based on literature review, WRF-FIRE has been evaluated only on its ability to simulate fire spread. Because our work will likely be of great interest to the fire modelling community we made our evaluation studies the focus of our abstract submission for AMS 2017 (see Appendix 1).

Much of the research focus over the last two quarters of the Reporting Period has been dedicated to WRF-SFIRE LES model evaluation. Following the presentation of our results at the AMS 2017 Annual Meeting in Seattle, Washington (Deliverable C, Appendix 3), we have been approached by a number of researchers offering collaboration on the topic (including: AirFire Team, USFS; Fire and Environmental Research Applications Team, USFS; Department of Meteorology, University of Utah). As a result, we have joint efforts with the above collaborators on further fire and plume behavior work with WRF-SFIRE alongside the model's original developers. The unforeseen interest generated by our model evaluation work combined with the challenges in obtaining observational data introduced delays into the original timeline.

Apart from the Activities outlined in the Project Agreement, we are pleased to report on additional contributions not included in the original proposal. Given the relevance of this work in the context of emergency response planning, the Project has benefitted from additional exposure at the CatIQ's Canadian Catastrophe Conference (C4). Nadya Moisseeva has been selected as one of the five Student Delegates across Canada to present her thesis work supported by the CLEAR Fund at the C4 2017 in Toronto. Extra Activities included the preparation and delivery of an oral and poster presentations on LES-based approach for modelling plume rise (see Table 7 and Appendix 4 and 5).

Deliverable Description

Please include copies of all deliverables with the final report (e.g. publications, presentations, research reports, etc.). The final report will be considered incomplete without copies of the project deliverables.

Table 6 Summary of Key Deliverable Accomplishments for the Reporting period

Deliverable*	Description	Description of Results
(A) Midterm Progress Report	Summary of activities including: model setup, data gathering, model evaluation, plume response to various conditions, model development.	Completed: September 30, 2016
(B) Final Report to CLEAR	Summary of activities: model evaluation, theory development, conference presentations	Completed: March 31, 2017 Revised: April 18, 2017
(C) Presentation – AMS Annual Meeting 2017	Report on evaluation of LES (WRF-SFIRE) using real prescribed burn data.	Oral presentation delivered January 23, 2017 (see Appendix 3)

*As outlined in the project contribution agreement or contract.

Please explain deliverables discrepancies (if any)

Apart from the aforementioned deliverables outlined in the project contribution agreement, we are pleased to include two additional accomplishments, summarized in Table 7 below.

Table 7 Summary of Additional Accomplishments for the Reporting period

Additional Deliverables	Description	Description of Results
(C2) Presentation – C4 2017	Overview of LES-based plume rise modelling approach	Oral presentation delivered February 1, 2017 (see Appendix 4)
(C3) Poster Presentation – C4 2017	Overview of LES-based plume rise modelling approach	Poster presentation delivered February 1 – February 3, 2017 (see Appendix 5)

DELIVERABLES

Appendix 1:

American Meteorological Society (AMS) 2017 Annual Conference (Seattle). Abstract Submission

Capturing plume rise and dispersion with WRF-Fire: an RxCADRE case study

The effects of wildfire smoke can cover a broad range of spatiotemporal scales and have a significant impact on regional air quality and human health. The buoyant phase of the smoke plume, which determines its final rise height, has a strong influence on pollutant concentrations downwind, and provides key input into global and regional chemical transport models. Lack of data for model evaluation is widely acknowledged to be the primary limiting factor in plume-rise model development and improvement. As detailed observations of turbulence, entrainment, and 3-D smoke concentrations are notoriously scarce, numerical models provide a valuable alternative to field studies with their ability to generate "synthetic data" for a wide range of conditions. In particular, large eddy simulations (LES) have proved useful in capturing turbulent boundary-layer processes, thereby presenting a viable approach to studying fire plume growth and dispersion. However, the ability of numerical models to simulate fire plume dynamics must still be evaluated with real-world observations.

