Increasing wildfire growth modelling decision support using ensemble weather forecasts over the province of Alberta, Canada

by

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Abstract

Across Alberta, wildfires ignite each fire season and a small number achieve a size greater than 100 hectares, which account for the vast majority of the area burned. These fires often require large suppression efforts that include wildfire growth simulation modelling in order to understand their trajectory and likely destination. To date deterministic wildfire growth simulation has been the industry standard. With advances in numerical weather prediction, it is now possible to perform probabilistic wildfire growth simulation modelling via the regional ensemble prediction system, which forecasts 3 days. When probabilistic wildfire growth simulation is employed, an average of 2% increase in overall skill. Additionally, over prediction (represented as bias) was reduced from seven to one. This approach performs superior to the deterministic methods in boreal regions. The limitations and implications are also discussed.

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List of Abbreviations

BUI	Build Up Index
CMC	Canadian Meteorological Centre
CSI	Critical Success Index
DC	Drought Code
DEM	Digital Elevation Model
DMC	Duff Moisture Code
EC	Environment Canada
ESRD	Environment and Sustainable Resource Development
FAR	False alarm ratio
FBP	Fire Behaviour Prediction
FBAN	Fire Behaviour Analyst
FIRES	Fire Information Resource System
FFMC	Fine Fuel Moisture Code
FWI	Fire Weather Index
GEM	Global Environmental Multi-scale
GEPS	Global Ensemble Prediction System
GRIB	Gridded Binary
HISI	Hourly Initial Spread Index
HFFMC	Hourly Fine Fuel Moisture Code
HFI	Head Fire Intensity
HR	Hit-Rate
IA	Initial Attack

IFMIS	Intelligent Fire Management Information System
ISI	Initial Spread Index
MODIS	Moderate Resolution Imaging Spectroradiometry
MSC	Meteorological Service of Canada
REPS	Regional Ensemble Prediction System
RMSE	Root Mean Square Error
ROS	Rate of Spread
SFMS	Spatial Fire Management System
SRTM	Shuttle Radar Topography Mission
U	East-West Wind Speed
USFS	United States Forest Service
V	North-South Wind Speed
WD	Wind Direction
WS	Wind Speed
WMA	Wildfire Management Area
WUI	Wildland Urban Interface

Chapter 1 Introduction

1.1 – Foreword

Human life has been sustained through the ability of people to develop tools and use the environment to their advantage. Since the discovery of fire, the process of ignition and combustion has fascinated people. With this fascination came a respect and often, fear of fire considering fire may become a destructive force; this was most prevalent during settlement. During settlement, the by-product of timber processing (bark, limbs etc.) was not cleared away, or reduced, to prevent fire risk. Additionally, timber processing produced ideal ignition conditions that resulted in fires starting in the processing waste; these fires threatened and sometimes destroyed settlements (McCaw and Burrows 1989). This was due largely to an inability and lack of capacity to manage fire on the landscape. Fires that damaged settlements include both anthropogenic and naturally occurring fire. As wildfire management organizations continued to modernize, the desire to know where a fire would be or spread before it got there remained at the front of a fire managers' mind. This hunger for enhanced information has led to the development of many decision support systems (fire growth simulation models, weather forecasting models, landscape assessment tools, etc.). These tools are used for wildfire management resource allocation, wildfire action prioritization and pre-suppression planning, among other activities.

Fire growth is relatively simple, mathematically speaking; it follows an elliptical pattern based on forward, backing and lateral (flanking) rates of spread measured as meters per minute (m/min), further described in Richards (1993). Further, Richards (1990) outlines the creation of the first fire growth model. Without this work, wildfire modelling would not be what it is today.

Along the boundary of a fire there are many points from which each of these ellipses, described as wavelets, will begin to grow; with each leading edge serving as the crest of a wave (Huygens' wave principle) (Huygens and Thompson 1912). Weather, topography, and fuels determine the rate at which each of these wavelets grow. Under realistic conditions, topography, fuels, and weather can vary greatly over small distances. Current modelling practices often use a single weather forecast from a single point interpolated across a landscape. This has resulted in challenges when using fire growth model outputs during operational fire management as the weather data available may be a great distance from the fire. Additionally, when there are values are risk (wildland urban interface (WUI), watersheds, timber, etc.) the challenge is further increased.

As urban centers continued to grow, the desire for accurate weather information over greater areas increased. In part, this drove the development of fine temporal and spatial resolution weather models. To develop greater confidence in these models, ensemble techniques were developed in order to combine multiple dissimilar forecasts together in order to generate a single forecast as a best estimate product (Taylor and Buizza 2003). Each member, or perturbation, within the ensemble had a slightly different starting point. The same general mathematics was used for each member to derive each individual forecast. In some cases, different equations were used to derive a variable, for instance the mixing length formulation (Government of Canada Environment Canada 2015a). The resolution of these models at the regional level was spatially as fine as 0.13°-by-0.13°, roughly 15-km-by-15-km (at the 60th latitude), and temporally as fine as fifteen minutes (Erfani *et al.* 2013).

When used together, fire and weather models have shown the greatest utility for wildfire managers and emergency response planners alike. This thesis focuses on combining these models over Alberta. The Regional Ensemble Prediction System (REPS) (Erfani *et al.* 2013) product from the Canadian Meteorological Centres' (CMC) Global Environmental Multi-scale (GEM) model provided by Environment Canada (EC) (Gagnon *et al.* 2013) provides weather for the Prometheus Wildland Fire Growth Simulation Model (Tymstra *et al.* 2010). This chapter briefly outlines the history of both fire and weather modelling, concluding with the objectives of this study and how they fit into the needs of wildfire managers.

1.2 – Wildfire in Alberta

The province of Alberta is responsible for wildfire suppression in ten wildfire management areas (WMA) within the province. Municipalities are responsible for the areas outside the WMAs known as the "white zone", WMAs are conversely known as the "green zone". Protection of each WMA is broken into five priorities set forward by the provincial government: human life, communities, watersheds and sensitive soils, natural resources and infrastructure (Government of Alberta ESRD 2012).These priorities assist in defining the level of response and number of resources on wildfires.

An average of 1 560 wildfires consumed 195 725 hectares annually in Alberta; roughly 41% are human caused and 59% lightning caused based on a ten year average from 2003-2012 (Government of Alberta ESRD 2014a). Ninety seven percent of area burned in Canada is attributed to fires over two hundred hectares (Stocks *et al.* 2002). As such, the focus and purpose of suppression crews has been to mitigate the occurrence of large wildfires by responding quickly to new starts. In order for initial attack to be considered successful, the fire must be suppressed before has reached two hectares in size. This suppression success metric is reflected in the Forestry Divisions objectives: 1) contain fire spread by 10:00 AM the following day and 2) initiate suppression prior to the fire reaching two hectares in size (Government of Alberta ESRD 2014b).

Traditionally, when a fire observation tower or other source reports a wildfire, an initial attack (IA) crew is dispatched. The current tactic for crews that have arrived on a wildfire incident is to work from the back and flank of the fire, primarily for safety reasons. These areas of the wildfire have the lowest intensity, and are prioritized for action in order to manage fire spread effectively. This tactic can lead to fires that appear thin in the initial hours of spread. If a wildfire exceeds the capacity of initial attack crews, they can spread rapidly, largely without the influence of suppression. Air tankers may be used to provide steering to a fire, this could account for some nuances seen in fire modelling outputs later in this thesis.

Throughout the history of the Wildfire Management Branch of Environment and Sustainable Resource Development (ESRD) policies have changed many times. These changes were articulated in Quinces' Master's Thesis (2009) seen in Table 1.1.

Table 1.1 – From Quince, 2009 titled major fire events and changes in fire management policy in the province of Alberta between 1948 and 2008.

Year(s)	Notable Fires	Area Burned (ha)	Percentage (%) of total area burned between 1961 - 2008	Significant changes and additions to wildfire management policy in Alberta	Hypothesized impact on wildfire management in Alberta
1948	-	-	-	- Development of the Forest Protection Area	-
1950	Chinchaga River	-	-	- Change in Protection Zone to include all forested lands	- Increased area that required coverage and need for suppression resources
1968	Vega	1, 074, 243	6.4	- Increased weather forecasting and fire control	- Increased number of suppression resources
1976	-	22, 849	0.3	- Objective stating that annual area burned should not exceed 1/10th of 1 percent	- Increased fire suppression action and fire exclusion - However, no change in management policy was made
1980-1982	Keane Fire	2, 773, 371	40.8	- Advent of the Presuppression Planning System - 15 minute response time to all new starts at high hazard - Addition of seasonally hired fire crews (8 Helitack) + (3) 25 man crews - Addition of the 0.1 ha size class	- Significant increases in the number and type of suppression resources available. - Decreased response times and more resources led to the detection of more small lightning caused fires - Increased containment success
1992	-	3, 545	0.05	- Addition of the Intelligent Fire Management Information System	- Spatial predictions of fire hazard, however, no associated change in management policy
1995	Mariana Lakes	336, 148	2.7	- Addition of the 0.01 ha size class	- Increase in the number of lightning fires < 0.1 ha recorded
1998	Melvin Mitsue, Virginia Hills Agnes Lake Roche Lake	726, 977	10.7	- Introduction of Spatial Wildfire Management System - Development of current PPS including Coverage Assessments	- Deployments begin being evaluated using Coverage Assessments that mandate 80% coverage - Coverage Assessments lead to more suppression resources being required to meet coverage need
2001	Chisholm	154, 123	2.3	-	-
2002	House River	496, 513	7.3	- Wildfire Reinsurance Plan - Development of the Ecological Wildfire Management Zones	- Change in wildfire records to include all ignition causes and sizes. - Increase in the number of small human-caused fires

Table 1.1 depicts the reaction to each large wildfire event from an organizational perspective of prevention. Each change was made in order to better contain wildfires early in an attempt to prevent another very large wildfire on the landscape. With each policy change, the desire for a greater understanding of the spatial complexities is abundantly clear. The introduction of the Intelligent Fire Management Information System (IFMIS) described by Lee

and Anderson (1989) and the Spatial Fire Management System (SFMS) described by Englefield *et al.* (2000) changed the way fire managers approached fire management. The advent of these systems allowed wildfire management activities to have a proactive edge allowing for greater span of control when large wildfires occurred on the landscape.

Notably, many of these policy changes occurred shortly after catastrophic wildfire events. This was no different in 2011 after a wildfire consumed a portion of the town of Slave Lake, Alberta. The report following the Slave Lake fire, the Flat Top Complex Wildfire Review, outlined additional policy changes to assist in the preparation for similar wildfire situations in the future. In accordance with the Flat Top Complex Wildfire Review, this thesis aims to comply with the Preparedness and Capacity theme, specifically recommendation 7: Ensure sufficient fire behaviour specialist capabilities (Flat Top Complex Wildfire Review Committee 2012). Additionally recommendation 20, outlining the collaboration and support of research, is also supported by this work (Flat Top Complex Wildfire Review Committee 2012). The work in this thesis aims to provide a greater amount of information to incident management staff to allow for greater confidence during decision-making.

1.3 – The Progression of Wildfire Management

Many wildfire management agencies developed after a catastrophic fire, sometimes out of existing forest management agencies. This was the case for the United States Forest Service (USFS) in 1905 just prior to massive fires in Montana in 1910 (Wotton *et al.* 2009). On any given landscape, many considerations that must be taken into account were required. As such, decision support tools were developed and implemented throughout the years. Each of these considerations influence the way decisions are made on that landscape.

Wildfire management agency responsibilities include the allocation of fire suppression resources; planning fire suppression and pre-suppression activities; planning prescribed fire activities; and maintaining the role of fire within forests while protecting valuable resources. Agencies fulfill these responsibilities and react to wildfire spread in many different ways depending on province, location of wildfire, resource availability, time of year, current and forecast weather, etc. ESRD uses a number of decisions support tools for everyday pre-suppression activities as well as emergency response. As an example, ESRD employs SFMS to forecast the next day's fire danger, burn probability, and resource allocation via information from the Fire Information Resource System (FIRES). Upon ignition, fire information is input into Dispatch (a resource management software), which allows wildfire managers to see spatially, where resources are located and the status of fires in their WMA. If a wildfire is not contained by initial attack and begins to spread rapidly, a wildfire incident management team is dispatched and a base of operations established. If the fire is of high enough priority, a Fire Behaviour Analyst (FBAN) is deployed with the team to provide fire growth forecasts and fire behaviour predictions.

1.4 – Fire Growth Simulation Modelling

Many tools are capable of fire growth simulation modelling. However, each tool has a specific job or jobs, for which they are suited. Throughout this thesis, the Prometheus Fire Growth Simulation Model is used (Tymstra *et al.* 2010). A brief overview of other fire growth models, how they work, and how they differ from the work in this thesis is provided in this section.

1.4.1 – Burn-P3

Burn-P3, a probabilistic fire simulation model, uses historical weather in order to generate many different fire scenarios across a landscape. The three P's of Burn-P3 are probability, prediction, and planning (Parisien *et al.* 2005). The output from this model is a burn probability grid that defined the relative occurrence of one cell burning in relation to any other over the number of iterations within the model run. Burn-P3 uses the Prometheus Fire Growth Simulation model as its engine for fire growth and runs on standard fire growth simulation information (fuel, weather, and topography). Burn-P3 is equipped with additional advanced options such as seasonal curing, wind grids, spread event day distribution, etc. These additional options allow a user to control Burn-P3 to better estimate what may occur in the area of interest. Burn-P3 is becoming a popular tool for fire management planners as it allows a modeller to capture greater natural variation with the additional inputs as mentioned above. The planning performed with the results from this thesis was short term in comparison to a tool like Burn-P3.

Weather selection can be completed randomly (a new "day" of weather each day of the simulation) or sequentially (the first day is random, each day after is the next in the list). In this way, the output from Burn-P3 is the probability of each cell burning relative to each other cell around it. The method of probabilistic output Burn-P3 has employed differs from this thesis as it uses historical weather data rather than forecast weather information. Burn-P3 is a retrospective analytical tool in order to define areas of higher relative ignition potential (Parisien *et al.* 2005).

1.4.2 – Farsite

Farsite is the United States fire growth simulator and it uses information from Rothermel, 1972 to characterize fire spread across a landscape (Rothermel 1972). Farsite uses weather, topography, and fuel inputs to simulate wildfires elliptically in a fashion similar to Prometheus. Farsite also provides raster and text outputs which describe the fire environment. Farsite is a deterministic model and is used operationally in the United States to support wildfire management decisions.

Farsite is used operationally very similarly to Prometheus. It differs from this thesis as it provides single outputs for wildfire management staff. Farsite could implement ensemble techniques in much the same way as this thesis has within Prometheus (Finney *et al.* 2011).

1.4.3 – PFAS

The British Columbia government currently uses this model operationally during times of high fire risk to better inform managers of potential fire growth. PFAS has three separate models that underpin it, short term, medium term and long term modelling. The long-term model is generally the focal point for operational use.

PFAS was the inspiration for the techniques employed in this thesis. The one fundamental difference is that PFAS uses historical weather to create a statistical distribution of weather from which it pulls data to model fire growth across a landscape. PFAS outputs probability perimeters to inform fire management organizations of potential growth over the forecast period (Anderson 2010; Anderson *et al.* 2007).

1.4.4 – Phoenix

Phoenix is the Australian fire growth simulation system. This system uses gridded weather data that was generated by the Bureau of Meteorology. Operationally, Phoenix automatically models all wildfires as they are reported in order to give large-scale situational awareness. These outputs however will not be used operationally until a fire behaviour analyst has signed them off. Phoenix is the Australian equivalent of Farsite and Prometheus.

Phoenix differs from the work in this thesis in the variety of data it uses for inputs. The weather is gridded at a 3-km-by-3-km resolution and they are collected automatically by Phoenix. The fuels information is also accessed directly by Phoenix. Information on Phoenix and the bushfire program can be found at http://www.bnhcrc.com.au/. Phoenix, Farsite, and Prometheus all follow a similar fire spread model, Huygens wave theory. The input data to propagate fire and the ability to model convection and ember dispersion are the major differences (Chong *et al.* 2012).

1.5 – Use of Fire Growth Models

Fire models have been typically used in two ways. Operational or reactive modelling, that assists in decision making during wildfire incidents and planning modelling, that assists in decision making for long term fire management strategies. The list of models above was by no means exhaustive; however, these models are commonly used by many organizations in North America, Australia and other nations around the world. From the list above, operational models include Prometheus, Farsite, PFAS, and Phoenix. All five models are capable of planning however; the primary model in this class is Burn-P3.

Fire modelling was also used to identify ecological trajectories with different pressures from fire, weather, succession, and climate. A study from Kean *et al.* (2013) used multiple model comparison to define how an environment would be altered under different combinations of fire (fire or no fire), weather (full record, five typical years), succession (limited succession, full succession), and climate (historical, warmer and wetter, warmer and drier). An important factor within this study was the way the fire simulation models were used. Rather than a single model used for each landscape (requires parameterization), each model was used for the area it was designed for (Keane *et al.* 2013). This had the potential to cause issue when comparing the outputs, however Keane *et al.* (2013) took measures to ensure that was minimized.

In the case of operational models, the forecast time for model outputs is an important factor for fire management agencies. Historically, fire growth simulation model outputs forecasted for a single day, however weather modelling technologies have advanced to the point that 3-5 day reliable forecasts are possible (Hamill *et al.* 2004). This thesis focuses on 2.5 day fire growth forecasts as forecasts beyond 3 days often degrade rapidly (Figure 1.1). Furthermore, fine resolution weather data beyond three forecast days is not currently available at the regional scale.

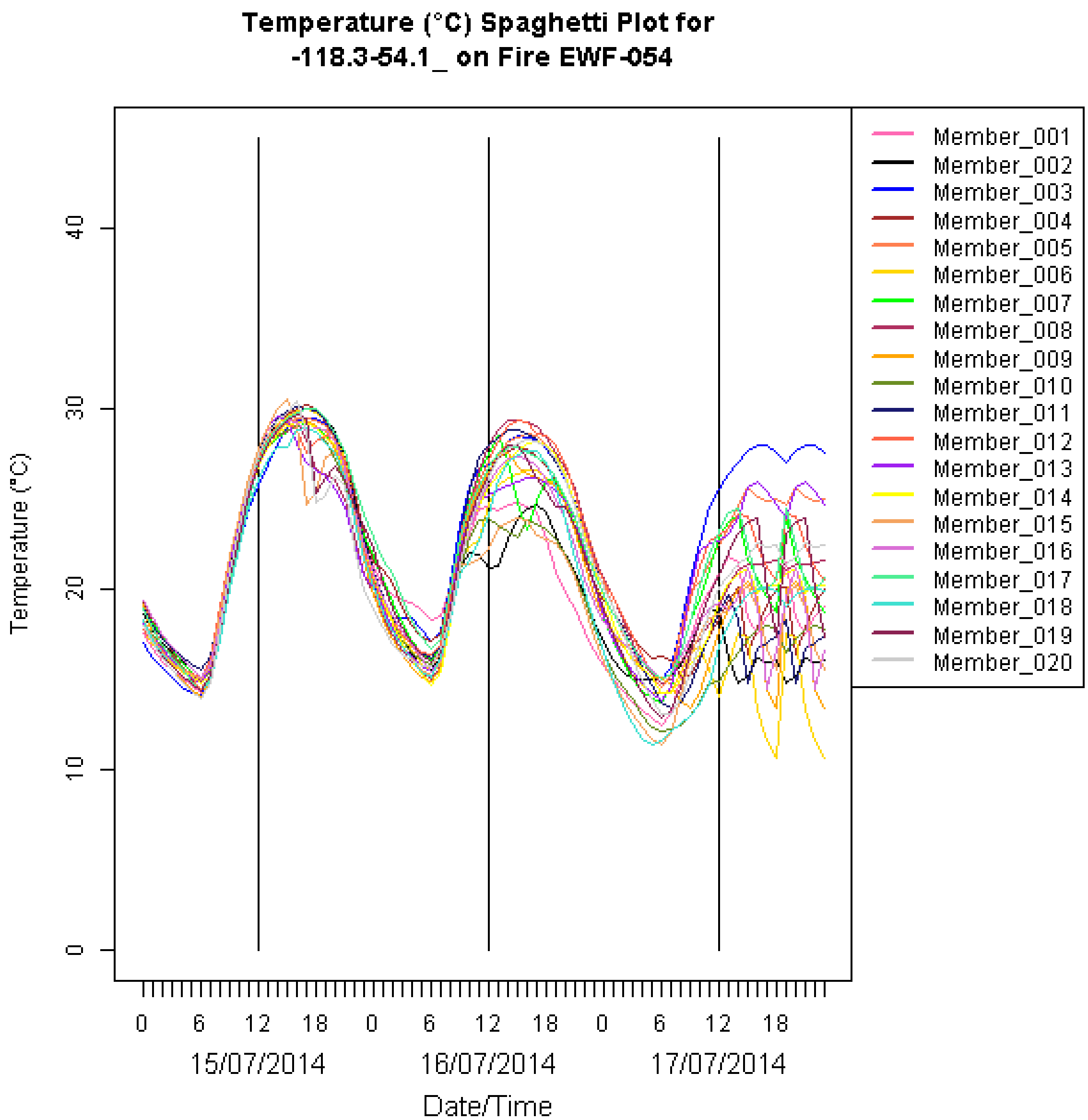


Figure 1.1 – Temperature spaghetti plot from Edson Wildfire 054 depicting the diurnal temperatures over 3 days from the 20 perturbed ensemble members.

Future planning was not the focus of this thesis; however, it may be a by-product of the results found or the subject of a future project. Modelling past events using forecast weather that was available during the actual incident may allow fire management organizations to calibrate decision support systems for greater accuracy during future incidents. This likely increases the chance that the actual fire growth can be captured through the modelling process.

1.5.1 – The Prometheus Fire Growth Simulation Model

In 1999, a steering committee was tasked with the development of a model to spread fire across a landscape using the Canadian Forest Fire Behaviour Prediction (FBP) system along with Huygens wave propagation equations (Tymstra *et al.* 2010, Richards 1993). This models name is Prometheus after the Greek titan who stole fire from Zeus and returned it to humans. Further, Prometheus translates to foresight and the model is set up to perform a forecasting function. Prometheus is governed by the FBP (Forestry Canada Fire Danger Group 1992) and Canadian Forest Fire Weather Index (FWI) (Van Wagner 1987) systems and can incorporate topography when spreading fire across a landscape (Tymstra *et al.* 2010). The intent of Prometheus was to provide an "easy to use graphic user interface" (Tymstra *et al.* 2010), which would later be incorporated into operational planning on wildfire incidents. The users of this modelling system were generally fire behaviour specialists. Users were assumed to have familiarity with the FBP and FWI systems as well as some operational experience to assist in decision-making. The version that was used through the course of this thesis was Prometheus version is 6.0.0 (released September 8, 2014 at http://www.firegrowthmodel.ca/prometheus/software_e.php).

Fire spread within Prometheus is based on wave propagation principle proposed by Huygens (1912). Fire spread begins from a single point and follows a series of partial differential equations, which allows Prometheus to "propagate and locate vertices" (Tymstra *et al.* 2010). Each of the new vertices then begins to spread in the subsequent time step iteratively until fire growth simulation is complete. When multiple vertices have grown within a time step (t), Prometheus uses tangential line segments along the furthest spread (from the previous resultant perimeter), which includes back, flank and head fire spread; this defines the resultant (t+1) perimeter.

In order for Prometheus to spread fire across a landscape, it requires information on fuel, topography, and weather variables. Fuel information is input as a grid where each cell was one of seventeen fuels as defined by the FBP system. Each of these cells is associated with a fuel model that defines the rate of spread and intensity of a fire based on the local weather. Spread visualization is made easier as the fuel grids were at a resolution of 100m-by-100m (1 hectare).