Weather Research and Forecasting Model (WRF-Fire) allows two-way coupling of LES with a semi-empirical fire growth model. Several studies have examined the ability of WRF-Fire to capture the ground-spread behaviour of a fire line. Yet to the authors' knowledge, no attempts have been made to assess the simulated fire plume dynamics. The recent Prescribed Fire Combustion and Atmospheric Dynamics Experiment (RxCADRE) provides detailed fuel, meteorological, and emissions data from a real prescribed burn. This presents a unique opportunity to perform a ground-truth comparison with WRF-Fire simulated plume rise and dynamics. Observations from RxCADRE are used to initialize the domain, as well as assess the accuracy of plume dispersion predictions.

Results highlight the strengths and limitations of using WRF-Fire for studying plume rise, and provide useful guidelines for modeling smoke dispersion with LES.

Appendix 2:
Overview Presentation of WRF-Fire Experiments
Power point presentation of some initial experiments with WRF-Fire is available at:
https://drive.google.com/open?id=0B6xm0qN-NcniYkxvVGxDa1VQbmM
To ensure proper image and animation playback, please download and view with Microsoft PowerPoint (99MB). Do NOT view this presentation in your web browser, because the animations on pages 16, 17 and 21 will likely not run properly.

Appendix 3:
American Meteorological Society (AMS) 2017 Annual Conference (Seattle). Recorded oral presentation is available at:
https://ams.confex.com/ams/97Annual/webprogram/Paper312089.html

Appendix 4:
CatIQ's Canadian Catastrophe Conference 2017 (C4 2017) presentation slides available at:
http://www.catiq.com/Portals/14/Docs/2017/C42017-Student_Delegate_Presentations_Nadya_Moisseeva.pdf (as published in official Conference Proceedings: includes basic slides only, no videos).

For a copy with proper animation playback, please download from the link below and open with Microsoft PowerPoint (65MB). Do NOT view this presentation in your web browser:
https://drive.google.com/open?id=0B6xm0qN-NcniaU45NkhYVkV6WXc

Appendix 5:
CatIQ's Canadian Catastrophe Conference 2017 (C4 2017) poster
(see attached).

Appendix 6:
Most recent VIPER plume rise theory, version 6.1.

VIPER (Vertical Injection of Particulates Emitted from Wildfires)
A Model for the Vertical Spread of Forest-fire Smoke within the Initial Smoke Plume— Version 6.1
Roland Stull
UBC

{Equation numbers correspond to those in the paper by Anderson, Pankratz, Mooney 2014 (APM).}

Let:
α = aspect ratio = (effective fire-line width) / (firestorm air inflow height) ≈ 1 (dimensionless)

a = fraction of heat released from surface combustion that goes into heating the ground ≈ 0.5
A = area (K·m) enclosed between the atmospheric sounding and the dry adiabat of the fire-warmed air.
b = fraction of heat released from all combustion that is lost into radiation ≈ 0.14
C_f = specific heat for forest fuels [≈ 1.7×10^3 J kg^{-1} K^{-1}]
C_p = specific heat of humid smoky air at constant pressure [1004.7 J kg^{-1} K^{-1} for dry non-smoky air]
C_w = specific heat for liquid water [4,185.5 J kg^{-1} K^{-1}]
E_{distr} = heat distributed vertically to warm the air to uniform pot. temp. (J/ m^2)
E_{in} = heat available: going into an air column from the fire (J/ m^2)
f = fraction of total fuels that are surface fuels
f_c = Kerry's fudge factor relating unburned fraction to Crown Fraction Burned ≈ 0.5
F_c = Crown Fraction Burned (CFB). Get from Canadian Forest-fire Behavior Prediction (FBP) system.
F_i = [(Total fuel mass) – w]/ w = relative amount of additional mass that does not burn
≈ f_c*F_c from Anderson eq. (8).
g = 9.8 m s^{-2} = magnitude of gravitational acceleration
H = heat of combustion (J/kg$_{dry\ fuel}$)
I = heat per unit length along the fire front (J m^{-1} s^{-1})
I_w = heat required to expel water from the fuel before burning
I_{fire} = heat released by combustion
I_f = heat required for fuel preheat
I_r = heat lost as radiation
I_s = heat lost into ground
I_{total} = total heat available to warm the air
L_o = heat required to warm liquid water to boiling and the boil it = $L_v + C_w \Delta T_1$ ≈ [2.794×10^6 J/kg$_{liq\ water\ in\ fuel}$]
L_v = latent heat of vaporization of water [2.501×10^6 J / kg$_{liq\ water\ in\ fuel}$]
q_L = mixing ratio of liquid water relative to dry fuel (kg$_{liq\ water\ in\ fuel}$ / kg$_{dry\ fuel}$)
r = rate of advance of fire line (m/s) ≈ ROS
s = |U – r| = speed of wind relative to the advancing fire line (m/s)
s_{fs} = horizontal inflow fire-storm wind (relative to the fire line) generated by the fire convection
T_b = boiling temperature [100°C at sea level, but decreases with increasing altitude]
T_e = ambient environmental air temperature, assumed equal to pre-burn fuel temperature [≈30°C]
$T_{combust}$ = temperature required for dried fuel to spontaneously combust [≈ 500°C]
$T_{nonburn}$ = final temperature reached by the fuel that does not combust [≈ 400°C]
U = wind speed relative to ground (m/s)
w = mass of the fuel content that <u>combusts</u> per unit surface area (kg$_{dry\ fuel}$ / m^2) ≈ TFC
w_T = total mass of vegetation content per unit surface area = combusted + noncombusted
= $(1 + F_i)\, w \approx (1 + f_c F_c)\, w$.
W = average updraft speed over the fire front, near the tree-top or flame-front-top