Weather is input on a station-by-station basis. Ideally, the weather would be input as a grid; however, that is not currently supported within Prometheus. A user must input one or more weather stations to model fire spread. Weather from multiple stations is interpolated across the entire landscape where closer weather stations will produce superior output results. Weather variables required for fire growth simulation modelling are precipitation (mm), 2-meter temperature (°C), and relative humidity (%), and 10-meter wind speed (km/h), and wind direction (°). Prometheus then calculates the FWI values basing the first day's indexes on the given starting codes from yesterday. The starting codes required are Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC), and Drought Code (DC). Fire weather Indexes can be thought of as primary, secondary and tertiary values. The primary indexes include FFMC, DMC and DC; these variables are calculated from weather variables directly. Secondary indexes, ISI and BUI, are calculated from FFMC and wind speed, and DMC and DC respectively. Finally, the FWI, the only tertiary index, is calculated using the BUI and ISI. Due to join probabilities, the FWI can be a challenging output to describe the fit of weather to fire weather indexes. The BUI, being a combination of DMC and DC, is a daily value and therefore a non-ideal candidate for comparison. In this way, the ISI is a suitable proxy for describing well a forecast is describing actual fire weather. The ISI fluctuates hourly, with the FFMC, and takes into account all weather variables (through FFMC). Initial Spread Index (ISI) is a special case as it has a FBP system variant that will be calculated which takes into account the local wind speed in order to cap the maximum ISI. Initial Spread Index influences rate of spread (ROS) and without a cap would result in excessive rates of spread that would not be realistic. The fuel models within the FBP system include all rate of spread formulae, which govern the distance spread by each vertex. Prometheus also calculates an hourly fire weather index from the hourly fine fuel moisture code (HFFMC) and the hourly initial spread index (HISI) (Tymstra *et al.* 2010).

Weather input occurred on a station-by-station basis, as such, weather was at a very coarse spatial resolution, which meant the weather stations were rarely near where a fire occurred. This led to the interpolation of spatial weather by Prometheus, which brought weather to the same spatial resolution as the FBP fuel grid. This interpolation was calculated via inverse distance weighting influenced by elevation. Elevation influenced weather variables were normalized to sea level, interpolated, and then returned to the pressure calculated based on the heights of the points (every grid cell). Fuels were the most important piece of the fire spread equation, "67.4% contribution from fuels, while weather contributed 29.2% and the position of the ignitions contributed 3.4%" to burn probability (Parisien *et al.* 2011a).

Though the position of the ignition was not assessed in this thesis, it was an important component to consider when fire growth simulations were performed. The study by Parisien (2011a) focused on landscape level fire, while Hély *et al.* (2001) focused on the indexes within the FBP System to define the importance of weather and fuels. To that end, it was found that extreme weather and fuels, specifically conifer fuel types, had a profound effect on fire behaviour indexes (Hély *et al.* 2001). Hély *et al.* (2001) found that extreme weather combined with conifer fuel types increased head fire intensity, rate of spread, and area burned.

Topography is the final variable influencing fire behaviour. Topography is input as a raster grid under the same projection, resolution, and extent as the fuel grid. Elevation plays two important roles: informs spatial weather interpolation and allows for calculation of effective wind speed. Effective wind speed is the driving force of wind adjusted by slope, which best directs a fire when terrain is present. Wind vectoring is performed within Prometheus in order to obtain a slope adjusted wind speed and direction, or effective wind speed and direction. This is one-step towards more "realistic" fire growth simulation taken within Prometheus. Weather variables change with altitude (Tymstra *et al.* 2010); as such, it is important that the elevation be incorporated during spatial weather interpolation.

Once this information is input into the model, fire simulation commences. The model allows many different outputs to be exported, of note: gridded fire intensity and polygon perimeter shapefiles. These two particular outputs allowed modellers to generate an ensemble output from the multiple members of the global environmental multi-scale model.

1.6 – The Global Environmental Multi-scale Model – Regional Ensemble Prediction System

Environment Canada (EC) currently owns and operates the Canadian ensemble model through the Meteorological Service of Canada (MSC) as well as global and regional deterministic models. Within the Canadian ensemble, forecasts there are both regional and global ensembles. A deterministic model is a model that will always produce the same outputs given the same inputs. An ensemble model is a series of deterministic model runs using differing starting values for each input within a "member". For these purposes, a member is a perturbation condition that is constant throughout all modelling for this ensemble. The ensemble forecasts MSC produces contain twenty members. The global models have initialization times of 00 UTC and 12 UTC meaning two forecasts each day, while the regional models initialize at 00, 06, 12, and 18 UTC yielding four forecasts daily. The global model will forecast up to 336 hours (14 days) after the initialization time while the regional generally only forecasts 72 hours (3 days). The reason for two initialization times for the global model is the computational requirements to forecast for 336 hours. Further, the global model generally forecasts every 6 hours while the regional model produces hourly or 3-hour outputs. The temporal resolution for regional modelling is more important than that of global considering a user is likely more interested in the short-term change than the overall trend that come from the global model output. Spatially there is a considerable difference between regional and global models. In the past, the global model was as coarse as 2°-by-2°, which is roughly 220-km-by-220-km at the 60^{th} latitude. Today the global model is operating at a 25-km-by-25-km resolution while the regional model can achieve 10-km-by-10-km and under the high-resolution scheme as low as 2.5-km-by-2.5-km resolution (Government of Canada Environment Canada 2015b).

Weather forecasting models improved throughout recent history as noted in Erfani *et al.* (2013), who detailed upgrades to the Regional Ensemble Prediction System (REPS) on January 15, 2014. The Regional Ensemble Prediction System was a branch of modelling done by EC and was the finest temporal (hourly) and spatial (15-km-by-15-km) resolution model currently operated by EC (Erfani *et al.* 2013). Environment Canada ensemble models were scaled to two levels, Global and Regional.

Global, as the name suggests, spans the world with a focus on Canada, but uses information for the greater global atmosphere. The global ensemble prediction system (GEPS) informs REPS at the highest vertical level of REPS (10 hPa) in order to initiate the regional model. The global model is continuously calibrated by EC to ensure the outputs are as accurate as possible similar to the calibration process described by Wilson and Vallée (2002) and Wilson and Vallée (2003). Due to the calibration of the global model, there is greater confidence in the regional subsystem.

Much of the information output from the EC weather model systems is available in the data mart. The data mart is a website location within EC; it is a portal to the data publicly available from EC. The data needed for this work was obtained from an employee of Environment Canada due to its highly specific nature (temporal and spatial resolution).

Environment Canada weather models are currently in use for the production of weather forecasts across Canada. The operational models are the same models that are in use by other individuals and agencies when forecast weather information is required. An example of this is SpotWx (spotwx.com). This system accesses the EC data in order to provide a user forecasts for areas much closer than a major city may be (Spot Weather). The SpotWx system provides a medium for the public to obtain forecasts for any point in Canada. The system will poll the forecast grid point closest to the point desired by the user and interpolate to the point desired. This system delivers forecasts at fine resolutions.

1.7 – Goals and Objectives

The purpose of this work is to provide an understanding of the influence of gridded ensemble weather on Prometheus fire growth simulation model outputs. Additionally, we sought to examine the utility of using a decomposed ensemble forecast (dividing into each individual member) to perform multiple fire growth simulations. An improvement in simulated fire perimeters is expected from the ensemble weather streams when compared to the deterministic weather stream. This assumption is due to the notion that the ensemble should better capture the variability of the weather. The motivation for this study is the increasing need for accurate fire growth simulations along with the recommendations in the Flat Top Wildfire Complex Review. Simulation outputs such as these will become more important in the event that wildfires become extreme. This work was performed in this way in order to derive a probabilistic output from perturbed forecasts rather than a single output from the final ensemble forecast. In this case, the perturbed forecast are the forecasts generated by each ensemble member. The objectives for this thesis are as follows:

1. Develop a methodology for implementing gridded weather data for fire growth simulation modelling
2. Derive probabilistic fire growth simulation outputs from ensemble member weather inputs
3. Derive percent agreement perimeters from probabilistic output (50 to 95 percent agreement, 5 percent increments)
4. Assess goodness of fit between ensemble and deterministic weather (RMSE)
5. Assess goodness of fit between agreement perimeters and actual final perimeter (Skill Score)

Currently the methodology is in a research ready state; however, it is our desire to continue to refine the process to allow the use of these methods in an operational environment. The final product from this work is a probabilistic growth map along with a goodness of fit metric. This metric will be the critical success index (CSI) as described in Stanski *et al.* (1989). Outputs including burn probability maps along with percent agreement perimeters with corresponding goodness of fit statistics that will increase situational awareness on a fire. Additional awareness will allow fire managers to make decisions surrounding resource allocation, resource requirements, and fire management strategies. Probabilistic fire intensity may be output from this methodology however, insufficient verification and validation data exist at this time.

Chapter 2 - Data and Methods

2.1 – Study Area

The study area for this work was the province of Alberta, buffered on the North, West, and East borders by one degree of latitude or longitude. The South was not buffered for two reasons: there were no large fires close to the Southern border in this study. Mountainous regions were not the focus of this study however; these regions did have representation in an attempt to define ensemble performance over mountains. The majority of fires were located within the boreal forest (Figure 2.1). This was critical considering the FBP and FWI systems were developed from primarily boreal data (Forestry Canada Fire Danger Group 1992; Van Wagner 1987).

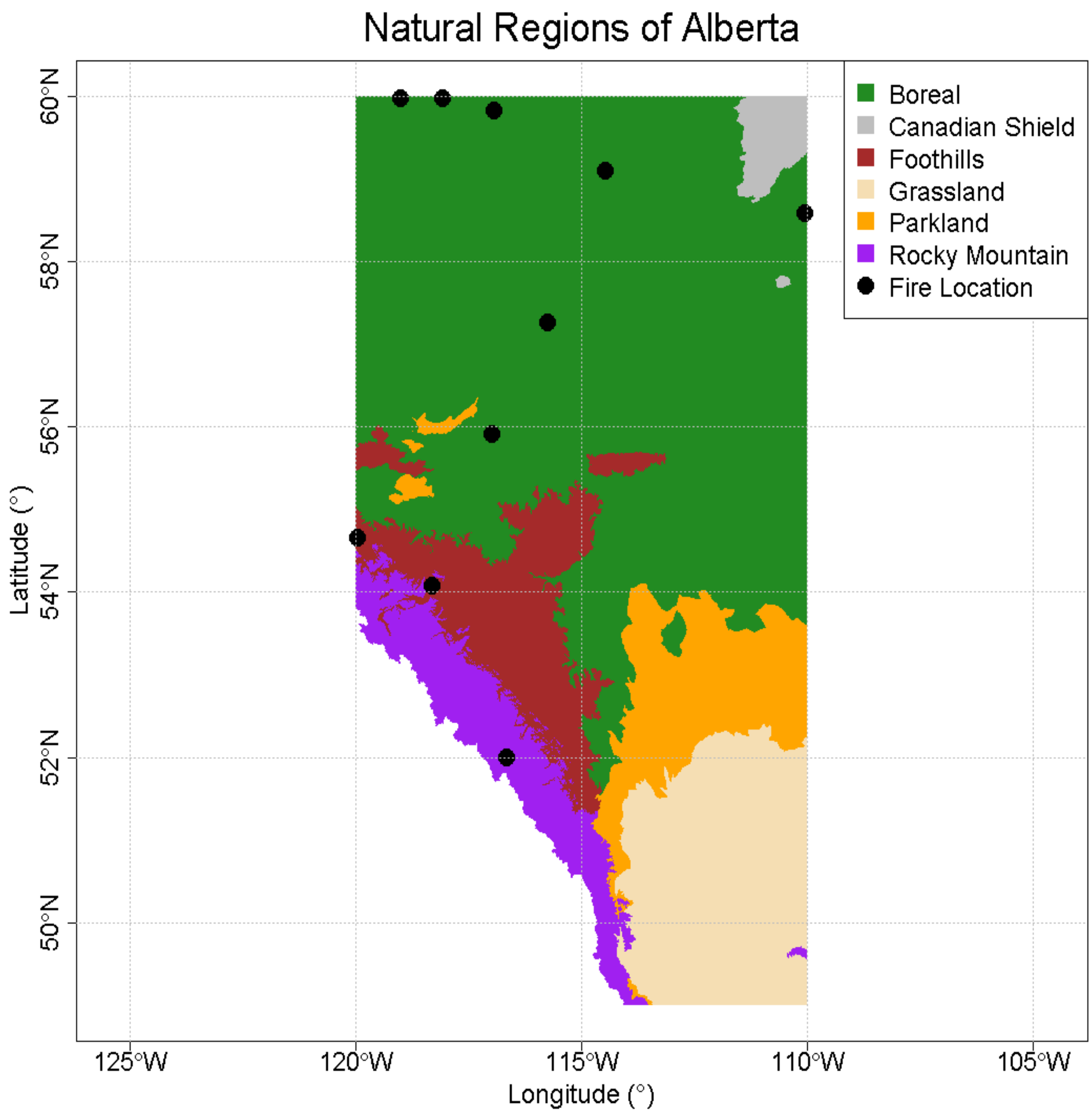


Figure 2.1 – The province of Alberta classified by Natural Region with locations of study fires (Government of Alberta ESRD 2005).

There were ten fires selected for this study seen in Table 2.1, each fire was over 100 hectares and fell within the weather data date range (May 12 – October 29, 2014). Notably some of the end dates differ considerably from the date the final size was achieved. This was due to other factors within the WMA and provincial level. For instance, if a fire was in a sensitive area, it was put on patrol status. This allowed the WMA to be confident the fire was out when it was declared extinguished. Fires prior to 2014 were not used in this study due to limitations of the Regional Ensemble Prediction System prior to the updates that occurred in 2013. This excluded large historical fires such as the recent fires near Slave Lake, Chisholm, and House River fires.

The overall flow of the study was captured within Figure 2.2.

Table 2.1 – Fire information for the ten fires within this study.

Fire Number	Start Time	Start Date	End Date	Final Size	Date Final Size Reached	Latitude	Longitude
EWF-054	1705	15-Jul-14	9-Aug-14	419	17-Jul-14	54.07	-118.29
GWF-044	2135	15-Jul-14	29-Aug-14	4173	16-Jul-14	54.66	-119.96
HWF-058	1243	1-Jun-14	9-Jun-14	702	02-Jun-14	59.97	-118.07
HWF-059	1308	1-Jun-14	9-Jun-14	198	03-Jun-14	59.97	-119.00
HWF-133	1520	3-Jul-14	11-Jul-14	130	03-Jul-14	59.83	-116.94
HWF-219	1912	17-Aug-14	7-Nov-14	182	18-Aug-14	59.10	-114.47
MWF-051	1501	30-Jul-14	14-Sep-14	2092	15-Aug-14	58.58	-110.05
PWF-116	1455	19-Sep-14	25-Sep-14	353	22-Sep-14	55.91	-116.98
RWF-034	2226	3-Jul-14	11-Sep-14	8972	7-Aug-14	51.99	-116.66
SWF-113	1411	8-Jul-14	22-Jul-14	4211	15-Jul-14	57.26	-115.76

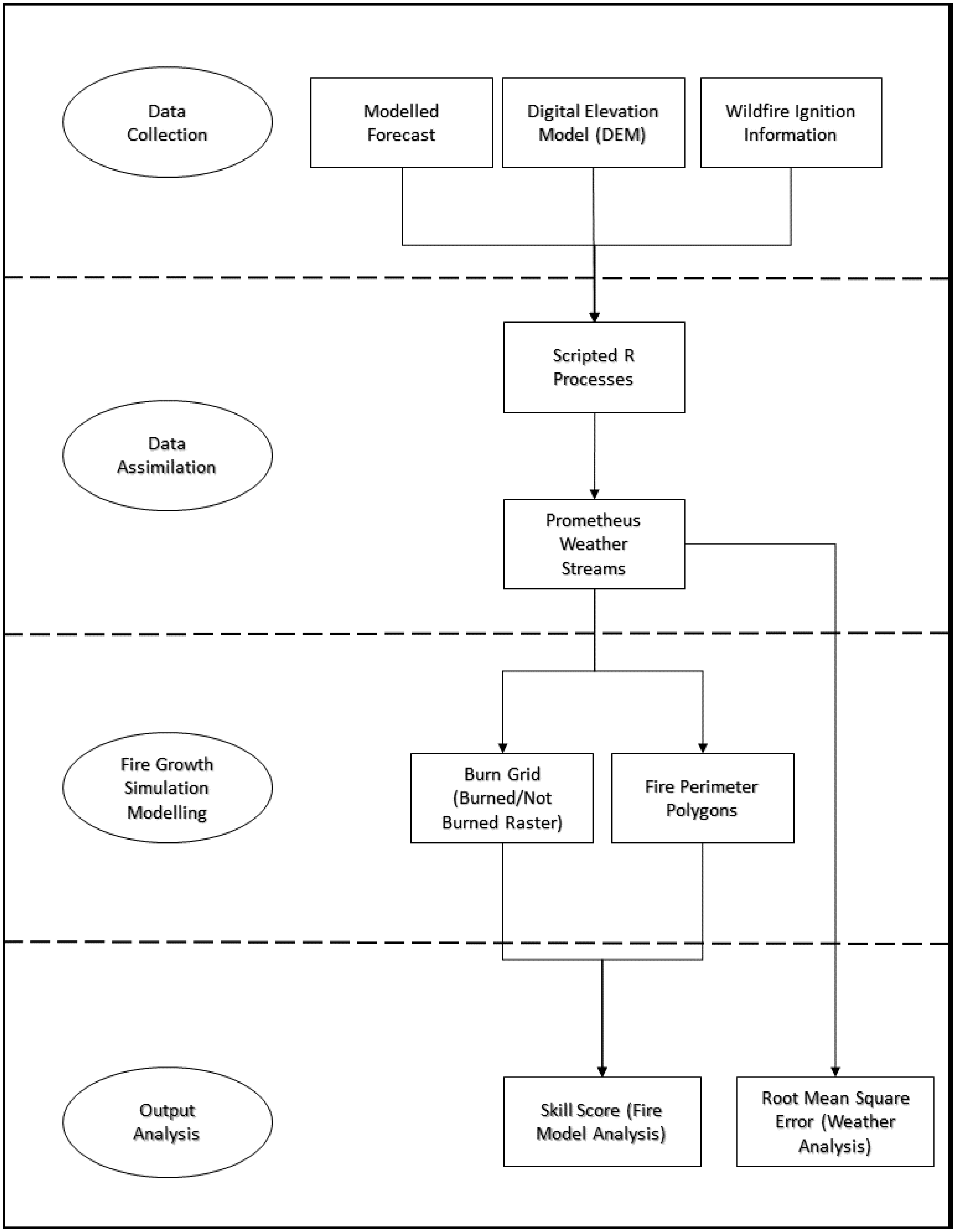


Figure 2.2 - Flowchart depicting workflow within this thesis.

2.2 – **Data Acquisition**

In order for the ensemble fire growth simulation model to be performed, ensemble weather information was required. This data was available through the Canadian Meteorology Center with Environment Canada. Due to the fine temporal and spatial resolution required for fire growth simulation, the publicly available data was insufficient (available at http://meteo.gc.ca/grib/grib2_ens_naefs_e.html). Public data for the ensemble was only available at a 1°-by-1° global format. Data was gathered by Ron Goodson of Environment Canada and was translated from its Environment Canada standard file format, to Gridded Binary (GRIB). The GRIB data was from the CMC Global Environmental Multi-scale model and contains information from each of the twenty perturbed members and a single control member. The twenty perturbed members had been selected from a larger pool of 192 perturbed members, and the control model was initialized with the average of these 192 perturbations, similar to the Global Ensemble Prediction System (Government of Canada Environment Canada 2015a). The variables within each GRIB file were temperature (K), accumulated precipitation (kg/m^2), U-vector wind (m/s), V-vector wind (m/s), pressure (Pa), and specific humidity (kg/kg). The U and V wind vectors were used to calculate wind speed and direction. The accumulated precipitation was decomposed into hourly precipitation. Pressure, specific humidity, and temperature were used to calculate relative humidity. The GRIB data was at a 10-km-by-10-km spatial resolution and a 1-hour temporal resolution. The native resolution of the GRIB data was 15-km-by-15-km; in order to achieve 10-km-by-10-km Environment Canada performed an initial interpolation. The interpolation scheme used was the standard Environment Canada downscaling scheme. This minimized the amount of interpolation that Prometheus performed during fire growth simulation.

As earlier mentioned topographic influences had recently been updated within the ensemble. This was critical for Prometheus as topography played a large role in fire spread direction.

The REPS model was initialized twice daily at 00 UTC and 12 UTC. This work uses the 00 UTC initialization time as it was a superior platform to begin simulations. In the Mountain Daylight Time Zone (-6 UTC), 00 UTC is 1800 LST of the day before. This resulted in fire simulation forecasts that only last 2.75 days (0000 LST of day 1 to 1800 LST of day 3).

Prometheus requires a full days' weather in order to accept a weather stream. To account for the final 6 hours that are missing due to the forecast ending at 1800 LST of forecast day 3, 6 hours of bogus data is applied as padding to the end of day 3. Additionally Prometheus scenarios simulated from hour 1 on day 1 to hour 66 on day 3, therefore, fire modelling discontinued at 1800 LST on day 3 to ensure bogus data was not used to simulate fire growth.

The FBP system fuel and digital elevation model grids were obtained from Environment and Sustainable Resource Development. Each of these grids was projected in NAD83 Forest AEP and was at a 100m resolution spanning the province. Weather station location and weather station data was also obtained from ESRD. Actual weather station locations are upwards of 200-km apart while the surrogate gridded weather values acting as weather stations are all 10-km apart as mentioned above (Figure 2.3). Fire ignition location and timing information as well as final fire perimeters were collected and extracted by ESRD.

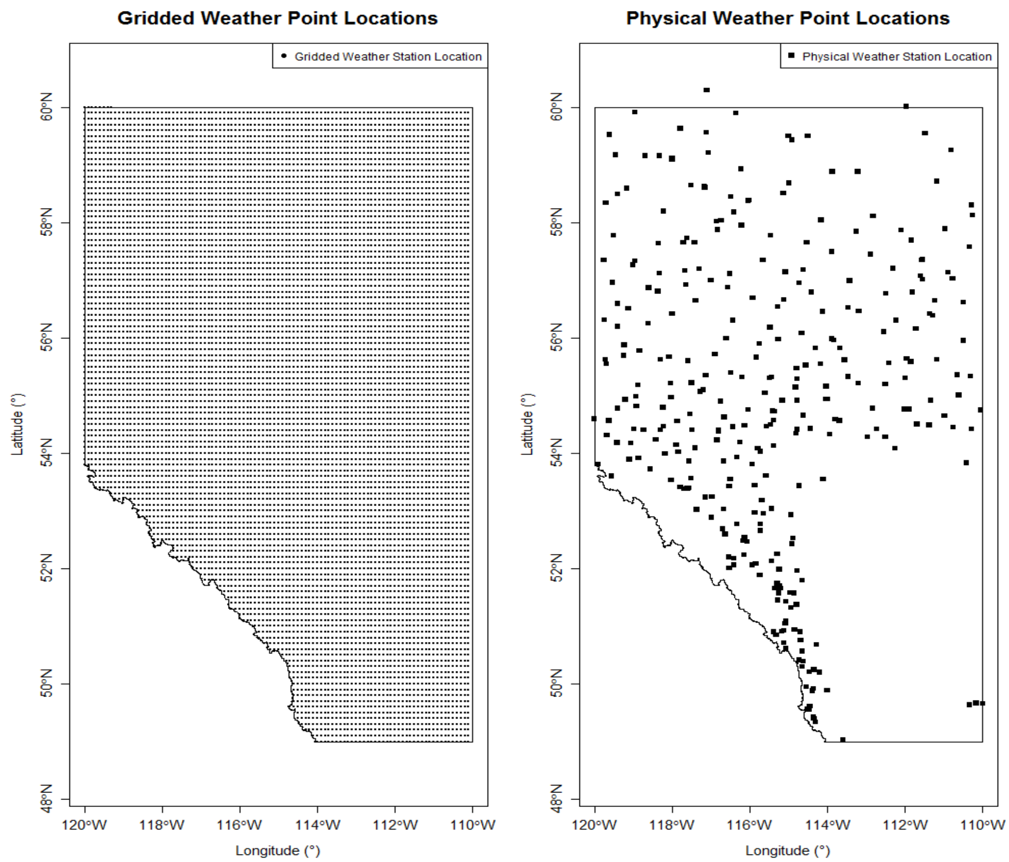


Figure 2.3 – Point location of weather station: modelled (left) and physical including temporary and decommissioned (right).