$\Delta T_1 = T_b - T_e$ = temperature increase needed to boil water ≈ 70 K.
$\Delta T_2 = T_{combust} - T_e$ = temperature increase needed for fuel spontaneous combustion ≈ 470 K = 470°C.
$\Delta T_{def} = \Delta T_2 - \Delta T_3 = T_{combust} - T_{nonburn}$ ≈ 100 K = 100°C.
ρ = average air density in the smoky air between the surface and the top of the smoky air column

Derivation: *{Equation numbers correspond to those in the paper by Anderson, Pankratz, Mooney 2014 (APM).}*

Energy released by the advancing fire line is proportional to vegetative mass w that combusts (Byram 1959):

$$I_{fire} = Hwr \tag{1}$$

Energy is used to expel water from the total vegetative mass w_T by warming the liquid up to boiling and then evaporating it:

$$I_w = q_L w_T r\left(L_v + C_w \Delta T_1\right) \tag{4a}$$

Using the typical value for ΔT_1 gives:

$$I_w \approx q_L w_T r L_o \tag{4b}$$

where $L_o = L_v + C_w \Delta T_1 \approx 2.794\text{x}10^6$ J/kg.
Then, using Anderson's parameterization $w_T = (1 + F_i)\ w = (1 + f_c F_c)\ w$ gives:

$$I_w = \left(1 + f_c F_c\right) w r q_L L_o \tag{4c}$$

All of the vegetation mass w_T is pre-heated to combustion temperature $T_{combust}$, even though not all of it burns. This pre-heat energy is:

$$I_f = w_T r C_f \Delta T_2 \tag{5a}$$

$$I_f = (1 + f_c F_c) w r C_f \Delta T_2 \tag{5b}$$

The amount of energy conducted and radiated down below the surface is related to the amount of surface fuels that are burning, which make up a fraction f of the total fuel:

$$I_s = afHwr = afI_{fire} \tag{6}$$

where a is the portion of surface combustion that is lost down into the ground.

Radiative energy loss is assumed to be a fraction b of the heat released in the fire:

$$I_r = bI_{fire} \tag{7}$$

Subtracting the energy losses from the energy released by the fire gives the total energy available to heat the air:

$$I_{total} = I_{fire} - I_w - I_f - I_s - I_r \tag{9a}$$

which can be rewritten as

$$I_{total} = I_{fire} - \left(1 + f_c F_c\right) w r q_L L_o - (1 + f_c F_c) w r C_f \Delta T_2 - afI_{fire} - bI_{fire} \tag{9b}$$

or

$$I_{total} = I_{fire}\left[1 - af - b\right] - \left(1 + f_c F_c\right) w r \left[q_L L_o + C_f \Delta T_2\right] \tag{9c}$$

or, using eq.(1):

$$I_{total} = I_{fire}\left\{1 - af - b - \left(1 + f_c F_c\right)\left[\frac{q_L L_o + C_f \Delta T_2}{H}\right]\right\} \tag{9d}$$

The **VIPER** model differs from plume-rise models. Plume rise models assume an unchanging environment through which a smoke plume rises and entrains environmental air along the way. The VIPER model assumes that the wild fire is sufficiently large (of horizontal scale ≥ boundary layer depth) with sufficient heat to create its own convective mixed layer. Turbulence in this fire-mixed layer distributes smoke in the vertical such that the amount of smoke injected at each height is proportional to the amount of warming that occurred at that height. The science behind this is that turbulence is "advective" in nature, so that the same turbulent motions that mix heat will also mix particulates in the same proportion.

Air is blowing past the flame front. Thus, as I_{total} (J m^{-1} s^{-1}) heat is released upward along each meter of the fire line, that heat is injected into the series of air columns that blow across the fire line at speed s (m/s). The resulting heat input into each square meter cross section of an air column base is

$$E_{in} \approx \frac{I_{total}}{s + s_{fs}} \qquad \text{(Stull's eq. 1)}$$

where $s = | U - r |$ is the speed U of air driven by the synoptic & mesoscale meteorology relative to the speed r of the moving flame front. Namely, U relates to external forcings.

An additional air speed (s_{fs}) driven by the local fire-storm convection relative to the moving flame front is shown in the appendix to be:

$$s_{fs} \approx \left[\frac{2g\alpha^2}{\rho C_p T_e} I_{total} \right]^{1/3} \qquad \text{(Stull's eq. 2)}$$

where environmental temperature T_e must be in Kelvin for this eq. This s_{fs} wind can exist even if there is no synoptic-scale wind s; namely, it is the wind created by the fire itself. s_{fs} is analogous to the Deardorff convective velocity scale w_*.

If this heat goes into the air, it warms and convectively mixes the bottom layer of air to become an adiabatic mixed layer (see Figure 1). Let A be the area (K·m) between this dry adiabat and the original sounding. The heat that is associated with this amount of warming is

$$E_{distr} = \rho C_p A \qquad \text{(Stull's eq. 3)}$$

The heat distributed in the air column must equal the heat that was input into the air from the fire:

$$E_{distr} = E_{in} \qquad \text{(Stull's eq. 4)}$$

Namely, the total heat input is sufficient to heat an area A (K·m) on a sounding diagram given by:

$$A = \frac{I_{total}}{\rho C_p \cdot \left(s + s_{fs} \right)} \qquad \text{(Stull's eq. 5)}$$

On a thermo diagram, experiment (i.e., iterate) with different dry adiabats until you find one such that the area between the environmental sounding and the adiabat is equal to the A from Stull eq. 5. The height where this adiabat hits the sounding is the top of the smoky air column. It is the maximum plume-rise equilibrium height. (Some of the buoyant air might initially overshoot this height before settling back down to this height.)

But the smoke doesn't all go to this plume equilibrium level. Instead, the proportion of smoke deposited in any layer is equal to the relative size of the layer rectangle ($\Delta z \cdot \Delta T$) relative to the total area A, in Figure 1. For example, in the sounding in Fig. 1, roughly 2/3 of the smoke would be trapped at and below the mid-level inversion (near the letter "s" in "sounding" in the fig.), with about 1/3 of the total smoke filling the top half of this particular sounding. The vertical smoke distribution would vary widely from fire to fire, depending on the shape of the shape of the environmental sounding on that particular day and the amount of heat and smoke emitted.

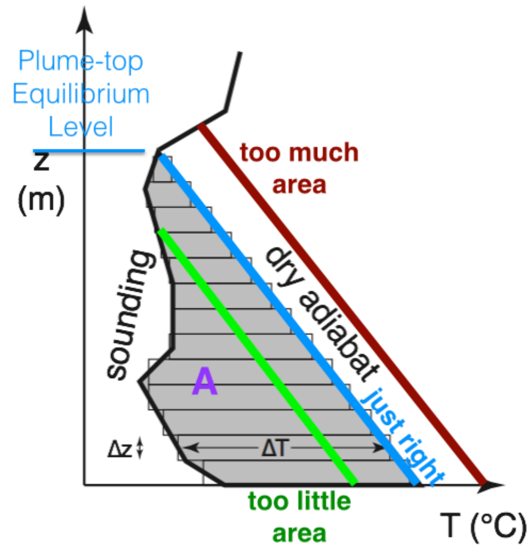

Fig. 1. *Grey area in figure above shows how the total amount of smoke is distributed in the vertical.*

Note: the theory above is for the initial smoke-plume near the fire. Subsequent downwind advection and dispersion must be handled by other models.