2.3 – Data Assimilation

The GRIB data was a raster grid that needed to be decomposed in order for functionality within Prometheus. The data was pre-processed within R (CRAN-R Project) (CRAN R-Project 2015) through a series of scripts that decomposed and reordered each file to generate a single 72-hour, hourly forecast for each member within the GEM. Each member forecast was used to simulate fire growth within the Prometheus Fire Growth Simulation model. Data used within Prometheus requires weather variables and Fire Weather Index System (FWI) codes. The weather variables were temperature, precipitation, relative humidity, wind speed and wind direction. The FWI codes were FFMC, DMC, DC, ISI, BUI, and FWI.

Data assimilation was carried out with five scripts:

1. Total Fire Season LatLong – This script was responsible for defining the “start” of the fire season. For ESRD purposes, the start of the fire season is March 1, however in this application the start of the fire season occurred when 80% of fire weather towers were active. This was to ensure that the interpolation of indexes to begin fire weather index calculation on weather grids were acceptable. This script used the resolution of the GRIB raster in order to interpolate weather station data to gridded points which, created rasters of daily weather from actual weather stations. Raster based daily weather was required as it was used for the calculation of FWI values that led up to the ignition. This served as a spin-up period for the model rather than interpolating the day prior to fire ignition. The rationale behind this method of index calculation followed the time lags for each index as described in Van Wagner, 1987. Output from this script was a stack of rasters ready for FWI calculation and three initial condition rasters containing FFMC, DMC and DC information. An additional failsafe was implemented where the length of time from index start up to fire ignition was taken into account. Weather stations deemed viable must have reported for at least 80% of the days between start up and ignition. This ensured weather stations that failed to report up to the ignition date were excluded. These rare occurrences would have been responsible for disrupting interpolation because of missing values.
2. Gridded Daily – The Gridded Daily script was responsible for decomposing the GRIB files into weather variables ready for FWI calculation. The aforementioned variables

within GRIB were not suitable for modelling within Prometheus therefore the following conversions were made.

a. Temperature – converted from Kelvin to Celsius.

b. Relative Humidity – Specific Humidity, temperature, and pressure were used in order to calculate relative humidity through the Goff-Gratch equation.

c. Wind Speed –Pythagorean Theorem was used on the U and V components and converted from m/s to km/hr.

d. Wind Direction – Wind Direction was calculated using the atan2 function within the R raster package (Hijmans 2014).

e. Precipitation and Accumulated Precipitation – Hourly precipitation was calculated by converting accumulated precipitation to hourly precipitation. Accumulated precipitation was used to define the daily precipitation for Prometheus, which was defined as the total precipitation from 1200 LST to 1200 LST the following day.

The output from this script was a set of binary files ready for FWI calculation.

3. FWI Batch – This script was responsible for calculating FWI through the fire season up to the ignition date. It used the binary weather files from the Gridded Daily script then calculated the daily FWI values within the GRIB data. The fwiBATT function from the fwi.fbp package was used to perform all FWI calculations (Wang *et al.* 2014a). The output from this script was daily FWI values for the fire season.

4. Hourly FFMC – Hourly indexes were then calculated after daily values were available. The hffmc function in the cffdrs package was used to perform these calculations (Wang

et al. 2014b). Hourly values were calculated on a point-by-point basis for the entire GRIB grid. The outputs from this script were hourly weather binary files with hourly FWI values.

5. Prometheus Ready Weather – This final script used the hourly index binary files to find the nearest point to a fire and its eight surrounding points. This was done to ensure a square 3-by-3 station network of weather stations for Prometheus in order to minimize spatial interpolation required around the ignition point. Notably this would constrain the maximum internal area of the weather 'box" to 90,000 hectares. For larger fires additional weather stations would be required to ensure modelling occurs within weather influence rather than interpolating beyond the available data. This script also clipped the digital elevation model and fire behaviour fuel grids to ensure they were ready for input into Prometheus. The output from this script was nine weather streams for each member ready for import into Prometheus and the grids required. All spatial data was projected in the NAD 83 10-TM Forest AEP format.

2.3.1 – Weather Output Validation

Completed weather streams were assessed against the weather from the closest physical weather station. This assessment was done with the root mean square error (RMSE) calculated for each of the four weather variables: temperature, relative humidity, and wind speed and direction. The RMSE outputs assisted in understanding the variation within each weather variable. This gave increased meaning to the overall forecast skill and accuracy. The RMSE did not describe the direction of the deviation, only the magnitude.

Root mean square error was calculated for the deterministic weather and each individual ensemble member. The ensemble member RMSE values were evaluated together within a box plot alongside the deterministic RMSE value. This showed the overall variability within the ensemble weather forecast in comparison with the deterministic value. The RMSE was calculated using the weather station closest to each wildfire and the grid point closest to that weather station. In this way, RMSE values were not being interpreted across long distances and represented the amount of error seen in the weather forecast in comparison to reality. All of the stations that were used were within 50 kilometers of the fire ignition position. Table 2.2 outlines the weather stations used for RMSE for each fire and the distance from the fire of those stations. Additionally, the distance from the station to the nearest point that was used for RMSE calculation is documented. Note, due to the ten-kilometer resolution of the gridded weather data it is impossible for the point nearest a weather station to be further than five kilometers away.

Table 2.2 – Fire and corresponding weather stations for RMSE calculation.

Fire Number	Station ID	Distance to Fire	Distance to Nearest Point
EWF-054	SI	17.08	2.41
GWF-044	G2	9.75	1.1
HWF-058	SV	35.43	2.2
HWF-059	F5	3.82	4.16
HWF-133	F2	40.87	4.16
HWF-219	WZ	51.19	1.55
MWF-051	L5	28.84	2.02
PWF-116	MC	13.61	1.28
RWF-034	R4	30.41	2.36
SWF-113	OL	36.00	2.58

2.4 – Model Setup

Within Prometheus, many options may be enabled or disabled to change the way that fire growth simulation is carried out. For the purposes of the simulation completed in this thesis, the model was setup as described in the next section.

2.4.1 – Scenario Inputs

Each scenario was assigned nine weather stations, the central weather station acted as the primary weather station. The primary weather station was defined in space as the GRIB point closest to the ignition. The start time was set to the ignition time as reported within the Fire Information Resource System; the end time was set to 1800 LST two days after ignition.

2.4.2 – Burning Conditions

Burning conditions influenced when fire simulation commenced. Fire simulation may be turned on or off hourly, simulated fire spread was dependent on the weather conditions. Fire spread was discontinued if relative humidity exceeded ninety percent or the FWI was less than ten. Often a minimum wind speed around 5 km/hr occurred during fire simulation modelling in order to obtain a FWI of at least ten. In the boreal forest, a FWI of nineteen is acknowledged minimum standard for fire spread however, during initial testing a FWI of nineteen yielded no growth in all but one wildfire in this study (Podur and Wotton 2011). Notably the fire spread discussed by Podur and Wotton, (2011) was assessed using Moderate Resolution Imaging Spectroradiometry (MODIS). The resolution for MODIS within Podur and Wotton (2011) was 1-km-by-1-km, which indicated that the growth seen in these images was very large. The fires focused on by Podur and Wotton (2011) were greater than 200 hectares.

During this study a fire weather index of nineteen resulted in little to no growth, this was not unexpected. Fires in this study were less than 100 hectares, which required the use of a much lower FWI value as the threshold for growth. Furthermore, Podur and Wotton (2011) focused on the boreal region; while many of the fires in this study were boreal fires, there were fires in other natural subregions. This further explained why some fires did not spread when a FWI of nineteen was present.

2.4.3 – Simulation Settings

Many of the Prometheus simulation settings were in the default position, however the settings of note were:

- Stop fire at data boundary
- Breaching on
- Acceleration on, with the exception of GWF-044, ignition began from a polygon.
- BUI effect on
- Terrain effect on
- Green-up where NODATA exists on
- Fire Weather Interpolation - Calculate FWI System values from spatially interpolated weather selected

These options will ensure every fire will be simulated under the same application conditions. An example complete Prometheus report can be seen in Appendix D.

2.4.4 – Assumptions for Special Scenarios (GWF-044 and PWF-116)

Two fires within this dataset followed different rules than the other eight fires. These fires require additional explanation as they are slightly modified to describe the actual fire scenario.

Grand Prairie wildfire 044 was a fire that started in British Columbia and crossed into Alberta on July 15, thus this fire was not starting from a point ignition rather, and it started from an established perimeter. Due to this fact, GWF-044 had acceleration turned off as the fire had already achieved its equilibrium rate of spread. The perimeter was obtained from ESRD's spatial fire database. Notably the perimeter used for simulation was taken on July 16. On this day, the fire was given a wide berth, as it was relatively active. This led to a large "unburned island" in the fire simulation outputs. This "island" was a result helicopter mapped fire perimeter being too wide, for safety reasons, and confounded the final simulation output.

Peace River Wildfire 116, when simulated, produce little to no growth, which, under the weather conditions, was concerning. Upon investigation the majority of fuel grid was classified as Vegetative Non-Fuel as seen in Figure 2.4a. This meant there was plant material in this area, but not deemed flammable. This was likely due to the close proximity of the area of this fire to the municipal protection area. There was a large agriculture sector in areas surrounding Peace River and much of this area was classified as either non-fuel or vegetated non-fuel. For this reason, satellite imagery from the ESRD Land use Framework Planning group was used to reclassify much of the vegetated non-fuel in this area to boreal spruce (C-2), as that was the dominant fuel type in Northern Alberta (Government of Alberta ESRD 2015). Due to the large amount of agricultural activity, the area was easily identified manually. There was a noticeable deciduous component in the area but very little fuel needed to be reclassified to deciduous (D-1).

The final reclassification can be seen in Figure 2.4b, the polygons seen within this panel are what Prometheus used in order to reclassify the underlying fuel types. The blue polygon reclassified all vegetative non-fuel to Deciduous, as did the yellow polygon within the red polygon to the East of the ignition point. The red polygon reclassified all vegetative non-fuel to boreal spruce (Figure 2.4b).

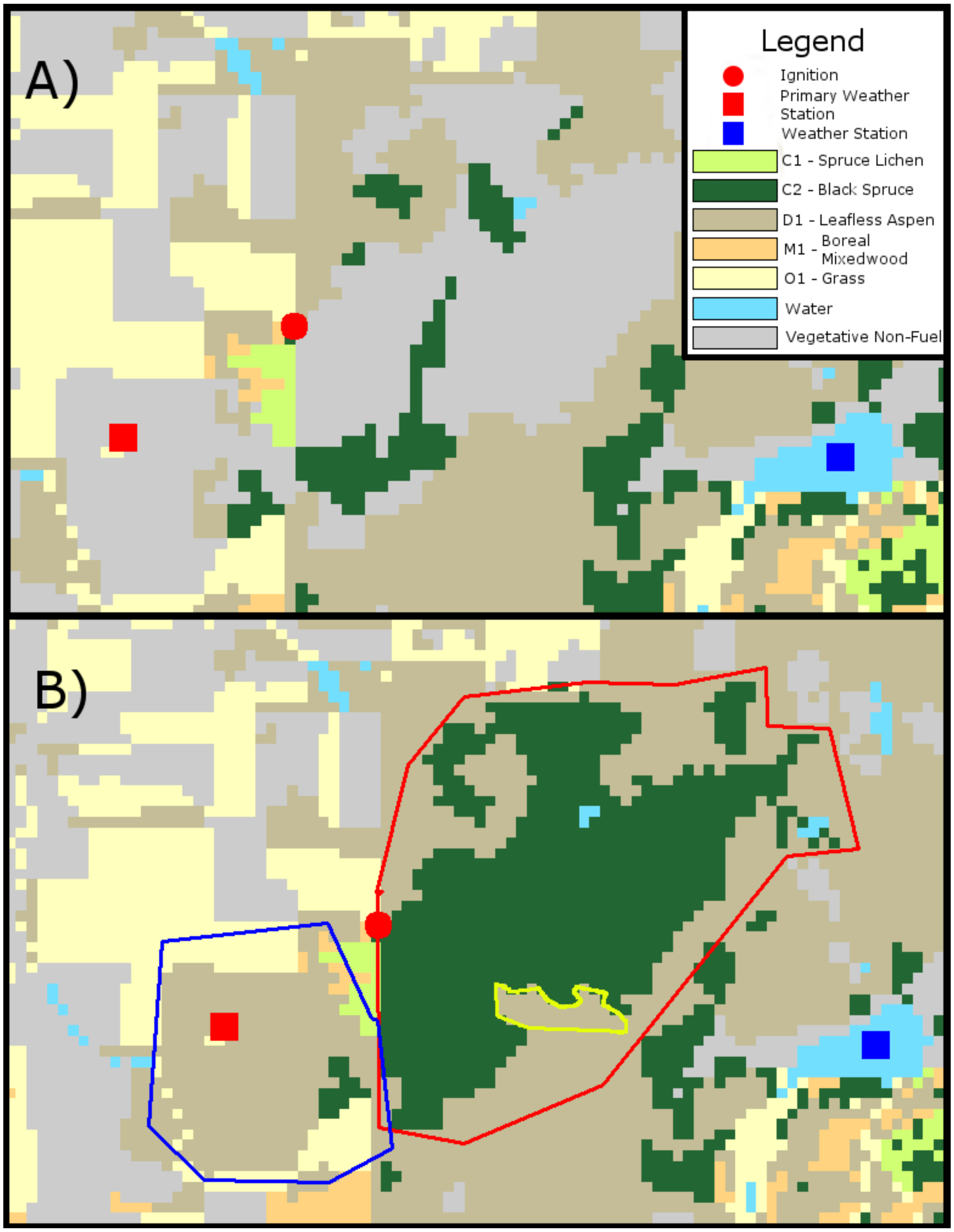


Figure 2.4 – A) The original FBP Fuel Type map from ESRD. B) The FBP Fuel Type Map used during fire growth simulation and depicts the fuel grid after modification from satellite imagery.

2.5 – Fire Growth Simulation

When the model was ready for initialization, the location of a fire was entered in decimal degrees into R along with the start date of the fire. R found the processed weather stream and determined which point location was the closest to the fire location. Next, R obtained the closest point and the eight surrounding points in order to create a nine weather station system for use within Prometheus. The weather grid resulted in an effective span of 30-km North-South and East-West. In order to propagate fire across a landscape, Prometheus required the input of a digital elevation model (DEM) layer and a Fire Behaviour Prediction (FBP) fuel layer. The simulation was carried out from midnight (0000 LST) day 1 to six o'clock (1800 LST) day 3. Outputs from the model were shapefile perimeters and a raster of head fire intensity (used inverse distance weighting). Each Prometheus simulated member resulted in 20 different rasters and shapefiles to be combined within R. All outputs from Prometheus were projected in the NAD83 Forest AEP format; these were projected to WGS4 for presentation purposes.

2.6 – Post-Processing

After all the outputs were obtained, head fire intensity rasters were input into R and combined to create a burn probability raster. The burn probability raster depicted the probability of any one cell having burnt over the series of scenarios simulated. In this case, there were 20 scenarios; therefore, probabilities are broken into five percent increments. The perimeters were used to generate agreement perimeters within R via the rasterize function in the raster package (Hijmans 2014). Each of the perimeters was rasterized based on time in order to generate a time based probability raster. Agreement perimeters were then generated based on the probabilities within the probability raster in five percent increments from fifty to ninety-five percent agreement. Agreement had been defined as probability in this output. A fifty percent burn probability meant those cells would form a fifty percent agreement perimeter. The ninety ninth percent agreement was not used, as the results were be the same as the one hundredth due to the number of scenarios simulated and rounding. A skill metric was also be derived in order to compare each ensemble member simulated fire perimeter against the actual fire perimeter as shown by Anderson (2009a).

2.7 – Analysis

In order to define success, a control output was needed for comparison. In this instance, the control output was obtained by performing a fire growth simulation with the control member (Member 0) from the ensemble model (Government of Canada Environment Canada 2015a). As previously mentioned, this control is made up of the average of 192 perturbed forecasts. This member was not used in the probabilistic forecast to ensure it could be used as a control. Under operational conditions the control member could be substituted for a meteorologists forecast or any other forecast source. The control member will be referred to as the deterministic output henceforth as would any single forecast simulation. This does not mean the ensemble members are stochastic outputs, all Prometheus outputs are deterministic as defined by Tymstra *et al.* (2010). Combining the ensemble members allows the user to emulate stochasticity using different inputs. This process allows one to create probabilistic outputs without a truly stochastic input dataset.

The initial analysis undergone in this study is a measure of the accuracy of the forecast via Root Mean Square Error (RMSE), which is commonly used by weather agencies to assess forecast accuracy. The RMSE is a statistic used to determine the overall accuracy of a forecast but does not describe the deviation direction (Stanski *et al.* 1989). The formula used to calculate RMSE from Stanski (1989):

$$\boldsymbol{RMSE} = \left[\frac{\mathbf{1}}{\boldsymbol{N}}\Sigma_{\boldsymbol{i}=\mathbf{1}}^{\boldsymbol{N}}(\boldsymbol{F_i} - \boldsymbol{O_i})^{\mathbf{2}}\right]^{\frac{\mathbf{1}}{\mathbf{2}}} \quad [1]$$

Where F_i is the forecast value on day i, O_i is the observed value on day i and N is the number of days forecast. Each forecast will have its RMSE calculated with an N of three. When calculating RMSE for ensemble members each member will have its RMSE calculated individually.

In order to analyze the model output data a comparison of fire size and spread is required. Agreement fire growth simulation perimeter rasters are compared against the control fire growth simulation perimeter rasters in order to ascertain model skill. The control member is being used in place of a meteorologists forecast in order to emulate a forecast given the day of fire ignition. This is important, as a forecast developed by a meteorologist now would have inherent bias due to knowledge of the actual weather during that time. The skill scoring technique used is the same technique used in Anderson (2009a) as defined by Stanski *et al.* (1989). The skills scores described by Stanski *et al.* (1989) hinge on the contingency table seen in Table 2.3.

Table 2.3 – Contingency table for describing forecasted and observed events.

		Observed	
		Yes	No
Forecast	Yes	A (Hit)	B (False Alarm)
	No	C (Miss)	D (Correct Non-Event)

Equations for calculating skill score based on Table 2.3:

$$\boldsymbol{Bias = \frac{A+B}{A+C}} \quad [2]$$

$$\boldsymbol{Hit - Rate = \frac{A}{A+C}} \quad [3]$$

$$\boldsymbol{False\ Alarm\ Ratio = 1 - \frac{A}{A+B}} \quad [4]$$

$$\boldsymbol{Critical\ Success\ Index = \frac{A}{A+B+C}} \quad [5]$$

Each of the skill scores have been articulated in Stanski *et al.* (1989) and others in the following ways (Roebber 2009):

Hit-Rate – The frequency of correctly predicted events, only accounts for hits.

False alarm ratio – The fraction of events incorrectly predicted, only accounts for misses.

Bias – The magnitude of over/under prediction.

Critical Success Index – A measure of forecast overall skill, taking into account both hits and misses.

The ideal values for bias, hit-rate, and critical success index are all a value of one; while false alarm ratio would ideally score zero (Stanski *et al.* 1989).Bias is the only skill score that may exceed one.

Within this study, a hit was defined as when the model and the actual fire both burned a cell. A miss was when the model fails to predict fire in a burned cell. A false alarm was the incorrect prediction of fire in a cell where no fire occurred. A correct non-event was when the model did not predict fire correctly (no fire occurred). Correct non-events were not used as the metric was a function of the area modelled, otherwise correct non-events would serve to "wash out" the actual values inflating skill artificially as spatial extent increases. The score used to define overall skill was the CSI. The CSI was used as a final measure as to whether or not the probabilistic output performed better than the deterministic output. The other three scores allowed a user to assess the meaning behind the CSI score. The CSI incorporates both hits and misses as seen in equation [5]. This resulted in a metric that was more indicative of the overall skill of any forecast or set of forecasts as opposed to the HR or FAR alone (Stanski *et al.* 1989).

The results describe the outputs generated and the skill scores derived from those outputs. The raster and image outputs were generated to serve as a deliverable for fire operations staff while the skill scores allow a modeller or researcher to define whether the model was performing well in comparison to reality. Visual outputs were generated in the form of burn grids. These burn grids were derived from a binary output, burn/no burn. When deriving the probabilistic burn grids a value from 0/20 to 20/20 were seen. Perimeter plots were also delivered to display the actual perimeter and an agreement perimeter (deterministic, 50^{th}, $75^{th,}$ and 95^{th}).

Chapter 3 - Results

This section was been broken into two components: forecast accuracy and fire growth simulation model predictive skill. The weather model forecast accuracy was measured via root mean square error while the Prometheus model output skill was measured by the critical success index. The outputs in this section were intended for two purposes: 1) a quantitative understanding of the overall weather forecast and wildfire modelling skill and 2) a final deliverable for fire management teams to support decision-making. The deliverable from this thesis was a set of figures (probabilistic fire growth simulation output and perimeter comparisons) and the skill scores pertaining to the fire growth simulation outputs. It is important to recall throughout these results that each fire was suppressed to some level. The amount of suppression effort for each fire was not quantified in this work; however, it is understood that suppression has a considerable effect on fire spread.

3.1 – Assessment of Model Forecast

Prior to defining the success of fire growth simulation, we must first ascertain the skill of the forecast, in this case both the deterministic and the ensemble forecasts. In order to assess the root mean square error, a boxplot for the ensemble forecasts was created. When interpreting the values seen in Table 3.1, it should be noted that a lower value depicts a smaller deviation and thus a better forecast.

Defining the skill of the forecast allows for a greater understanding as to where the error lies. For instance, if the forecast error is low yet the skill of the fire model simulation is low, one can safely assume that the error is from the fire model, rather than the weather forecast. Understanding the greatest source of error will inform future updates to the models, whether updates to the fire growth simulation model need to occur or the source of the weather forecast needs to be changed or better understood. Often fire management agencies have superior access to the fire growth simulation modelling community than they do the weather modelling community. As such, amendments surrounding fire growth simulation model error may be more readily applied. Ideally, both forecast and model error will be low, which would indicate both the input data and the modelling process have accounted for as much stochasticity as possible.

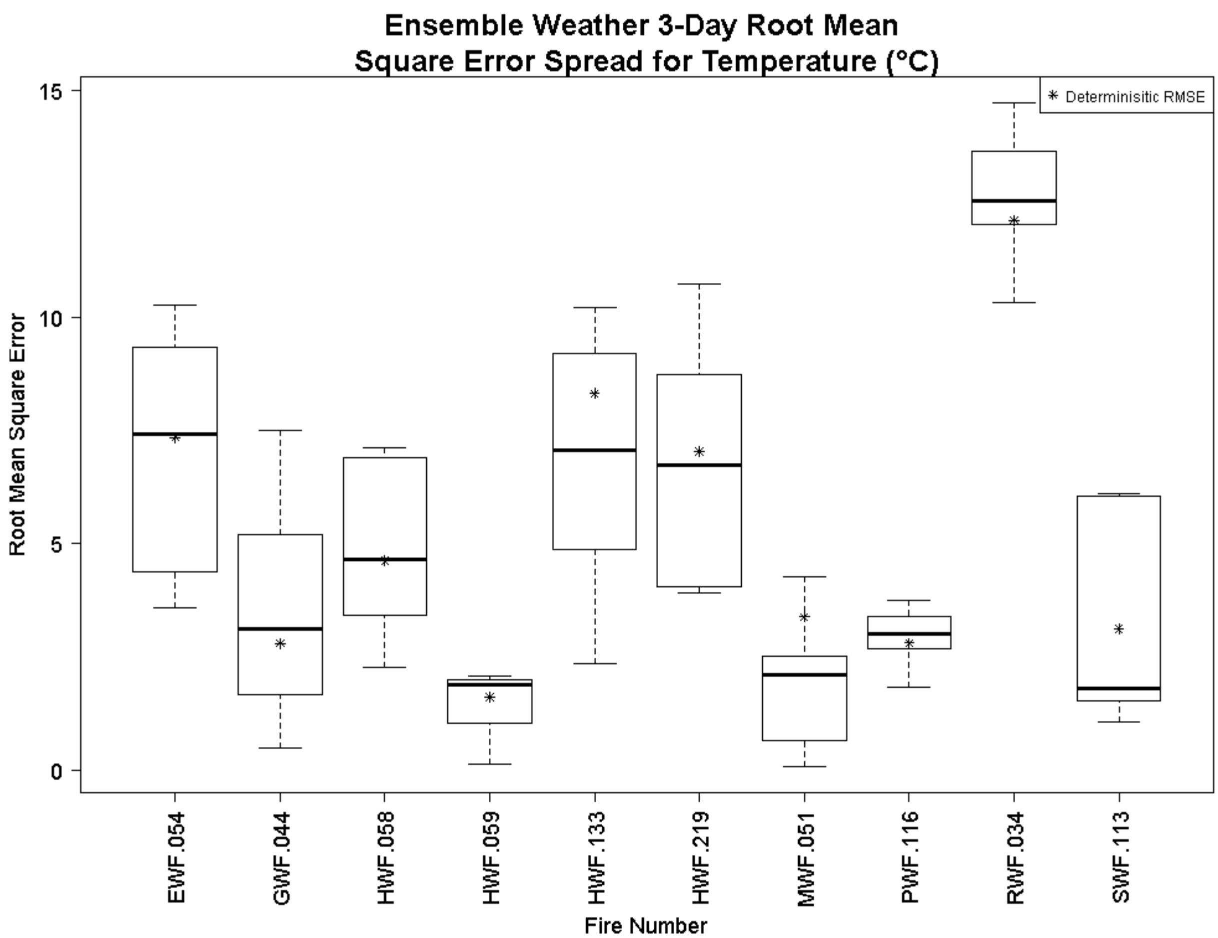


Figure 3.1 - Root Mean Square Error comparisons for temperature for the deterministic and ensemble for each fire.

This information can be visualized in Figure 3.1 in the form of a boxplot comparing actual, deterministic and ensemble member forecasts. These boxplots allow for a practitioner or researcher to describe the relative fit between actual and forecast values. Further, these boxplots display the variability within the ensemble. The variability displayed in the ensemble model allows users to ensure the ensemble encapsulates the deterministic and actual values. During real scenarios, the actual weather would not be available until after a fire incident. This is solely for visual assessment. After the assessment occurs a more rigorous analysis, the RMSE, may be used to define the accuracy and fit of the forecast as seen in Table 3.1 and the average bias in Table 3.2 (Stanski *et al.* 1989). To identify how well the weather model fit into the fire modelling scenario the RMSE for hourly fire weather indexes was calculated. Figure 3.2 displays the RMSE of the Initial Spread Index. In all cases, the error is relatively low with good agreement between ensemble members, as noted by a thin boxplot spread. All RMSE boxplot comparisons can be found in Appendix A. Variability in the modelled values is seen in Figure 3.3. This information allows a user to understand the degree of confidence in the forecast. Horel *et al.* (2014) also used gridded weather to calculate FWI indexes for the purposes of fire behaviour forecasting and found applicability of gridded FWI indexes under real conditions.

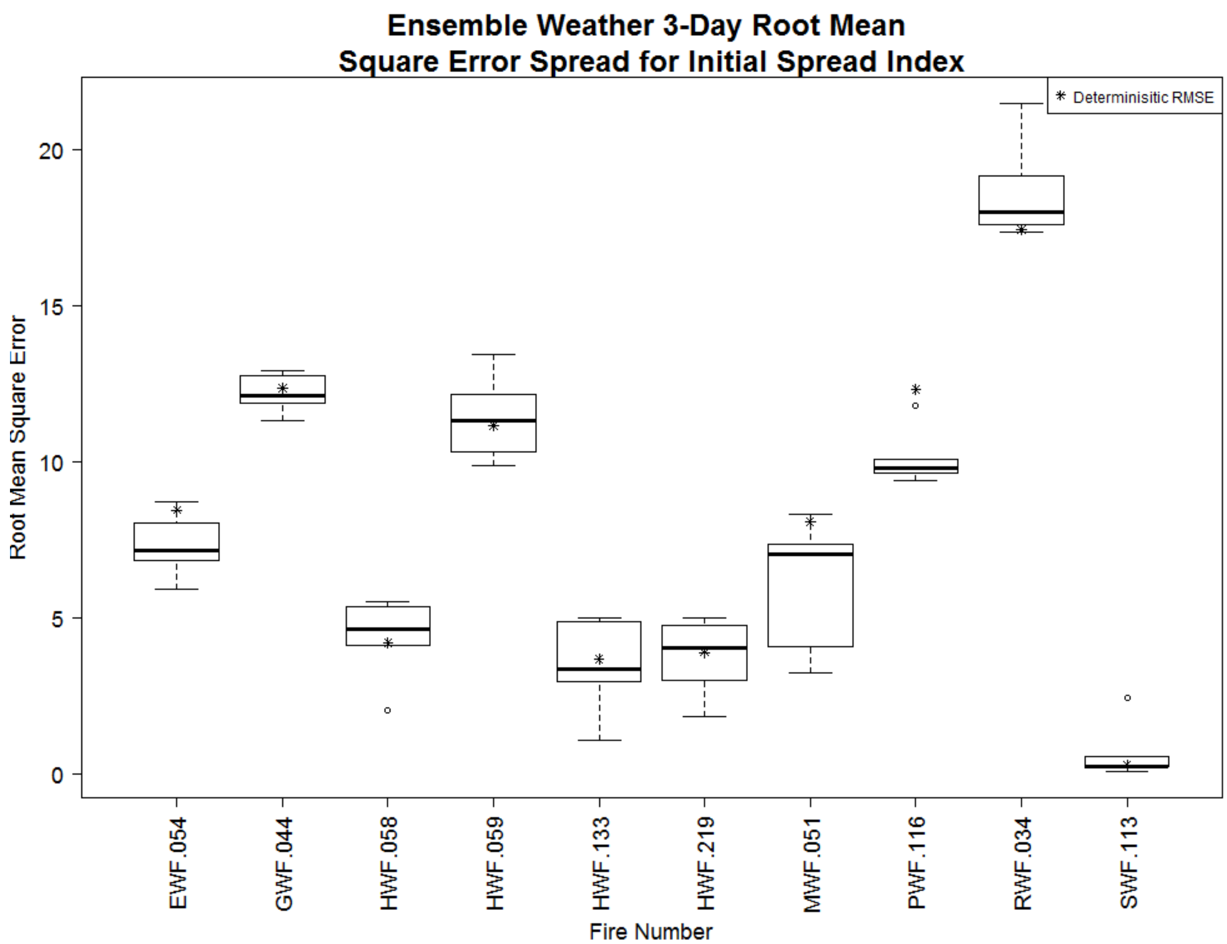


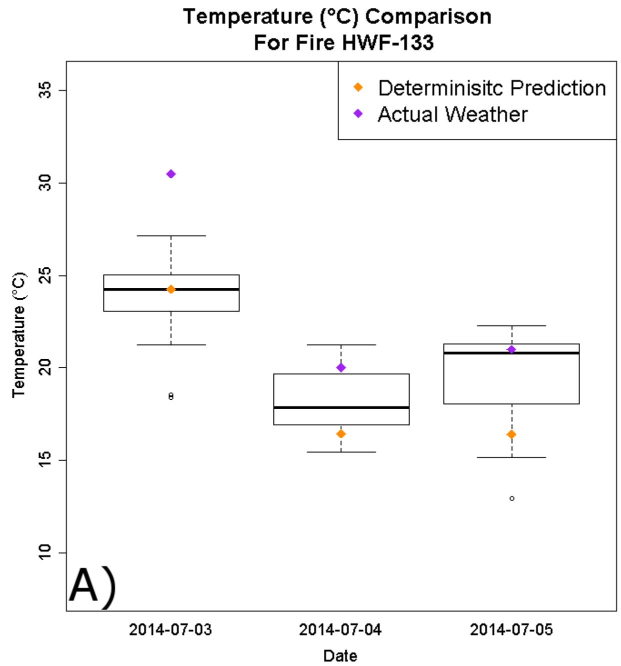
Figure 3.2 – Initial Spread Index RMSE comparison of deterministic and ensemble outputs for all ten fires.

Table 3.1– Average and (standard deviation) root mean square error for each weather variable under the deterministic and percent agreement model thresholds.

	RMSE Deterministic	RMSE Ensemble 50th Percent Agreement	RMSE Ensemble 75th Percent Agreement	RMSE Ensemble 95th Percent Agreement
Temperature	5.32 (3.30)	3.86 (1.95)	4.89 (1.67)	5.74 (1.96)
Relative Humidity	25.4 (18.91)	20.29 (8.94)	25.14 (7.76)	32.60 (7.03)
Wind Speed	11.67 (5.27)	7.41 (2.59)	7.79 (2.57)	8.48 (2.69)
Precipitation	2.85 (5.45)	3.00 (5.26)	3.22 (5.70)	3.60 (5.60)
Wind Direction	77.15 (51.68)	70.68 (49.18)	97.00 (54.79)	135.83 (66.89)

Table 3.2– Average and (standard deviation) bias for each weather variable under the deterministic and percent agreement model thresholds.

Weather Variable	Deterministic Bias	Ensemble Bias
Temperature	-0.37	-0.04
Relative Humidity	18.96	4.18
Wind Speed	-20.21	-6.79
Wind Direction	-41.2	-10.55
Precipitation	-4.76	-1.76



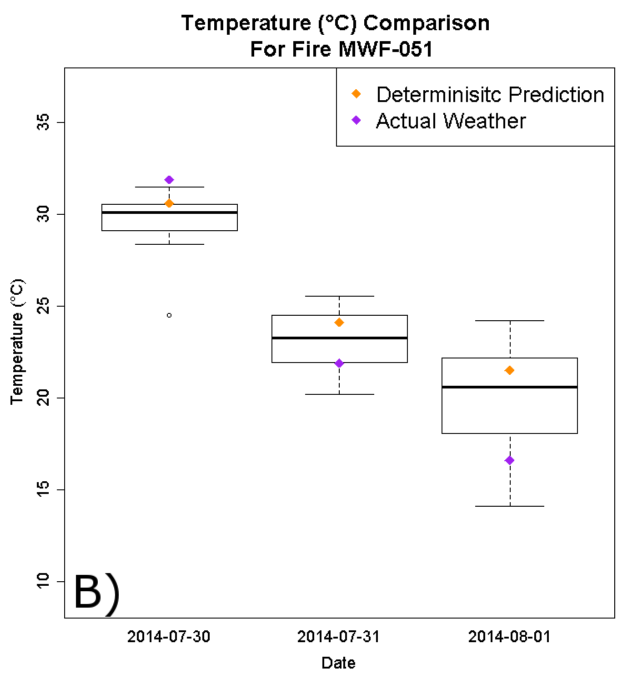


Figure 3.3 - Panel A) displays a relatively "poor" agreement between actual, deterministic and ensemble forecasts while Panel B) displays a relatively "good" agreement. Each of these Panels displays the forecast and/or actual weather values over the forecast period.

3.2 – Deterministic versus Probabilistic

The product from the probabilistic modelling technique in Figures 3.4 and 3.5, are intended to assist fire management teams during the decision making process on long-term fire incidents. Traditionally a fire management team would receive a deterministic output as depicted in the top panel of Figure 3.4 in grey. This may assist in the decision making process; however, the actual fire perimeter, depicted in black, is considerably larger than the deterministic output. The bottom panel of Figure 3.4 would allow scenarios to be established to allow a fire management team to have multiple plans. In Figure 3.4, the burn grid plots for both the deterministic and probabilistic fire growth simulation outputs can be seen. These outputs can be used as a visual estimate of where a fire may progress over the 2.75-day forecast. The intent of these outputs was to inform, without a large amount of rigor, as to where the final perimeter would be after 2.75 days even though this would not be known in an operational setting. When interpreting these outputs, it is important to recall that Prometheus does not simulate fire suppression activities; this will be discussed further in the next section. The probabilistic output in Figure 3.4 allows for greater situational awareness in terms of the overall spread potential. The agreement perimeter outputs in Figure 3.5 serve to identify a potential best and worst-case scenario. The deterministic outputs were derived from the deterministic ensemble member (Member 0).

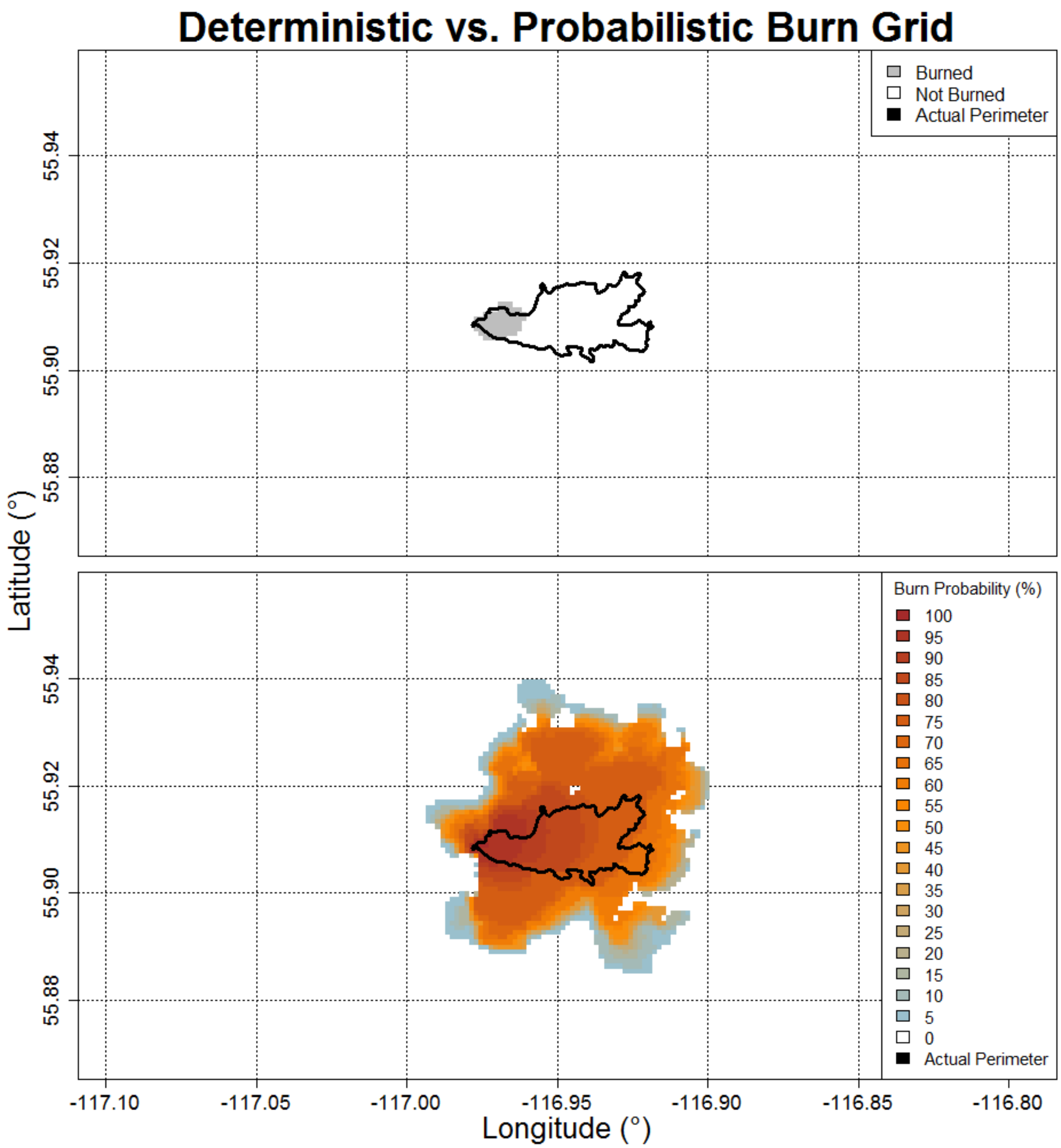


Figure 3.4 - The deterministic (top) and probabilistic (bottom) model outputs plotted with the actual fire perimeter (black polygon) for fire Peace River Wildfire 116 (PWF – 116).

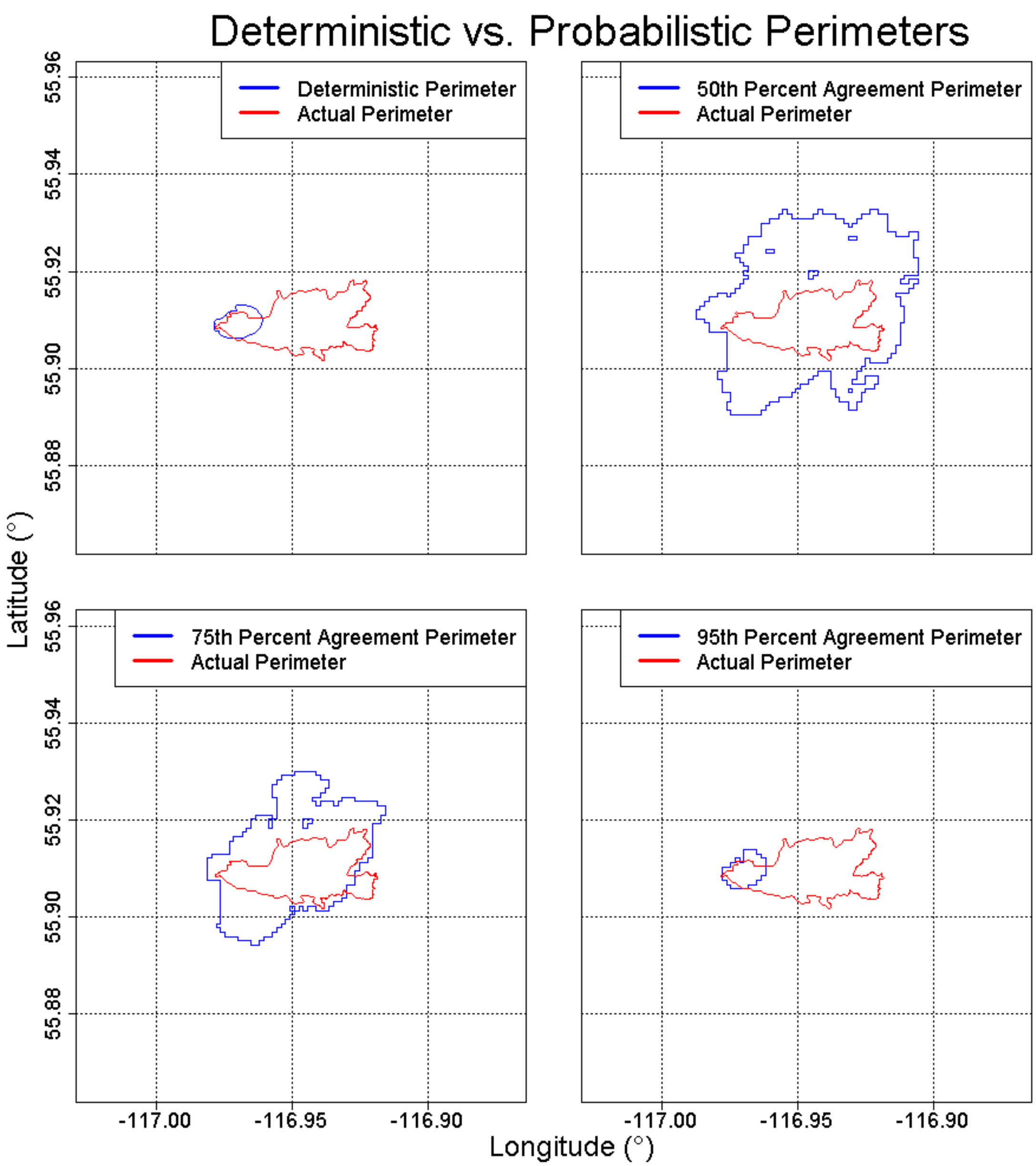


Figure 3.5 – Actual fire perimeter plotted with deterministic, 50th, 75th, and 95th percent agreement perimeter outputs for Peace River Wildfire 116 (PWF – 116).

3.3 – Skill Score

The skill score method used in this work was used to define how well a statistically generated probabilistic fire growth simulation fits an actual perimeter (Anderson *et al.* 2007). Each fire was scored separately, an example of which can be seen in Table 3.3. Each score was then averaged in order to generate an overall skill score as seen in Table 3.4. These score tables give an indication to the trend seen in hit-rate, bias, false alarm ratio, and critical success index.

Table 3.3 – Single fire (PWF-116) skill score with scores for the deterministic run and 50th, 75th and 95th percent agreement perimeters.

		Deterministic Run	50% Agreement	75% Agreement	95% Agreement
Fire Size (ha)	353 (Actual)	61	1581	915	61
PWF-116-2014	Bias	0.31	4.52	3.24	0.31
PWF-116-2014	Hit-Rate	0.21	1.00	1.00	0.18
PWF-116-2014	False Alarm Ratio	0.34	0.78	0.69	0.43
PWF-116-2014	Critical Success Index	0.19	0.22	0.31	0.16

Table 3.4 – Average skill score over nine* fires. *RWF-034 though included did not propagate fire due to weather model limitations in mountainous areas, with scores for the deterministic run and 50th, 75th, and 95th percent agreement perimeters.

	Deterministic Run	50% Agreement	75% Agreement	95% Agreement
Bias	7.44	9.19	3.19	0.96
Hit-Rate	0.55	0.60	0.45	0.22
False Alarm Ratio	0.67	0.62	0.61	0.47
Critical Success Index	0.16	0.16	0.17	0.13

The trending across Bias, Hit-Rate (HR), and False alarm ratio (FAR) is mixed however; the important trend to notice is the CSI. Most notably, 95% agreement does not always result in the greatest overall skill. This was anticipated and will be discussed further in the next section. Further assessment may be visually attained in Figures 3.6 and 3.7. Each of these figures presents a method of assessing the skill of each forecast in comparison to deterministic output. In each case, it can be seen that the ensemble performed better under most agreement conditions. A trend of this scoring method is seen in the relationship between hit rate and false alarm ratio. As seen in Figure 3.7, a higher hit rate resulted in a higher false alarm ratio. This is to say the more likely a model correctly predicts, the more likely that model is to produce false alarms. This could lead fire modellers and fire managers alike to have a greater understanding, and therefore greater confidence, in wildfire model outputs. All single fire skill scores and average skill score results can be found in Appendix A.