VIPER Appendix. Derivation of Firestorm-generated Winds (s_{fs})

Let s_{fs} = net horizontal near-surface inflow component of wind generated by the firestorm.
Let w_{up} = updraft speed
Air mass (volume) conservation requires inflow = outflow: $s_{fs} \cdot \Delta z = w_{up} \cdot \Delta x$
Let α be the fire line cross-section aspect ratio $\alpha = \Delta x / \Delta z$ (assume ≈ 1)
Thus:

$$s_{fc} = \alpha \; w_{up} \qquad \text{(Stull eq. 6)}$$

Recall from thunderstorm theory that the potential energy (*CAPE*) associated with buoyancy can be equated to the kinetic energy/mass ($0.5\, w_{up}^2$) of the updraft. Solving for w_{up}:

$$w_{up} = \sqrt{2 \cdot CAPE} = \sqrt{2 \cdot A \cdot g / T_v} \qquad \text{(Stull eq. 7)}$$

where *CAPE* = convective available potential energy/mass,
A = shaded area (K·m) in the sounding of Fig. 1 above.
g = gravitational acceleration magnitude
T_v = absolute virtual temperature of the environment.

Combine Stull eqs. 6 & 7 to give:

$$s_{fs} = \alpha \sqrt{2 \cdot A \cdot g / T_v} \qquad \text{(Stull eq. 8)}$$

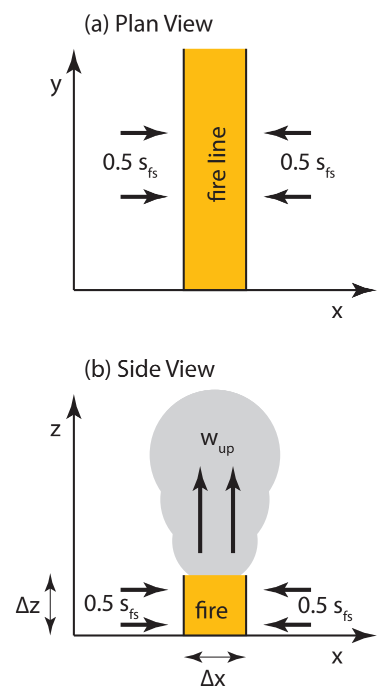

Fig. 2*. Sketch of winds.*

But we know what *A* must be, from Stull eq. (5). Plug this eq. into Stull Eq. 8 to give:

$$s_{fs} = \alpha \left[\frac{2 \cdot g}{T_v} \frac{I_{total}}{\left| s + s_{fs} \right| \rho C_p} \right]^{1/2}$$ (Stull eq. 9)

Square both sides and rearrange to give:

$$\frac{s_{fs}^{\ 3}}{\alpha^2} + \frac{s\ s_{fs}^{\ 2}}{\alpha^2} = \frac{2 \cdot g}{\rho C_p T_v} I_{total}$$ (Stull eq. 10)

We are most concerned with firestorm winds generated when the background ambient winds are light or calm. For this special case, in the limit of $s \to 0$, the eq. above reduces to:

$$\frac{s_{fs}^{\ 3}}{\alpha^2} = \frac{2 \cdot g}{\rho C_p T_v} I_{total}$$ (Stull eq. 11)

Moving alpha to the right side and taking the cube root gives the answer:

$$\boxed{s_{fs} = \left[\frac{2 \cdot g \cdot \alpha^2}{\rho C_p T_v} I_{total} \right]^{1/3}}$$ (Stull eq. 2 from above)

Where T_v is the environmental virtual absolute temperature ≈ T_e environmental absolute temperature. Eq. 2 has nice characteristics — it looks very similar to the Deardorff convective velocity w^*.