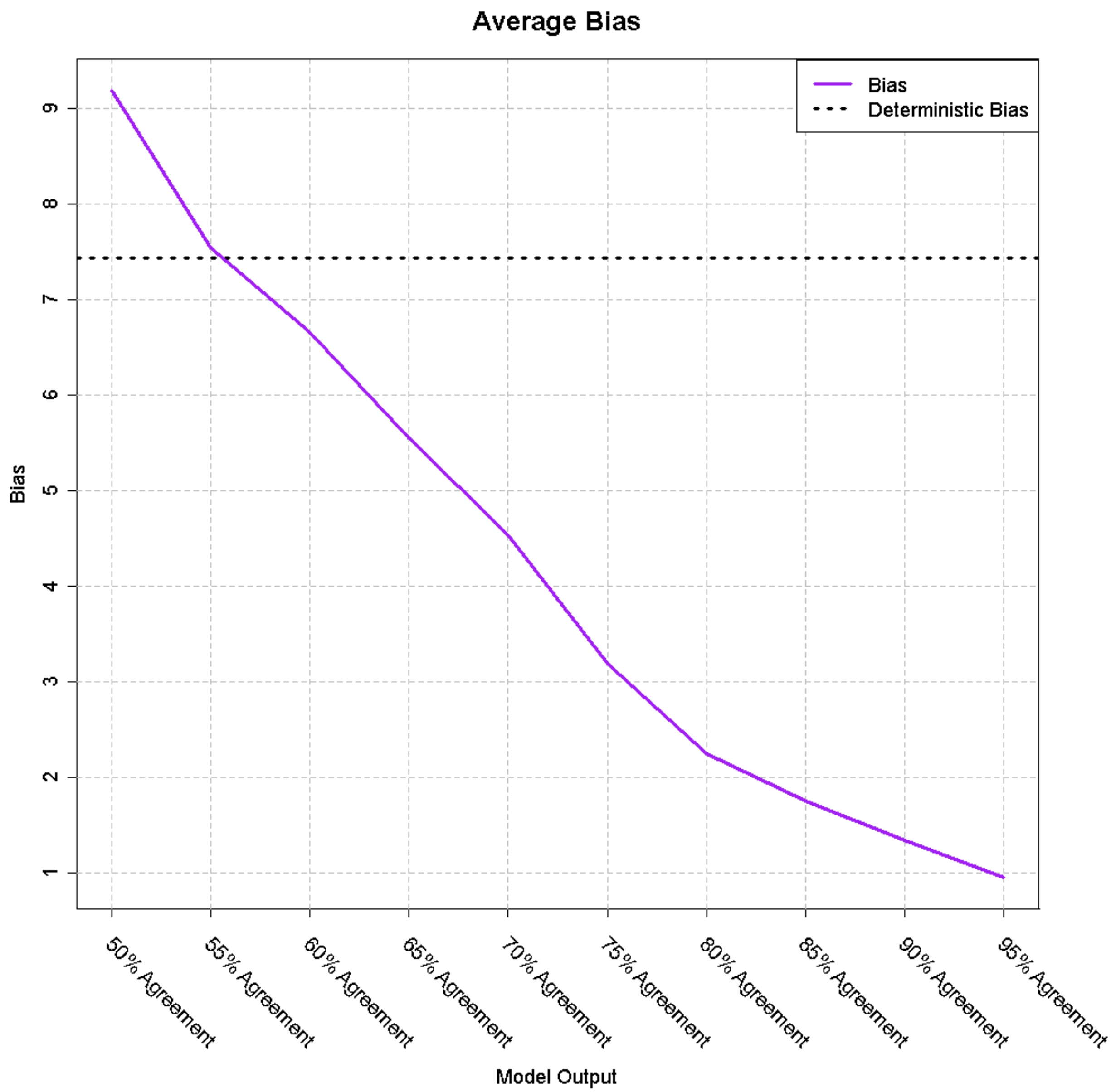


Figure 3.6 – Average ensemble bias plotted alongside the bias found within the deterministic forecast bias.

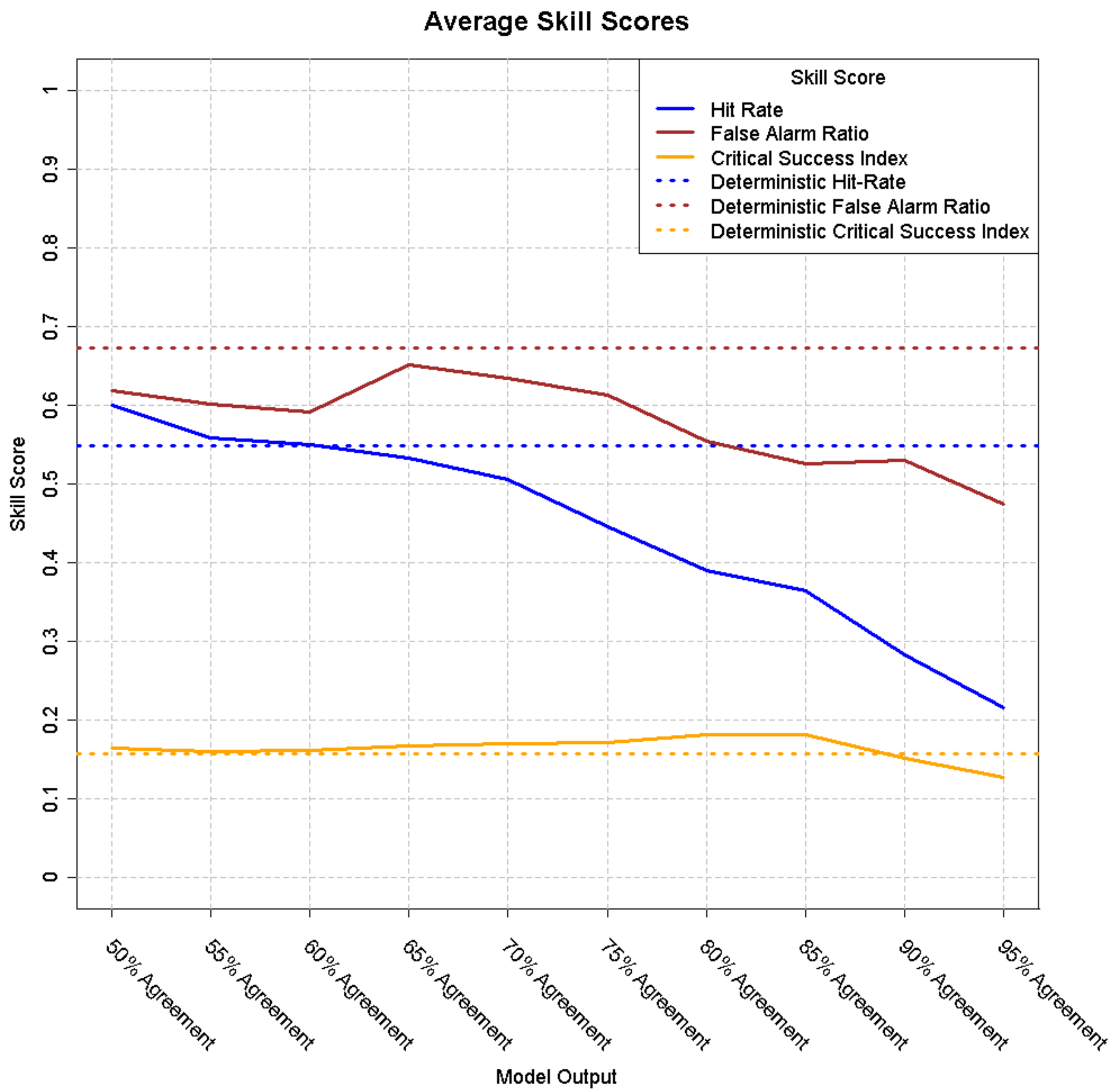


Figure 3.7 – Average ensemble hit-rate, false alarm ratio, and critical success index plotted alongside the deterministic forecast scores.

3.3.1 – Quantitative Assessment of Fire Growth Simulation Modelling

In general, eight of ten fires modelled had a superior critical success index under one of the percent agreement scenarios (50 – 95%). The two fires that failed to perform better than the deterministic were MWF-051 and RWF-034. RWF-034, which did not propagate at all, was not removed from this study. It was considered an accurate representation of what may occur in reality, as forecast weather may not always result in fire growth simulation success. Seven of ten fires performed better than the deterministic at a percent agreement of 65%. On a fire-by-fire basis, six of ten fires performed superior within a percent agreement range of 65% to 85%. This is not a generalization that may apply to all fires, as this dataset is still small.

The average CSI for the deterministic output was 0.16 while the probabilistic outputs ranged from 0.13 (95% agreement) to 0.18 (80% agreement). Individual fires had deterministic CSI scores ranging from 0.03 to 0.66 while probabilistic CSI ranges from 0.004 to 0.74 (across all fires). These results were similar across all scores with the probabilistic output generally performing better than the deterministic. The maximum CSI and the percent agreement at which that CSI occurred can be seen in Table 3.5. Notably within Table 3.5 in only one instance was the deterministic the superior model output, in terms of the CSI. The next section will discuss the impacts these scores.

Table 3.5 - Maximum CSI followed by the percent agreement at which that CSI occurred.

Fire Number	Critical Success Index Maximum	Percent Agreement Maximum Occurred
RWF-034	0.00	Not Applicable
HWF-133	0.08	50% Agreement
SWF-113	0.39	65% Agreement
HWF-058	0.14	70% Agreement
HWF-059	0.13	70% Agreement
PWF-116	0.51	85% Agreement
EWF-054	0.20	95% Agreement
GWF-044	0.75	95% Agreement
HWF-219	0.07	95% Agreement
MWF-051	0.13	Deterministic

Chapter 4 - Discussion

In any modelling exercise, interpretation is required. Within this work, there are many levels of interpretation for instance, fuels, topography, weather, and fire behaviour to name a few. Understanding the requirement of this interpretation underscores the necessity of experienced individuals (both in the theory and practice of fire modelling and fire behaviour) to interpret results in a thoughtful and meaningful way.

4.1 – Forecast Skill Interpretation

Weather forecasting by experienced meteorologists is a complicated process at the best of times. When wildfires are active, a forecaster is required to provide forecasts, commonly referred as a spot forecast, for each high priority wildfire incident. A spot forecast is a forecast for a specific area, generally for an area over a wildfire incident. This is superior to the general area forecast, which covers many hundreds or potentially thousands of square kilometers. These spot forecasts are time consuming and with limited staff and time, providing forecasts for multiple fires may not be possible. To ensure the forecasters are providing accurate weather they go through the process of validating their forecast through skill scoring. These techniques are implemented on forecast weather obtained through Environment Canada's modelling process in the same fashion, to ensure accurate outputs (Erfani *et al.* 2013).

In Table 3.1, it is seen that the ensemble forecast is performing better than the deterministic at predicting temperature and wind speed. The ensemble performs on par or slightly worse than the deterministic when predicting relative humidity and wind direction are concerned under high agreement percentages (95% agreement). Though the accuracy of the ensemble is only marginally better than the deterministic, a superior weather forecast allows us to describe fire growth simulation errors as errors within the fire model itself. Some of the error within the fire model itself may be described by the way the FBP system has been established. Using the Van Wagner hourly FFMC calculation has been seen to result in an overestimation of the index (Anderson 2009b; Anderson *et al.* 2009). This can be defined as forecasting for the worst-case scenario; however, in the business of fire, if preparations are made for the worst-case scenario, anything less will be manageable. This is important when considering ensemble forecasting as the FBP system is providing a worst-case scenario under each weather scenario. Over predictions are likely under most weather conditions but due to the nature of the ensemble, a middle ground should be attained.

As the forecast progresses through time, the ensemble begins to display greater amounts of spread as seen in Figure 3.3. This is a well-known occurrence in forecasting, both modelled weather and meteorologist based, days 1 and 2 generally have superior fit to actual weather than days 3 and beyond (Gagnon *et al.* 2013; Erfani *et al.* 2013). This study only deals with day 1 to 3 and displays the greatest spread in the ensemble forecast at day 3 as seen in Figure 3.3, that degradation over time was also noted in Horel *et al.* (2014).

Within the average RMSE table, Table 3.1, it can be seen that the deterministic prediction rarely performs superior to the ensemble quantile agreements. Under the circumstances, surrounding fire acceptable weather, which is often, regarded as “extreme” weather it is not surprising that the deterministic did not perform as well as the ensemble. This is largely because the models that make up the deterministic are geared towards forecasting most probable weather, which is generally along the same scheme as historic weather (Figure 3.3). Extreme weather events that serve to propagate fire would be more readily caught under the ensemble scheme as it has fewer members going into the model with a more balanced scheme for detecting extreme and standard weather patterns. Though this notion has not been formally documented, it is logical, as multiple different forecasts would have a better chance of capturing greater variability than a single forecast.

When attempting to assess the effectiveness of the forecast within fire simulation the Initial Spread Index was used as a proxy for goodness of fit. As such, RMSE was calculated for ISI to assess the overall applicability of the weather forecast from a fire weather index perspective. In Figure 3.2, it can be seen that the ISI error has relatively little variability and has low error scores. This is an indication that the modelled weather should perform well during fire simulation when compared to reality.

4.2 – Fire Growth Simulation Skill Score Interpretation

Overall, it can be seen that there is an increasing trend in the average critical success index. Notably this trend is relatively small 0.13 to 0.17 (Table 3.4); however, on a case-by-case (fire-by-fire) basis greater CSI increases are noted (Appendix A). These values though, small in magnitude, lead to an understanding that additional data points may be required; with more data a better understanding of the potential impact ensemble fire growth modelling can have on decision making. This study focuses on fires greater than 100 hectares in order to focus on modelling fires that, for some amount of time, were essentially free burning. Free burning refers to a period where the fire is burning unaffected by fire suppression. The focus on fires that are free burning is an important factor because Prometheus is not currently capable of modelling fire suppression efforts.

Each fire within this study had some form of suppression activity occurring which influenced the final perimeter as seen in Figures 3.3 and 3.4. In the absence of suppression, fires were capable of spread largely around the entire perimeter. This lack of suppression modelling was seen in Figures 3.3 and 3.4. The actual fire was considerably narrower than the fires modelled. Ideally, the weather streams derived from ensemble forecasts would project a best possible average scenario. Future works surrounding probabilistic fire growth modelling may require additional fire information in order for any generalizations about the trends in skill scores to be made. Ideally upper and lower percent agreement would be suggested for use by practitioners.

Weather forecast skill scoring will ensure that the error in the forecast is acceptable for fire modelling purposes. The forecast skill also serves the purpose of informing modellers of the relative accuracy of the forecast when compared to actual weather. Additionally the spread of the ensemble forecast serves to inform a user of the agreement of the forecast. The spread of the forecast serves to increase a fire behaviour specialists' confidence in the fire growth simulation model. Environment Canada controls increasing weather model accuracy, as updates occur confidence in the forecast outputs may be increased. Superior weather inputs will continue to improve the capacity of Prometheus to output realistic outputs.

4.3 – Probabilistic Fire Growth Simulation Modelling

This work has been undergone in order to better prepare wildfire managers, planners and modellers alike for future wildfire growth. A further intent of this work is to continue to automate more of the wildfire modelling process. The automation of this process will ensure that the best available information is delivered in a timely manner and give modelling staff the longest possible lead-time for output interpretation. Time for interpretation is one of the most critical components to ensure the best possible information is delivered with the best possible understanding of the wildfire model outputs.

4.3.1 – Benefits

As discussed previously, there is a marginal increase in the overall skill of the probabilistic fire growth simulation model outputs. A qualitative perspective, seen in Figure 3.4, should give fire management teams a superior perspective and greater situational awareness surrounding the wildfire incident. This information could lead to a safer fire line and better prepare fire behaviour specialists for the potential future fire growth. Additionally, resource allocation may be improved when the probability of burning is understood.

Another major benefit is the receipt of outputs that are no longer simply a single perimeter. The probabilistic output seen in Figure 3.4 is a qualitative analysis tool, which assists fire-modelling personnel in describing the fact that fire modelling is not an exact science. This also gives a better indication to the amount of uncertainty on a single incident. This will require the individuals interpreting the outputs to have an understanding of the inputs and the modelling process however, that should lead to greater comfort when using these and other tools that provide a probabilistic output.

This work will also provide accountability to fire managers displaying that multiple scenarios were explored prior to making a decision. It will also allow fire managers to have more confidence during the decision making process. Further, it will give opportunities for multiple scenario evaluation during consultation periods for prescribed fire or fire smart treatments. Multiple scenarios could be run under current fuel conditions with many potential weather streams in order to evaluate the potential risk faced by values in forested areas. Additionally prescribed fire ignition dates could be modified based on the probable spread of a fire during the period of time that the forested area is in prescription.

A by-product of this process is a gridded weather forecast that has FWI indexes associated with it at a 10-km-by-10-km grid. This will further enhance wildfire weather forecasting in order to deliver the potential indexes in the forecast. This information may also enhance the preparedness of fire behaviour specialists, allowing them to provide the best possible information to an incident management team. Gridded weather gives an opportunity to produce spaghetti plots of each weather variable. Spaghetti plots further understanding of forecast agreement leading to a better understanding of the stability of the atmosphere and forecast over the next few days.

The entire input data preparation process is currently scripted, which results in time and money saved. This will give fire-modelling staff a greater opportunity to interpret the results of fire growth simulation modelling to ensure a quality product is delivered. This will also give fire management agencies more time to understand simulation outputs before being required to act on the information. These scripts are intended to be enhanced and worked into a package for use by a wider audience than just the research community.

4.3.2 – Implications for Fire Managers

As far as managers are concerned probabilistic fire growth modelling opens many possibilities for resource management and placement. As forecasts and fire growth simulation models improve, the capacity for fire managers to reallocate resources should also improve. Further managers would have an increased confidence that other fire incidents would not become unmanageable. When meteorologists forecast in an area for many years they develop an understanding of the local weather conditions and weather phenomena triggers. This knowledge generally leads to better forecasts. Meteorologist input into weather models has given forecast models the best opportunity to accurately predict weather. As climate changes, meteorologists continuously update numerical weather prediction models to forecast weather under a changing climate. The changing climate would likely result in greater instances of ignition and greater area burned creating a necessity for superior weather forecasting (Flannigan *et al.* 2009). This is not intended to replace fire weather forecasters, rather it is meant to supplement their forecast by giving additional scenarios, painting the broadest picture possible.

4.3.3 – Limitations

Bad data in, bad simulation projection out. Simply put, without accurate fuel, topography and weather information Prometheus (arguably any model) was unable to simulate fire growth with any accuracy (Parisien *et al.* 2011a). This was especially prevalent with fire PWF-116 where the initial fuel grid values indicated the fire burned in non-fuel. These were not the only areas where bad data can influence the outcome of fire growth simulation modelling. All information surrounding the ignition was critical, from position to timing. An additional hour of burning was the difference between 100 and 200 hectares under the right weather conditions. For most of the fires within this study, all of the data components were acceptable to generate well-fitted fire growth simulation model outputs.

The duration of the model forecast at the regional ensemble scale is only three days (Erfani *et al.* 2013). Due to the offset from the Mountain Standard Time Zone (-6 UTC) only 2.75 days of forecast is effectively available. Many fire management agencies would like to see a three to five day fire growth simulation projection; however, with the ensemble data in its current state that is not a possibility. Fine resolution deterministic forecast data is available publicly; this means it may be possible to begin defining the accuracy of modelling three to five days of fire growth.

4.3.4 – Sensitivity of the Model to Input Data

Any model using inputs that have the possibility for stochasticity will display sensitivity to those inputs during the modelling process. Sensitivity in fir modelling is generally focused on three elements: fuel, weather and ignition position. As mentioned earlier Parisien *et al.* (2011a) describes variation can be accounted as "67.4% to fuels, while weather contributed 29.2% and the position of the ignitions contributed 3.4%".

Fuels information in the form of the FBP fuel grid is required to be both accurate and up to date. Keeping a provincial fuel inventory up to date for a provincial such as Alberta can be a very large task. Each year the base fuel information is maintained and annual large fire perimeters are reclassified as non-fuel. These fires are to be classified as fuel once field staff feel that the regenerated vegetation is capable of carrying fire. As previously mentioned fuel grid accuracy was an issue for Peace River Wildfire 116.

Dowdy *et al*. (2010) have documented sensitivity to weather variables and the indexes they yield. Dowdy *et al.* (2010) described wind speed as one of the most influential factors on FWI. Temperature and relative humidity had impact however, not to the same degree (Dowdy *et al.* 2010). This is similar to the results found in this study, weather forecast with highly variable wind RMSE values (Appendix C) resulted in lower skill scoring (Appendix B).

Ignition position is the final area of sensitivity that has a high chance of variability. In a case such as MWF-051 the ignition position has a profound effect on the final modelled outputs.

Further analysis on this particular case was not completed; the intent was to ascertain how the data might perform without major modification.

4.4 – Challenges

Major challenges encountered within this work were found largely in data consistency issues. Peace River wildfire 116 burned in non-fuel, Rocky Mountain House wildfire 034 did not burn during simulation, and Fort McMurray wildfire 051 had its location altered to the middle of the perimeter polygon. These issues are bound to surface when dealing with large amounts of information and may be overcome relatively easily. Notably the fuel type issue in Peace River wildfire 116 was rapidly corrected using satellite imagery.

Rocky Mountain House wildfire 034 was an interesting case considering it was the most mountainous region out of all the fires used in this study. Mountainous terrain was always a challenge for numerical weather prediction and was often a focal point during of model forecast upgrades (Erfani *et al.* 2013; Gagnon *et al.* 2013; Vaillancourt *et al.* 2012). Furthermore, because of the spatial resolution of 10-km-by-10-km, the point at which a forecast falls should be within 10-km of the ignition point. If a forecast, point fell on a peak or in a valley, the overall forecast may not be a representative forecast of the local area resulting from terrain. Due to this fact, only nine of the ten fires were considered during the analysis phase of this study.

4.5 – Future Directions

The initial requirement to continue this work is to obtain more fires within the data window as well as additional years of gridded weather information. This additional information will allow for generalization about model skill to be made, as noted above. Further, this information will allow recommendations to be made surrounding what percent agreement perimeters should be used to define best and worst-case scenarios. As this product is developed, operational fire management staff involvement will be required in order to ensure outputs are optimal for use in the field. An important future study would look into the relationship between fire size and skill scores.

Research is also required surrounding directly measuring head fire intensity will allow for the verification and validation of probabilistic head fire intensity. Probabilistic head fire intensity could allow fire management to allocate resources in the most efficient manner. This information would allow for further expansion of the decision support capacity of probabilistic fire growth simulation modelling. All future research directions will further increase situational awareness and resource allocation.

Full automation is another critical milestone for this work. Strategic gains may be made by having fire growth simulation model outputs available early in the day. Further, it may become possible to have more than one simulation output per day. Ideally this process could occur in the background to allow fire behaviour specialists to focus on how the fire is reacting to the fuels it is encountering.

4.5.1 – Implementing Operationally

The task outlined throughout this thesis is intended to be used in the field by wildfire management planners. In order for this analysis technique to be used in the field, training, and data are important priorities. The training necessary to run this system would include Prometheus training, data analysis training and wildfire behaviour training. Wildfire behaviour is a critical component within this training regime as realistic outputs are necessary for good decision-making. The important part of this system is the automation; the ideal scenario is to reduce the workload in the field while providing the best information. Finally, a technology transfer to currently established wildfire management agencies should be relatively rapid as many of these agencies already have wildfire modellers.

Chapter 5 - Conclusions

In conclusion, this work has displayed the capacity of the Prometheus fire growth simulation model to act as a probabilistic model. Fire management agencies and fire behaviour specialists alike could benefit from the findings in this work as it may allow them to understand the progression of wildfires. This addresses the 7th recommendation of the Flat Top Complex Review. The advances in fire modelling that can be made through a better understanding of the process of fire progression satisfy the 20th recommendation. Although the number of fires used for this work is relatively small, an indication of a trend is evident. That trend being the probabilistic approach produces a superior output when compared against the deterministic output. This is evident in the probabilistic CSI of 0.18 compared to the deterministic CSI of 0.16. With continued research in this area, definitive trends may be identified and recommendations for best practices made. Another important metric is the bias, which was considerably closer to 1 under probabilistic conditions 0.96 versus the deterministic at 7.44 on average. The massive over prediction by the deterministic leads one to believe a fire is going to get considerably larger than it may in actuality. Probabilistic outputs serve to minimize the interpretation of a catastrophic wildfire event by displaying multiple possibilities.

As confidence in both fire and weather modelling increases, the capacity (efficiency and lead time) of fire management agencies to allocate resources should increase dramatically. Having an understanding of where and when fires will arrive after ignition is critical in the prioritization of suppression activities as these activities are expensive. Additionally this information could strengthen the notion of hands-off fire management, allowing fires to consume amount of the landscape to provide a fuel mosaic. As it stands, we can see a considerable degradation of weather forecasting in forecast day three (Figure 3.3).

Continuing advancement in the area of weather forecasting would deliver a strong impression of what should occur in the next three days. This will be the greatest strength of the products developed in this thesis.

Continuing to collect information and measure the success of modelling efforts is critical to the advancement of this field. The rigor added by the skill scoring process allows a modeller to have a great deal more confidence in the work performed on behalf a fire management team. Additionally the accountability added should serve to assist the consultation process by better informing stakeholders of the risks associated with fire in the area.

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AppendixA

Individual Fire Burn Grids and Comparison Perimeters

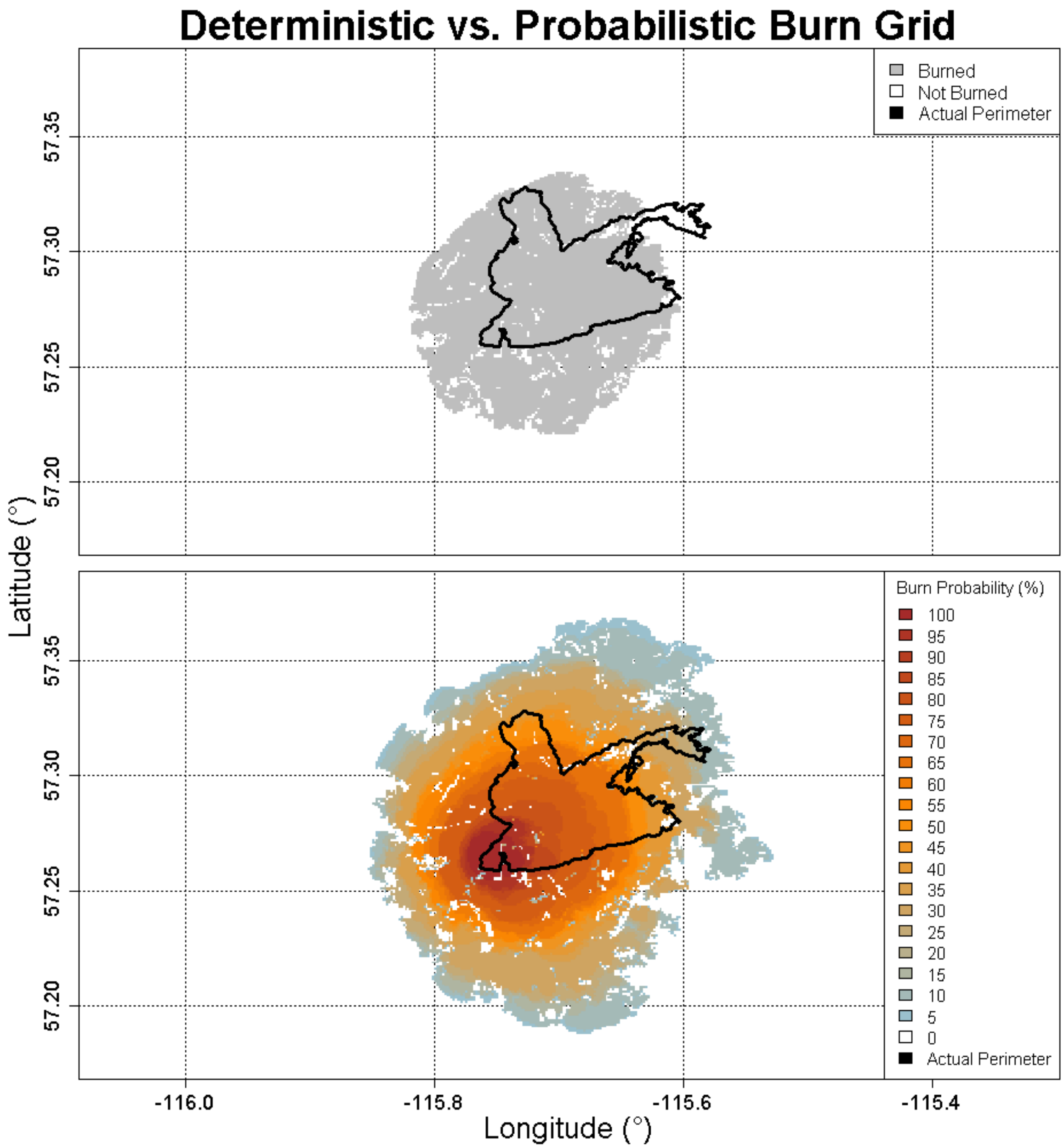

Figure A.1 – Burn grid comparison for Slave Lake Wildfire 113 (SWF – 113).

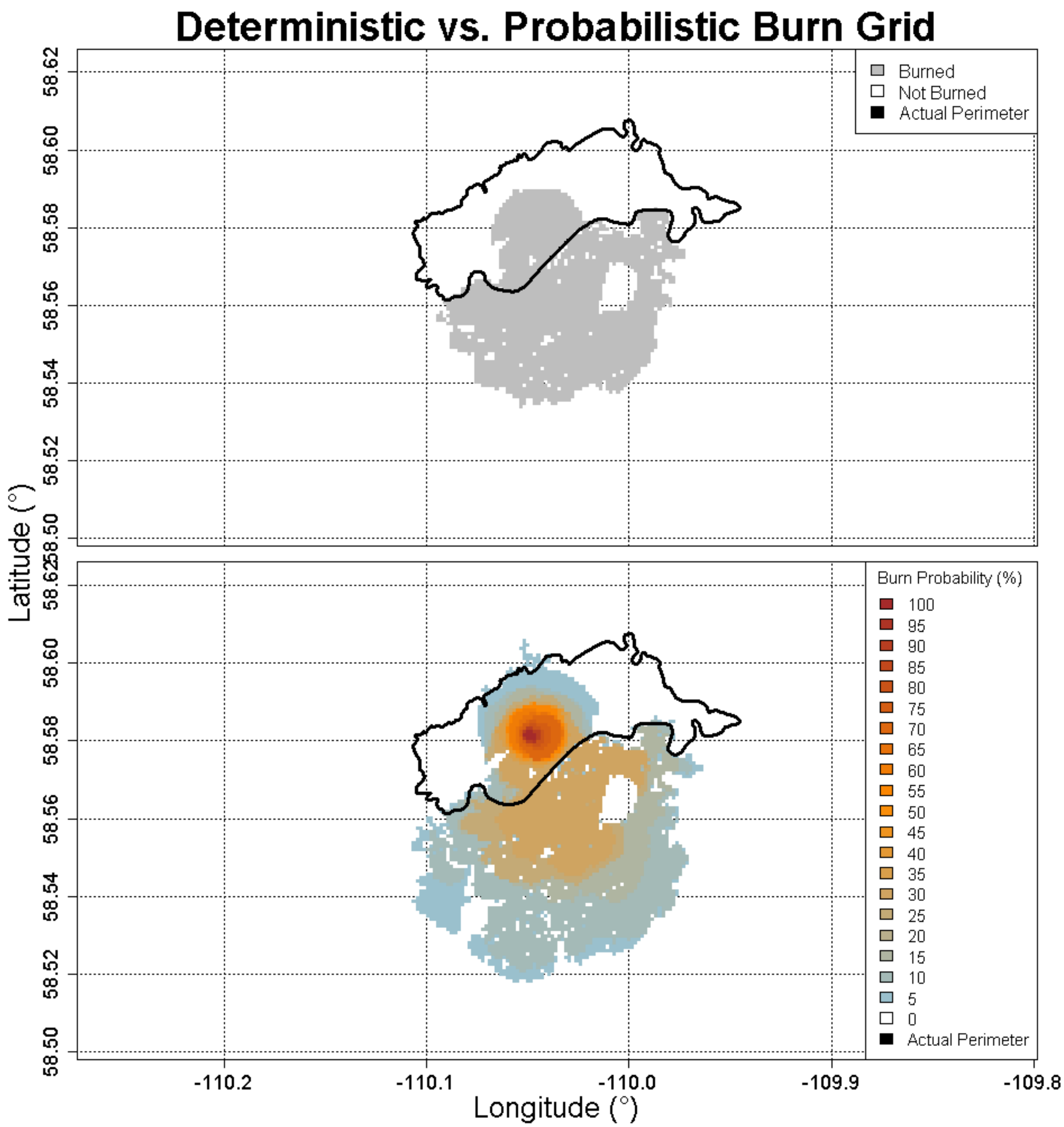

Figure A.2 – Burn grid comparison for Fort McMurray Wildfire 051 (MWF – 051).

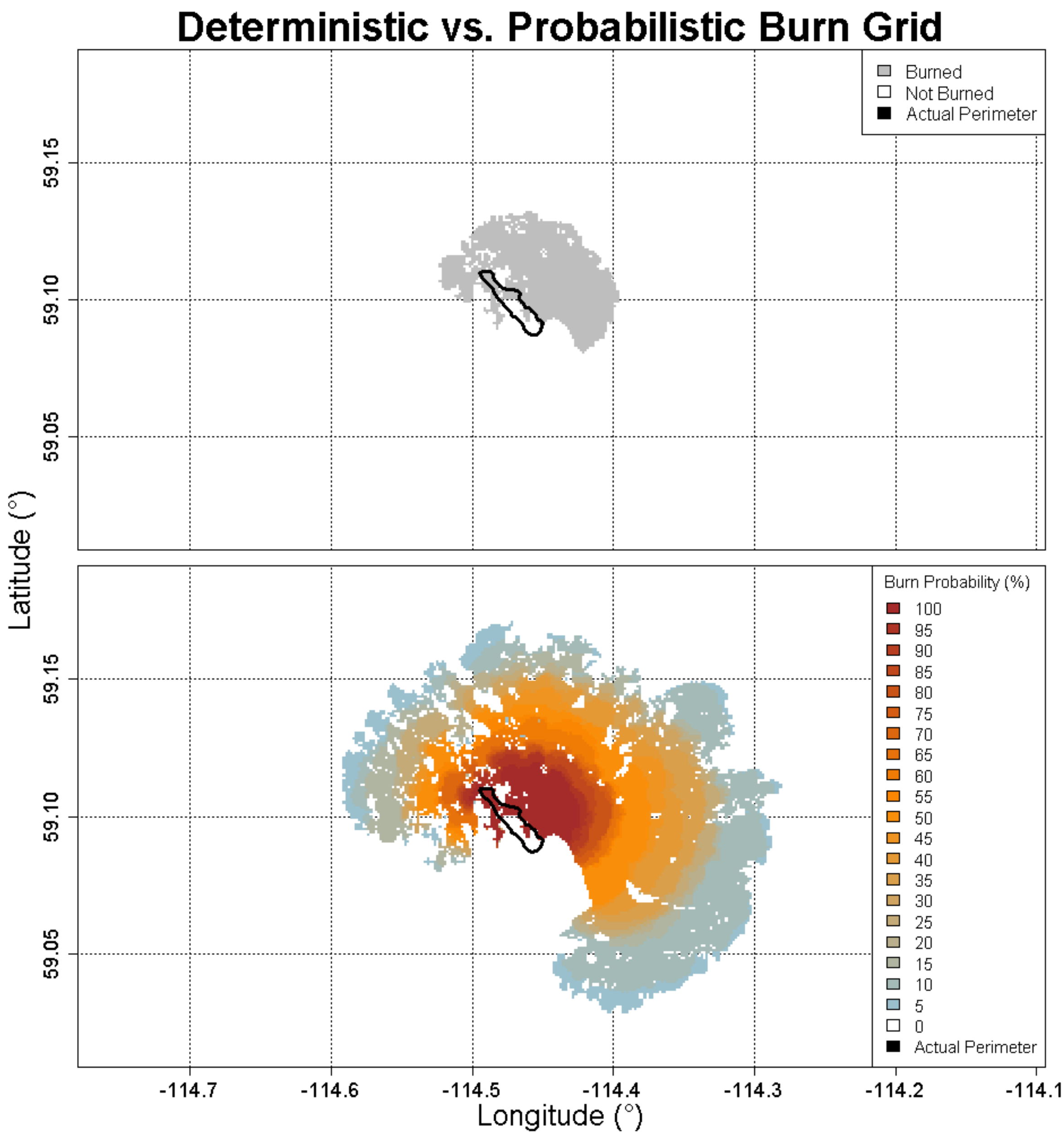

Figure A.3 – Burn grid comparison for High Level Wildfire 219 (HWF – 219).

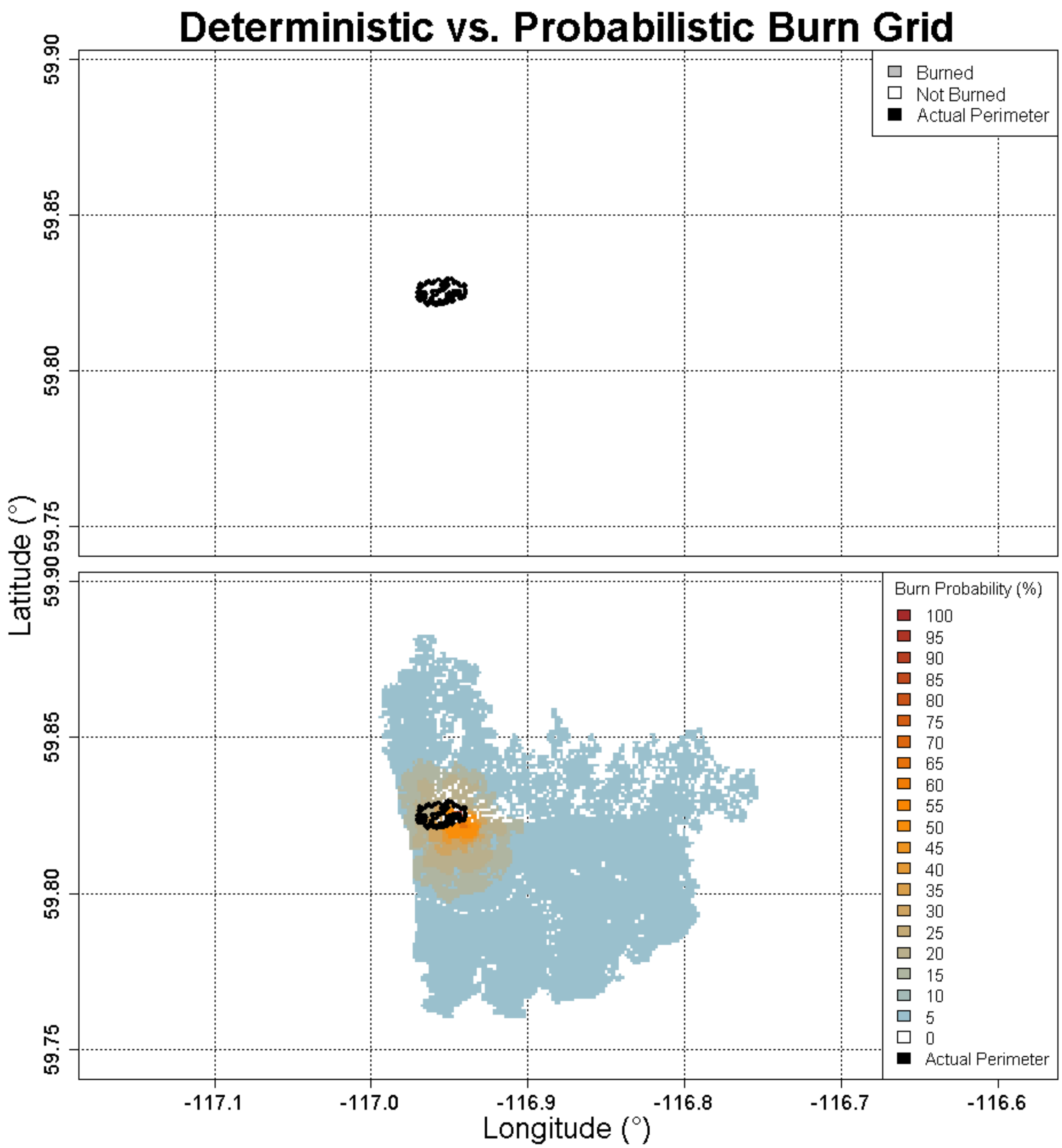

Figure A.4 – Burn grid comparison for High Level Wildfire 133 (HWF – 133).

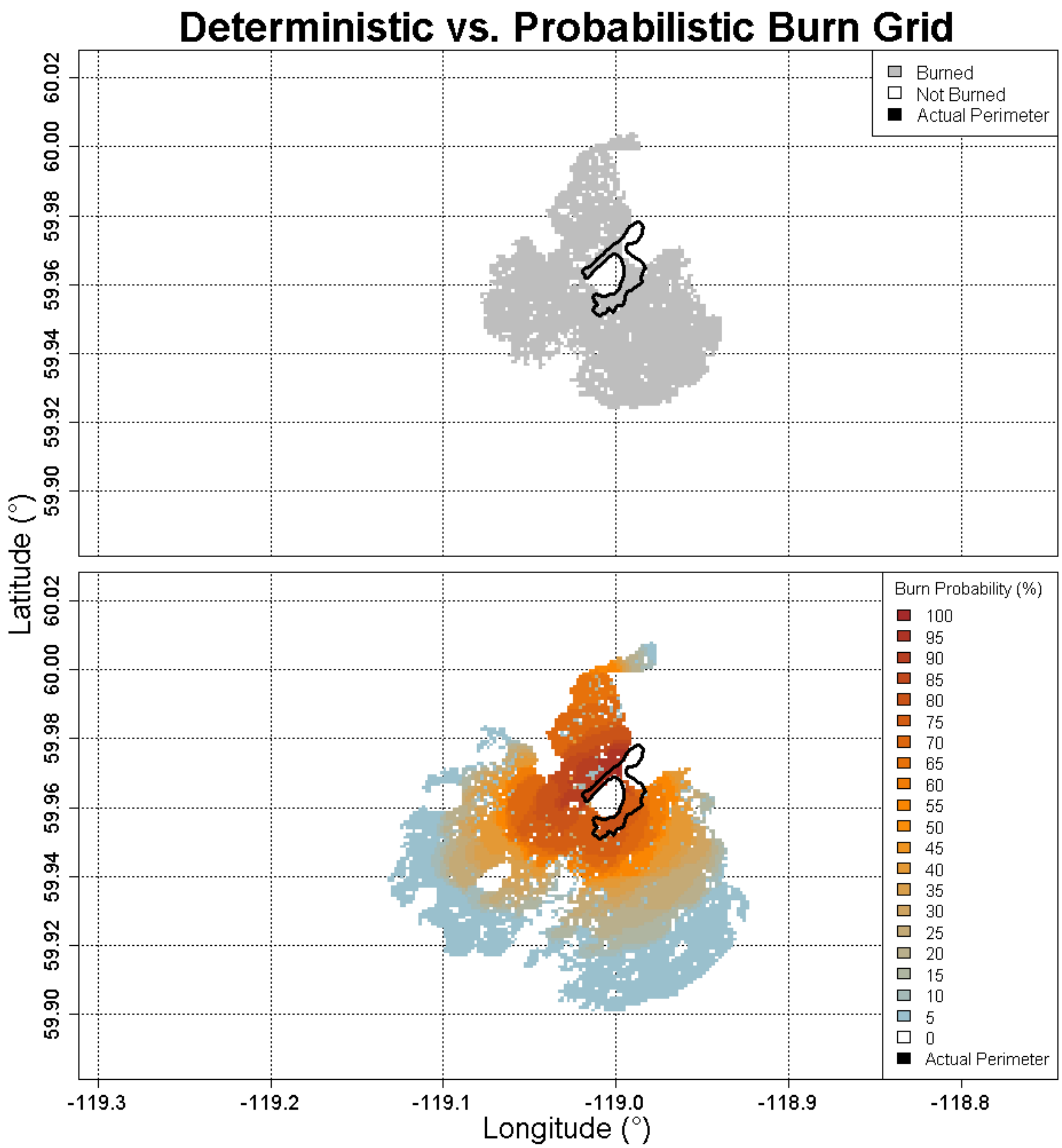

Figure A.5 – Burn grid comparison for High Level Wildfire 059 (HWF – 059).

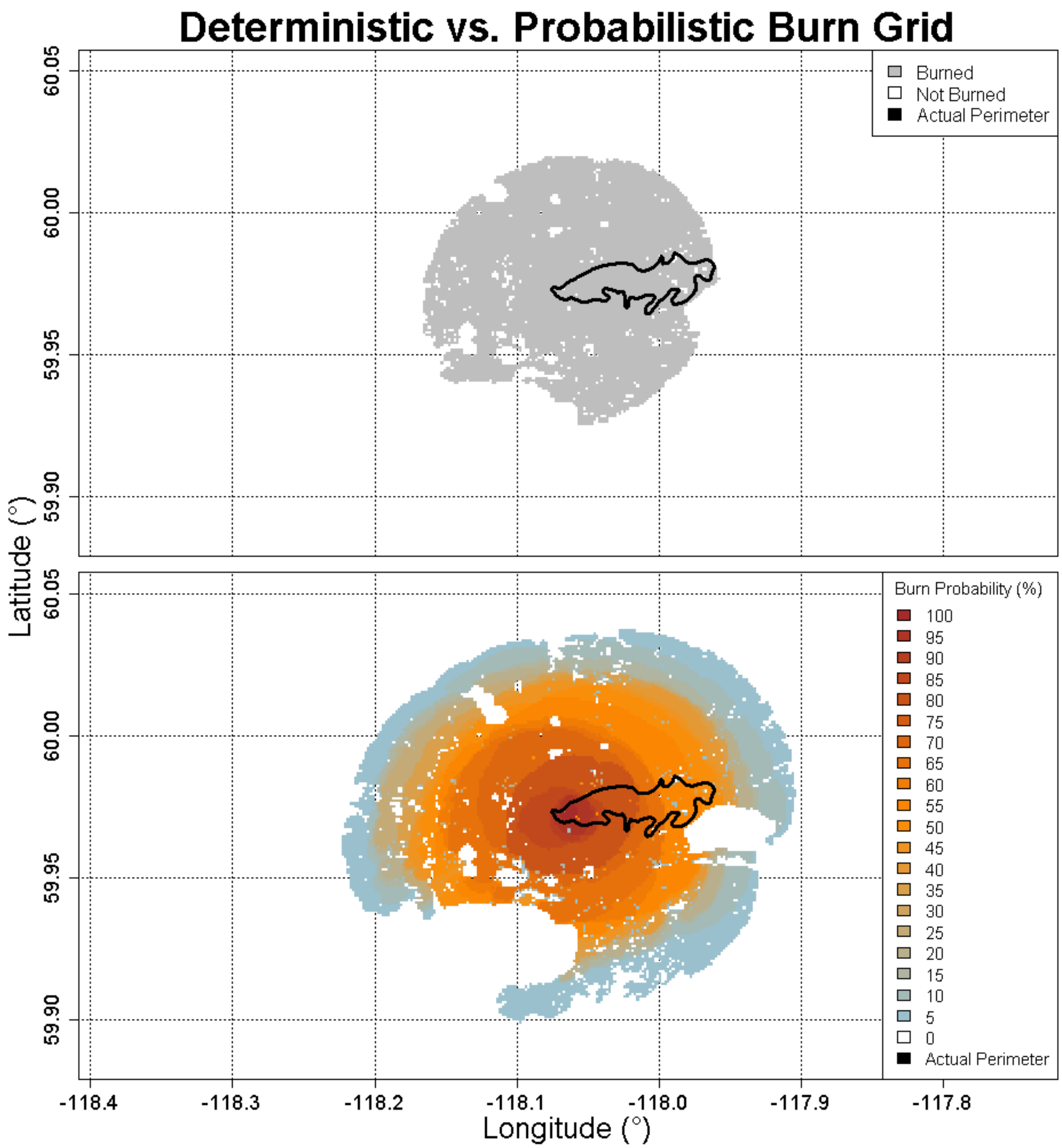

Figure A.6 – Burn grid comparison for High Level Wildfire 058 (HWF – 058).