Note that using the full eq (10) above, we anticipate that s_{fs} decreases as ambient winds s increase:

$$s_{fs} = \left[\frac{2 \cdot g \cdot \alpha^2}{\rho C_p T_v} I_{total} - s\ s_{fs}^{\ 2} \right]^{1/3}$$. Namely, in a windy environment, you can neglect s_{fs}.

Appendix 7:
VIPER evaluation

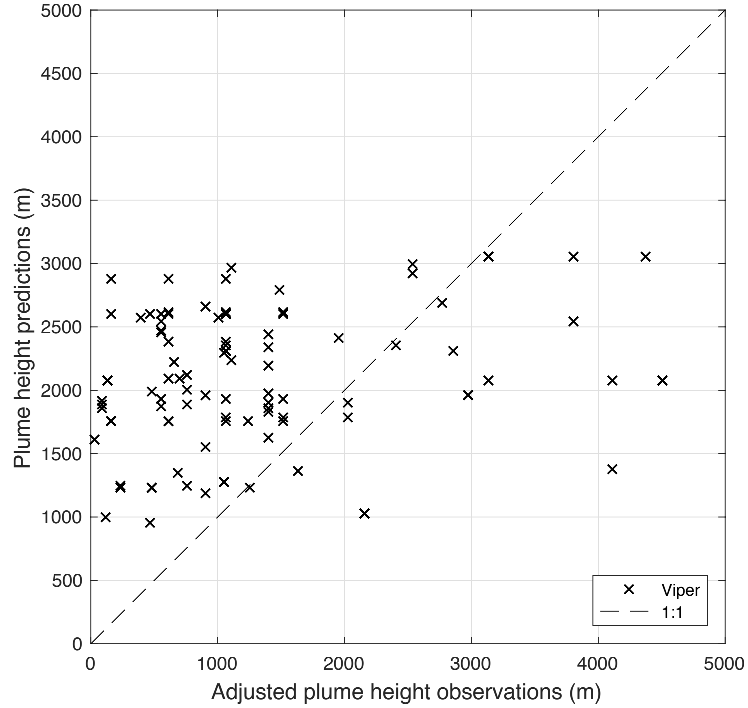

Figure 1 VIPER-predicted plume height compared with plume height observations adjusted for tower height and the curvature of the earth. The linear fit is also plotted (dashed line).

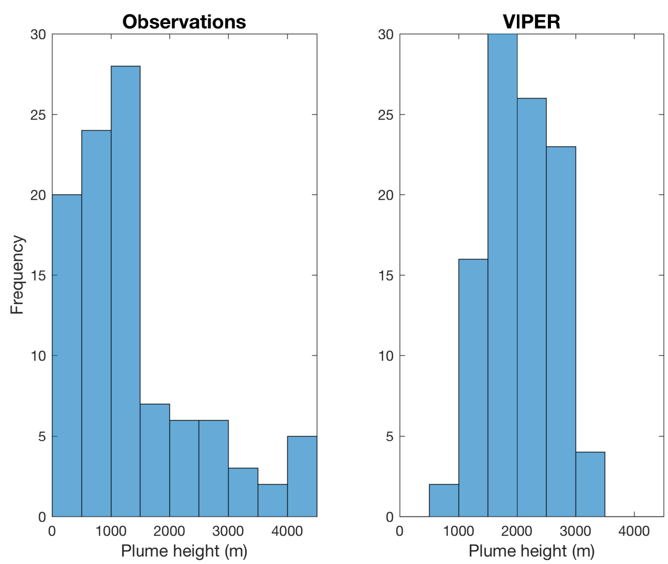

Figure 2 Plume-height frequency distribution of (left) observations and (right) VIPER output, for 102 fires in Alberta, Canada during 2014 and 2015.

Appendix 8: References

Anderson, K.R., 2011: *A thermodynamic approach to estimating smoke plume heights*. In 9th Symp. on Fire and Forest Meteorology, Oct 2011, Palm Springs, CA. Am. Meteorol. Soc., Boston, MS.

Anderson, K.R. *et al.*, 2015: *Development and Structure of the Canadian Forest Fire Emissions Prediction System*, pp19, Natural Resources Canada.

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