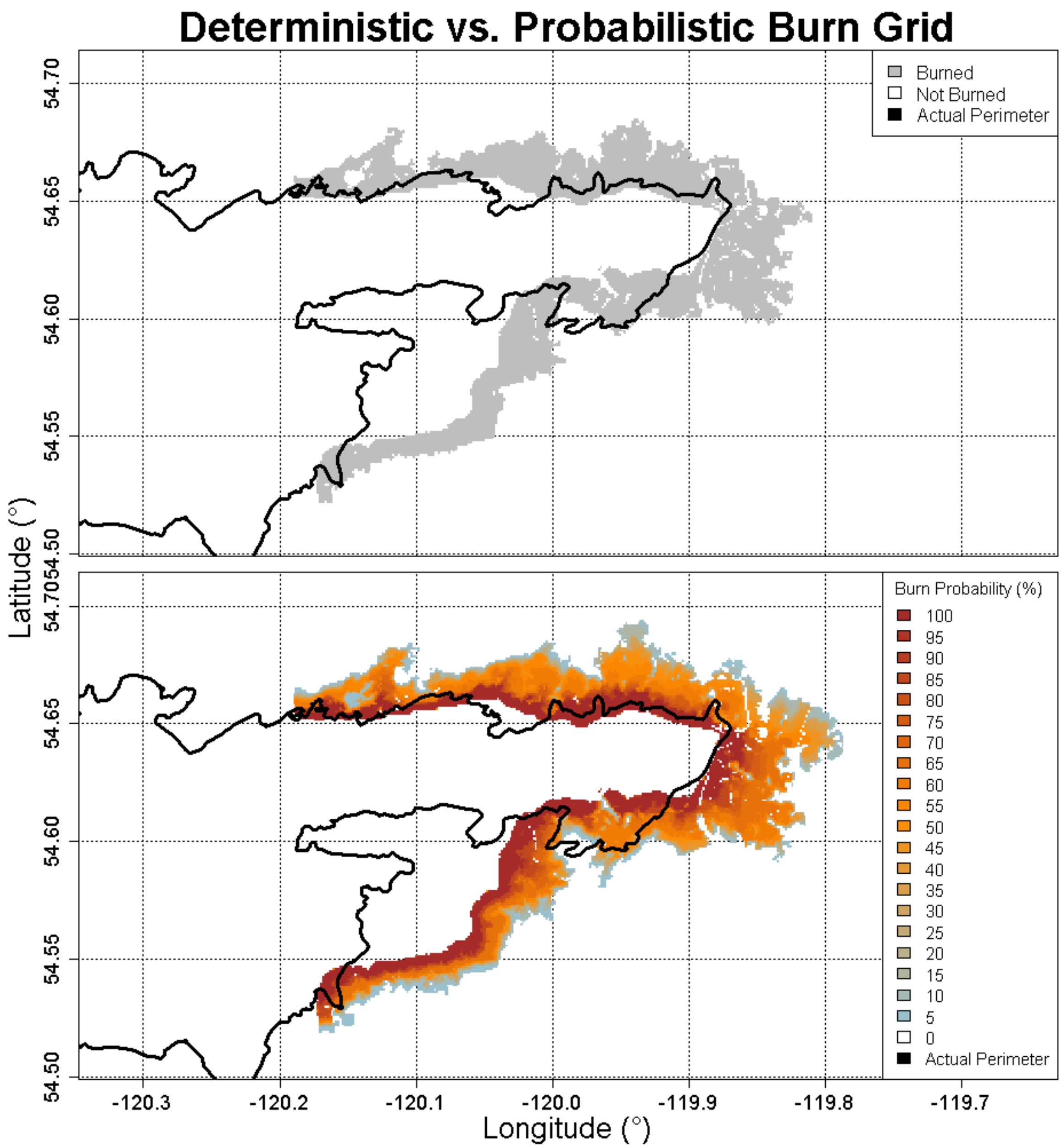

Figure A.7 – Burn grid comparison for Grand Prairie Wildfire 044 (GWF – 044).

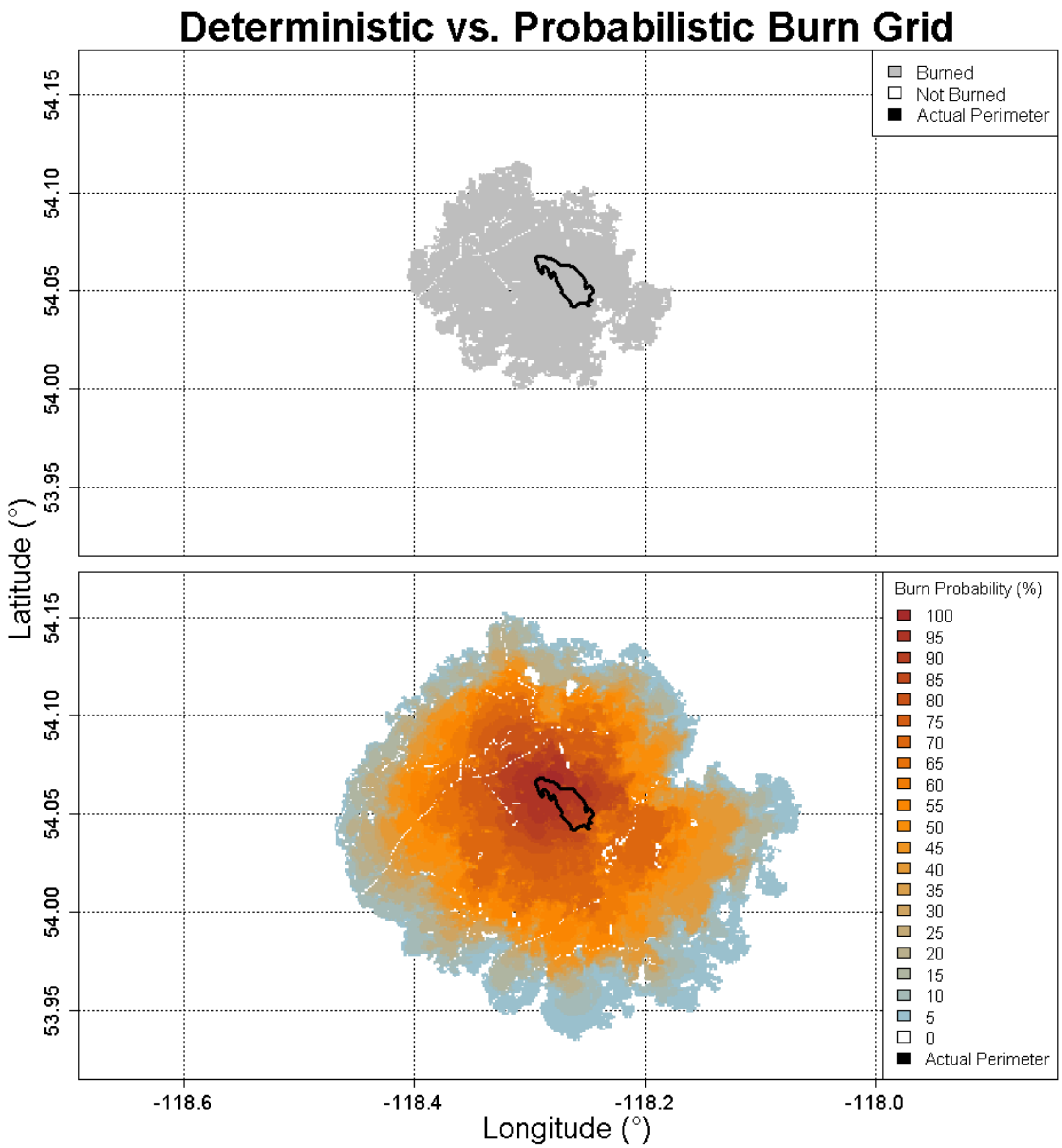

Figure A.8 – Burn grid comparison for Edson Wildfire 054 (EWF – 054).

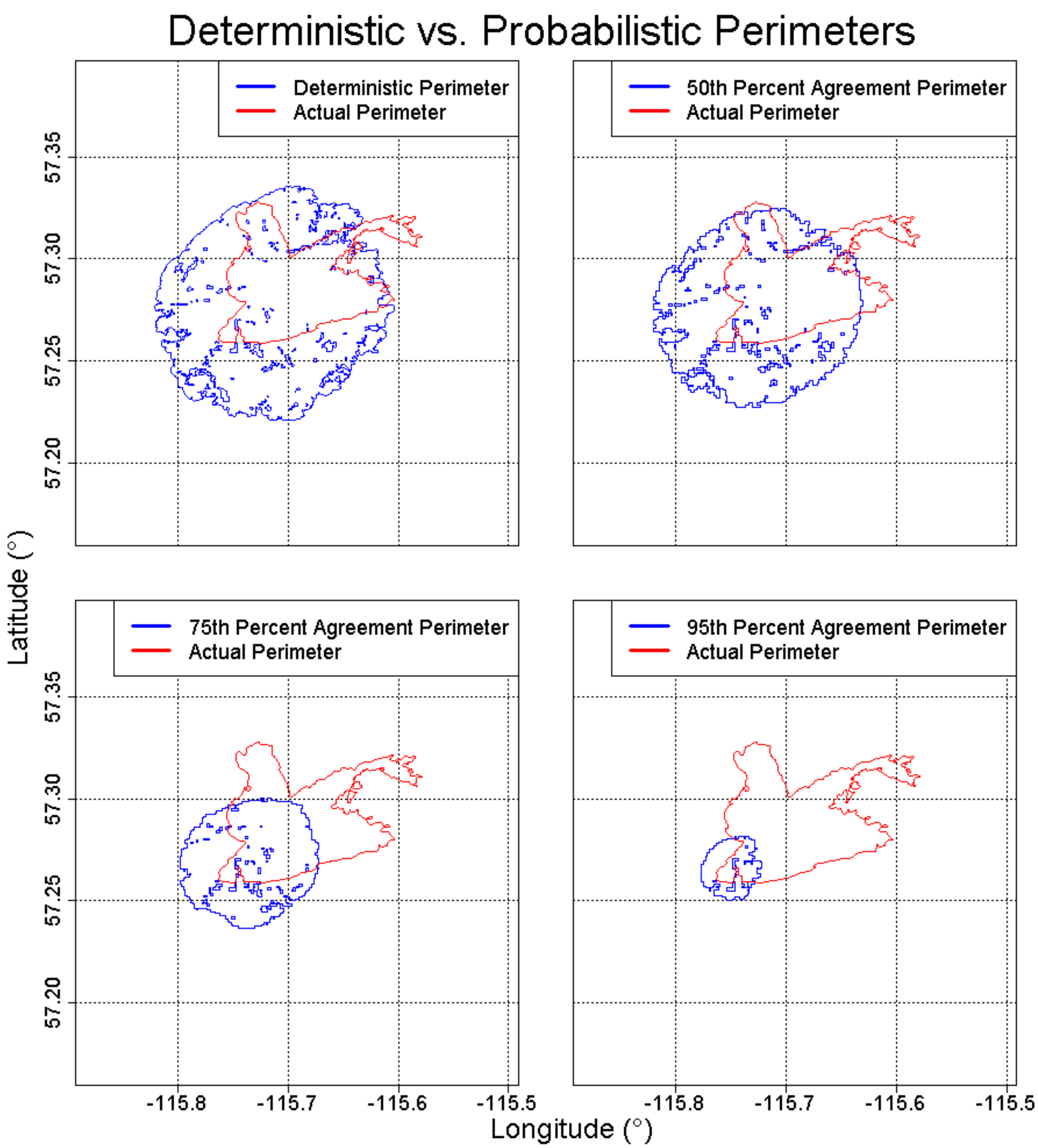

Figure A.9 – Perimeter comparison for Slave Lake Wildfire 113 (SWF – 113).

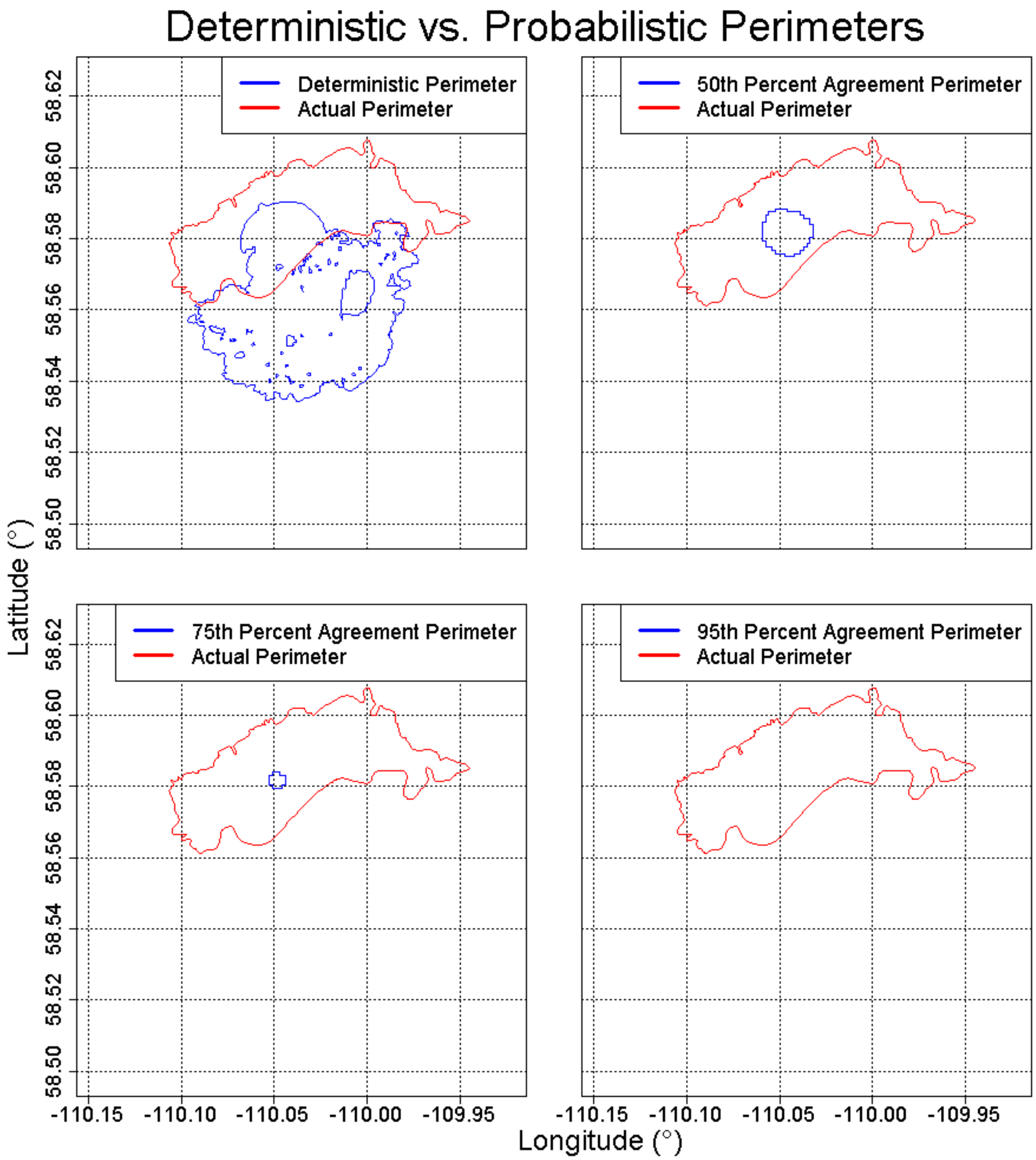

Figure A.10– Perimeter comparison for Fort McMurray Wildfire 051 (MWF – 051).

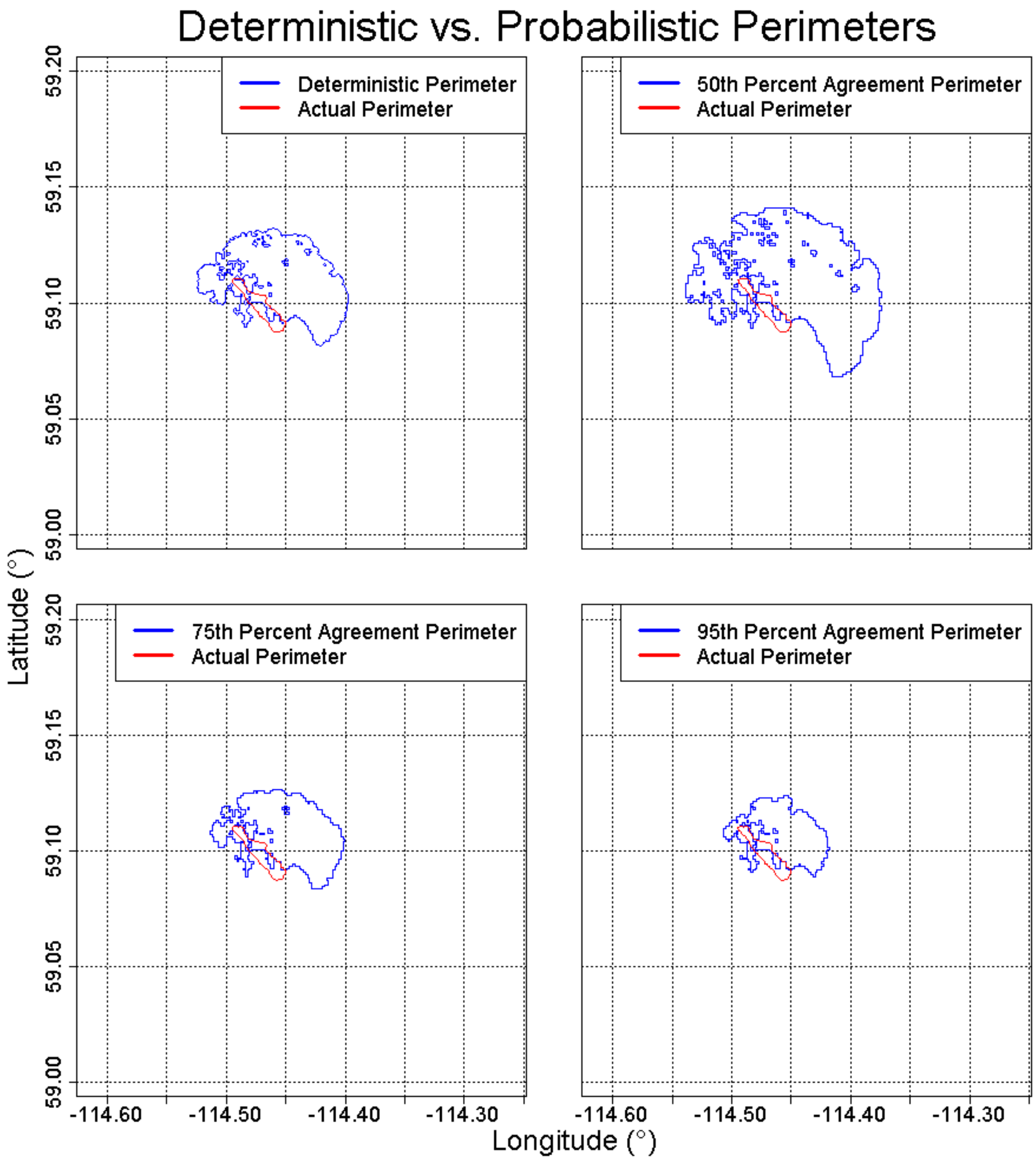

Figure A.11– Perimeter comparison for High Level Wildfire 219 (HWF – 219).

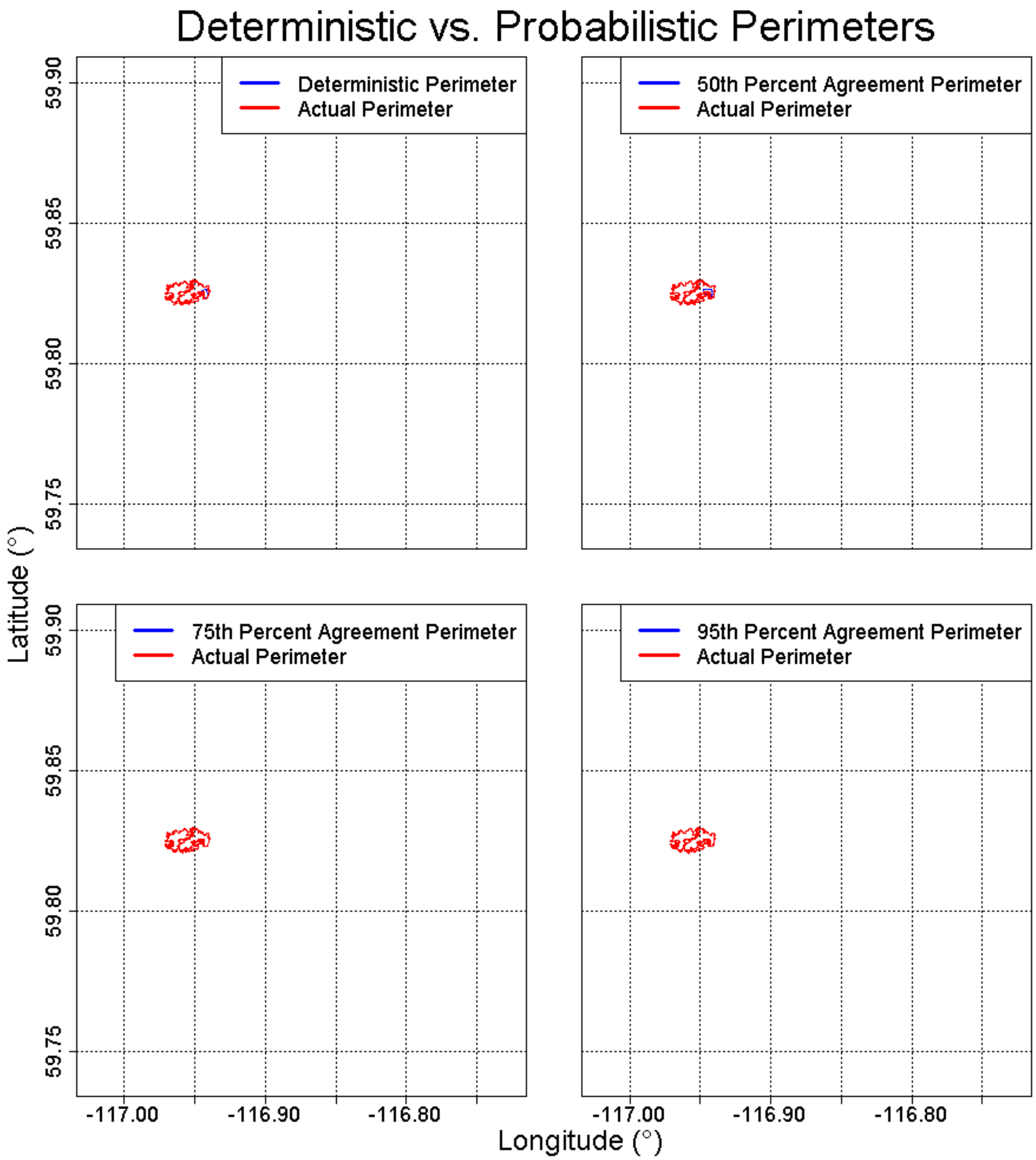

Figure A.12 – Perimeter comparison for High Level Wildfire 133 (HWF – 133).

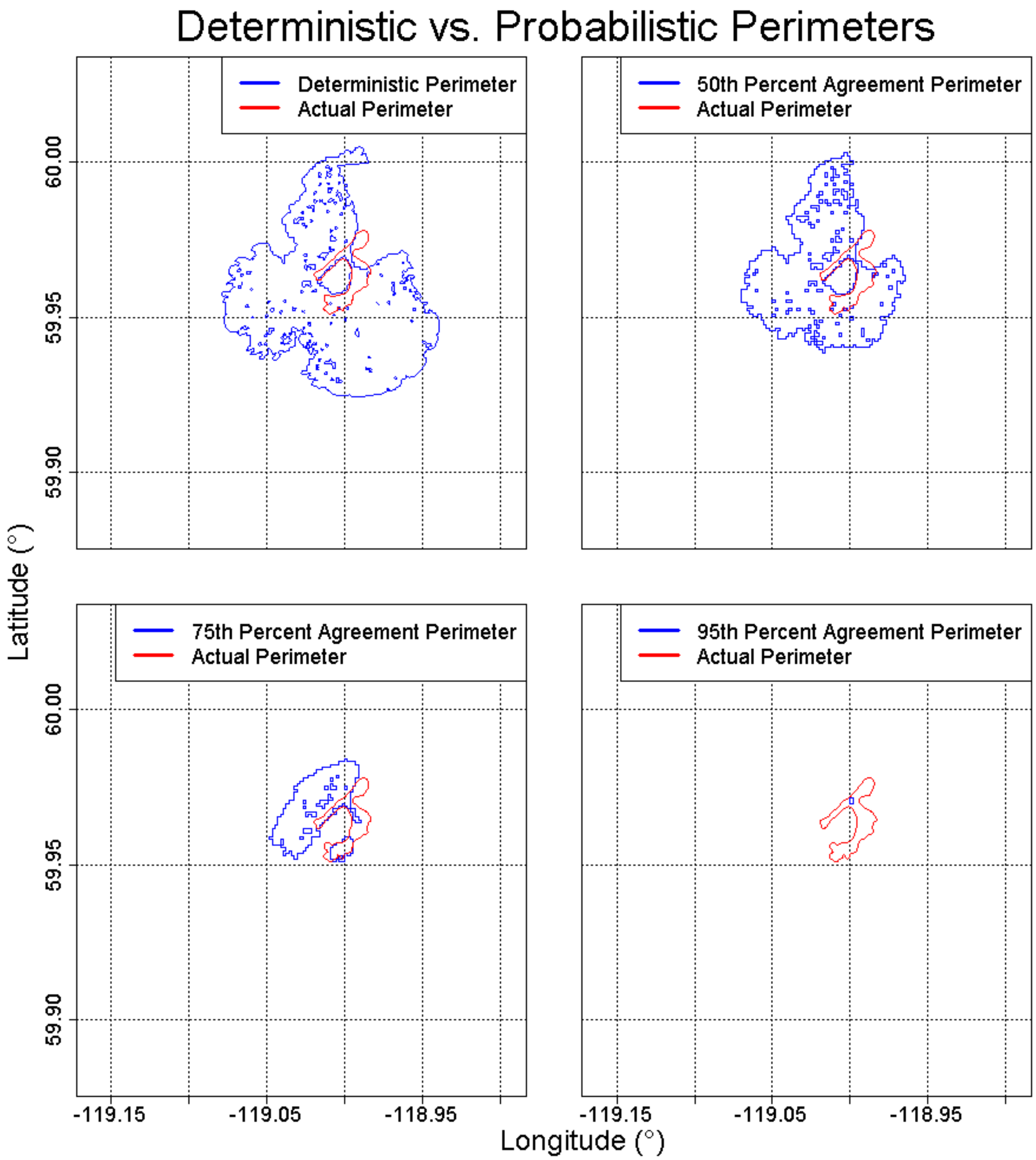

Figure A.13– Perimeter comparison for High Level Wildfire 059 (HWF – 059).

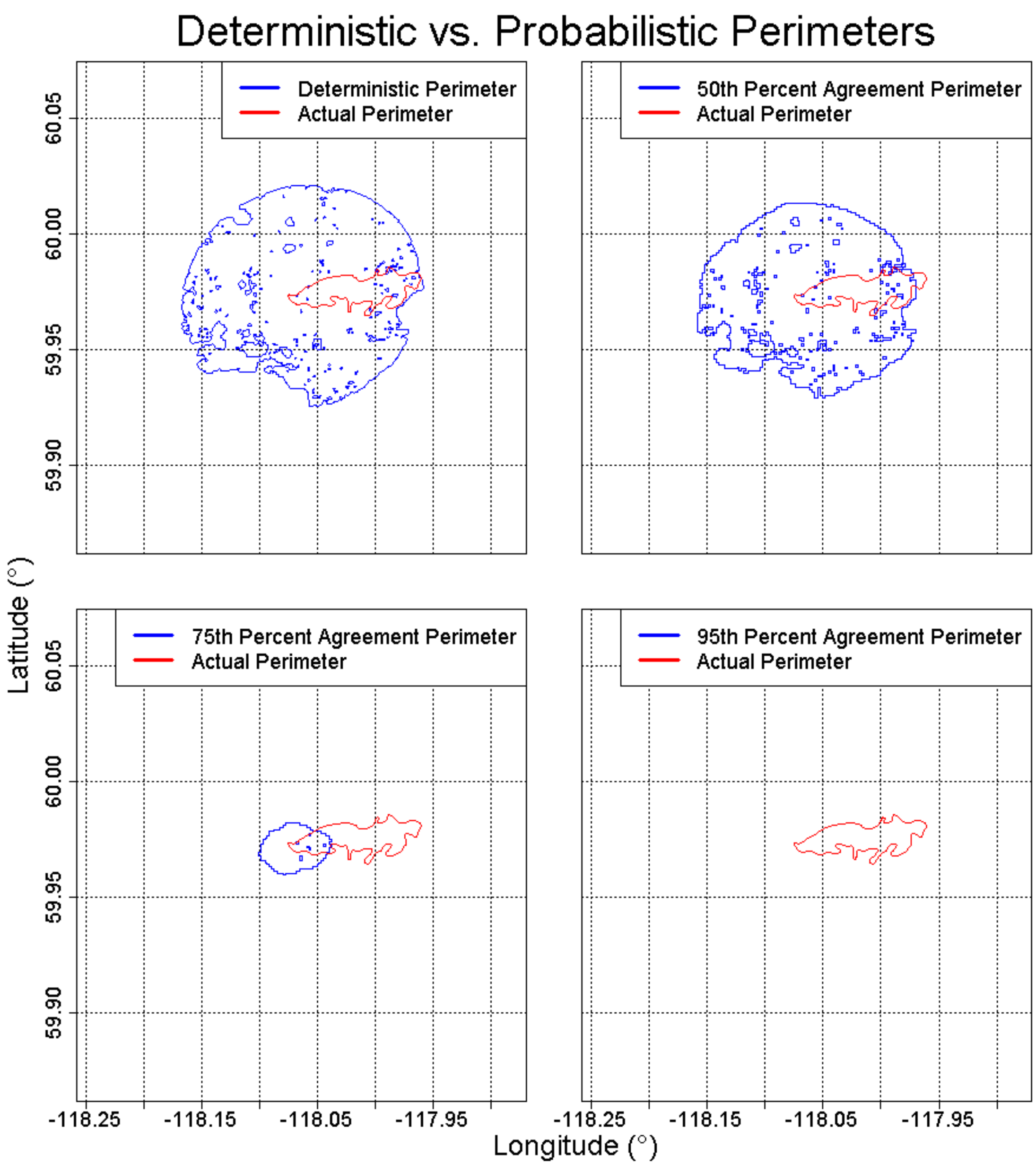

Figure A.14– Perimeter comparison for High Level Wildfire 058 (HWF – 058).

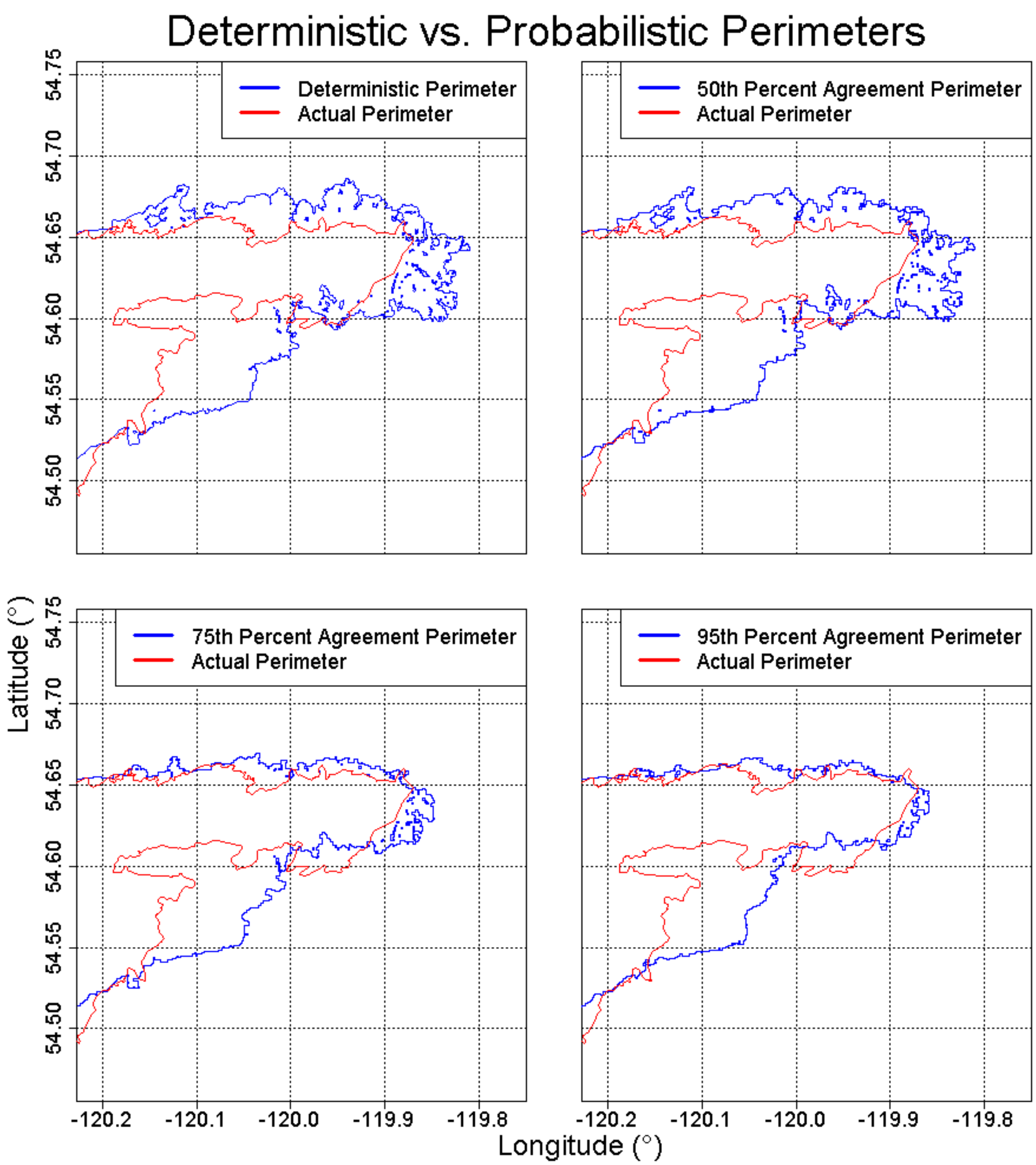

Figure A.15– Perimeter comparison for Grand Prairie Wildfire 044 (GWF – 044).

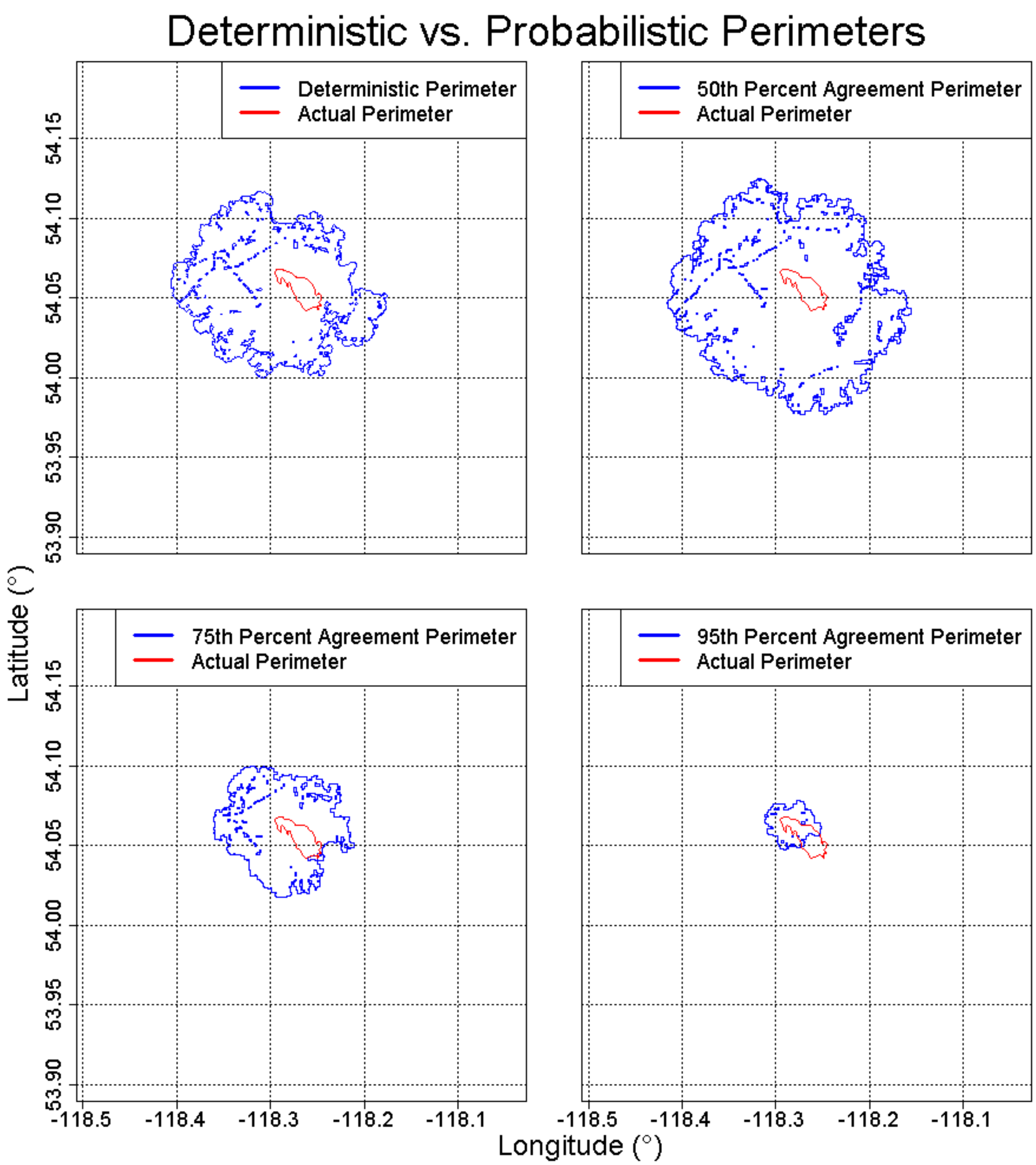

Figure A.16– Perimeter comparison for Edson Wildfire 054 (EWF – 054).

AppendixB
Individual Fire Skill Score Charts

Table B.1 – Skill scores for Edson Wildfire 054 (EWF – 054).

		Deterministic Run	50% Agreement	75% Agreement	95% Agreement
Fire Size (ha)	419 (Actual)	11195	17006	5389	826
EWF-054-2014	Bias	27.71	41.95	13.34	2.04
EWF-054-2014	Hit-Rate	1.00	1.00	1.00	0.51
EWF-054-2014	False Alarm Ratio	0.96	0.98	0.93	0.75
EWF-054-2014	Critical Success Index	0.04	0.02	0.07	0.20

Table B.2 – Skill scores for Slave Lake Wildfire 113 (SWF – 113).

		Deterministic Run	50% Agreement	75% Agreement	95% Agreement
Fire Size (ha)	4211 (Actual)	10978	8540	3831	774
SWF-113-2014	Bias	2.62	2.03	0.91	0.18
SWF-113-2014	Hit-Rate	0.90	0.82	0.44	0.08
SWF-113-2014	False Alarm Ratio	0.66	0.60	0.52	0.57
SWF-113-2014	Critical Success Index	0.33	0.37	0.30	0.07

Table B.3 – Skill score for Rocky Wildfire 034 (RWF – 034).

		Deterministic Run	50% Agreement	75% Agreement	95% Agreement
Fire Size (ha)	8972 (Actual)	0	0	0	0
RWF-034-2014	Bias	0.00	0.00	0.00	0.00
RWF-034-2014	Hit-Rate	0.00	0.00	0.00	0.00
RWF-034-2014	False Alarm Ratio	NA	NA	NA	NA
RWF-034-2014	Critical Success Index	0.00	0.00	0.00	0.00

Table B.4 – Skill scores for Fort McMurray Wildfire 051 (MWF –051).

		Deterministic Run	50% Agreement	75% Agreement	95% Agreement
Fire Size (ha)	2092 (Actual)	2664	182	20	0
MWF-051-2014	Bias	1.27	0.09	0.01	0.00
MWF-051-2014	Hit-Rate	0.26	0.09	0.01	0.00
MWF-051-2014	False Alarm Ratio	0.80	0.00	0.00	NA
MWF-051-2014	Critical Success Index	0.13	0.09	0.01	0.00

Table B.5 – Skill scores for High Level Wildfire 219 (HWF – 519).

		Deterministic Run	50% Agreement	75% Agreement	95% Agreement
Fire Size (ha)	182 (Actual)	2223	4005	1701	1063
HWF-219-2014	Bias	12.49	22.37	9.56	5.97
HWF-219-2014	Hit-Rate	0.49	0.49	0.49	0.48
HWF-219-2014	False Alarm Ratio	0.96	0.98	0.95	0.92
HWF-219-2014	Critical Success Index	0.04	0.02	0.05	0.07

Table B.6 – Skill scores for High Level Wildfire 133 (HWF – 133).

		Deterministic Run	50% Agreement	75% Agreement	95% Agreement
Fire Size (ha)	130 (Actual)	6	8	0	0
HWF-133-2014	Bias	0.07	0.09	0.00	0.00
HWF-133-2014	Hit-Rate	0.06	0.08	0.00	0.00
HWF-133-2014	False Alarm Ratio	0.17	0.13	NA	NA
HWF-133-2014	Critical Success Index	0.06	0.08	0.00	0.00

Table B.7 – Skill scores for High Level Wildfire 059 (MWF – 059).

		Deterministic Run	50% Agreement	75% Agreement	95% Agreement
Fire Size (ha)	198 (Actual)	3303	1957	567	2
HWF-059-2014	Bias	16.85	9.98	2.89	0.01
HWF-059-2014	Hit-Rate	0.70	0.69	0.41	0.01
HWF-059-2014	False Alarm Ratio	0.96	0.93	0.86	0.00
HWF-059-2014	Critical Success Index	0.04	0.07	0.12	0.01

Table B.8 – Skill scores for High Level Wildfire 058 (HWF – 058).

		Deterministic Run	50% Agreement	75% Agreement	95% Agreement
Fire Size (ha)	702 (Actual)	8319	6735	601	0
HWF-058-2014	Bias	11.82	9.57	0.85	0.00
HWF-058-2014	Hit-Rate	0.97	0.91	0.21	0.00
HWF-058-2014	False Alarm Ratio	0.92	0.90	0.75	NA
HWF-058-2014	Critical Success Index	0.08	0.09	0.13	0.00

Table B.9 – Skill scores for Grand Prairie Wildfire 044 (GWF – 044).

		Deterministic Run	50% Agreement	75% Agreement	95% Agreement
Fire Size (ha)	33796 (Actual)	43545	43070	38308	36825
GWF-044-2014	Bias	1.29	1.27	1.13	1.09
GWF-044-2014	Hit-Rate	0.91	0.91	0.90	0.89
GWF-044-2014	False Alarm Ratio	0.29	0.28	0.21	0.18
GWF-044-2014	Critical Success Index	0.66	0.67	0.73	0.75

AppendixC

Individual Fire Root Mean Square Error Values

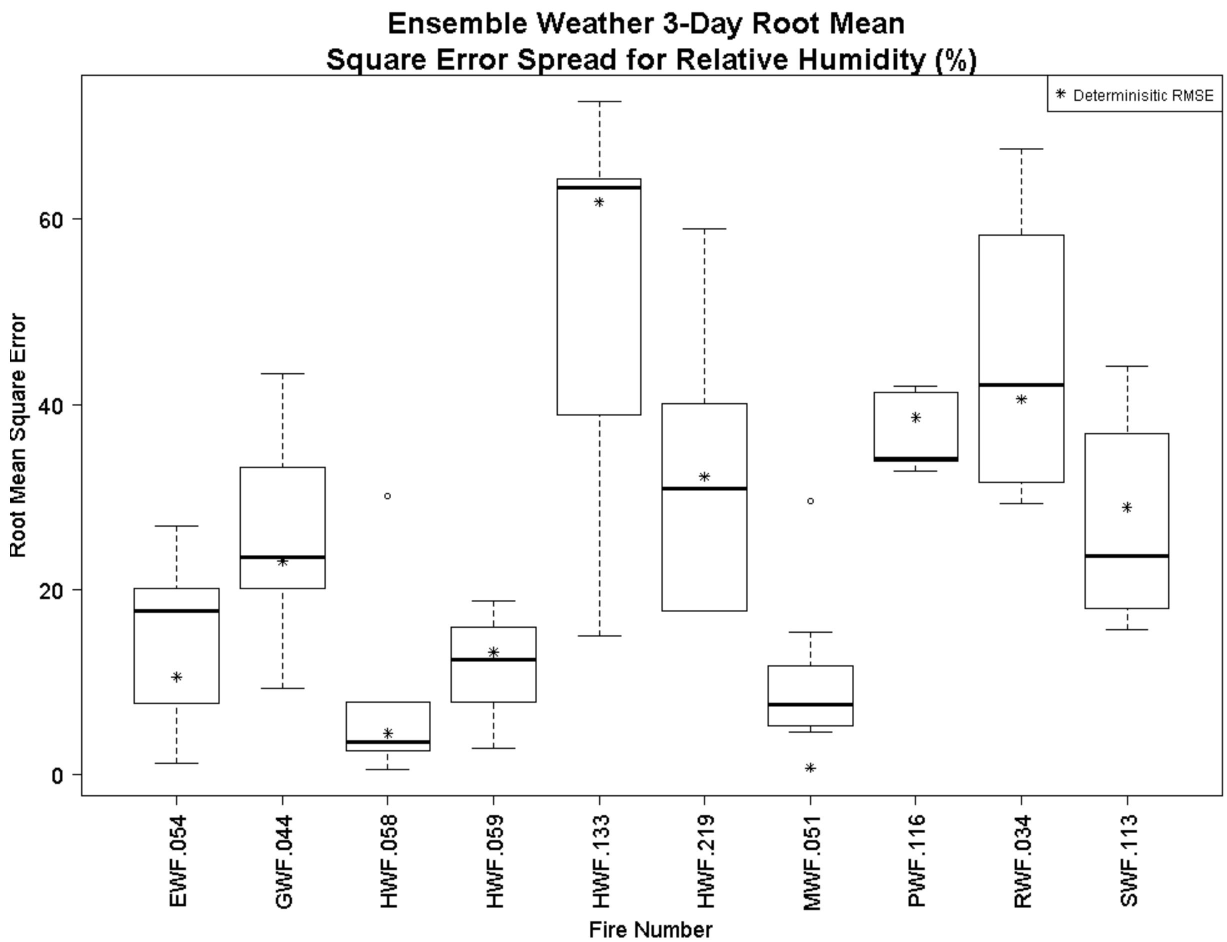

Figure C.1 – Relative Humidity RMSE comparison of deterministic and ensemble outputs for all ten fires.

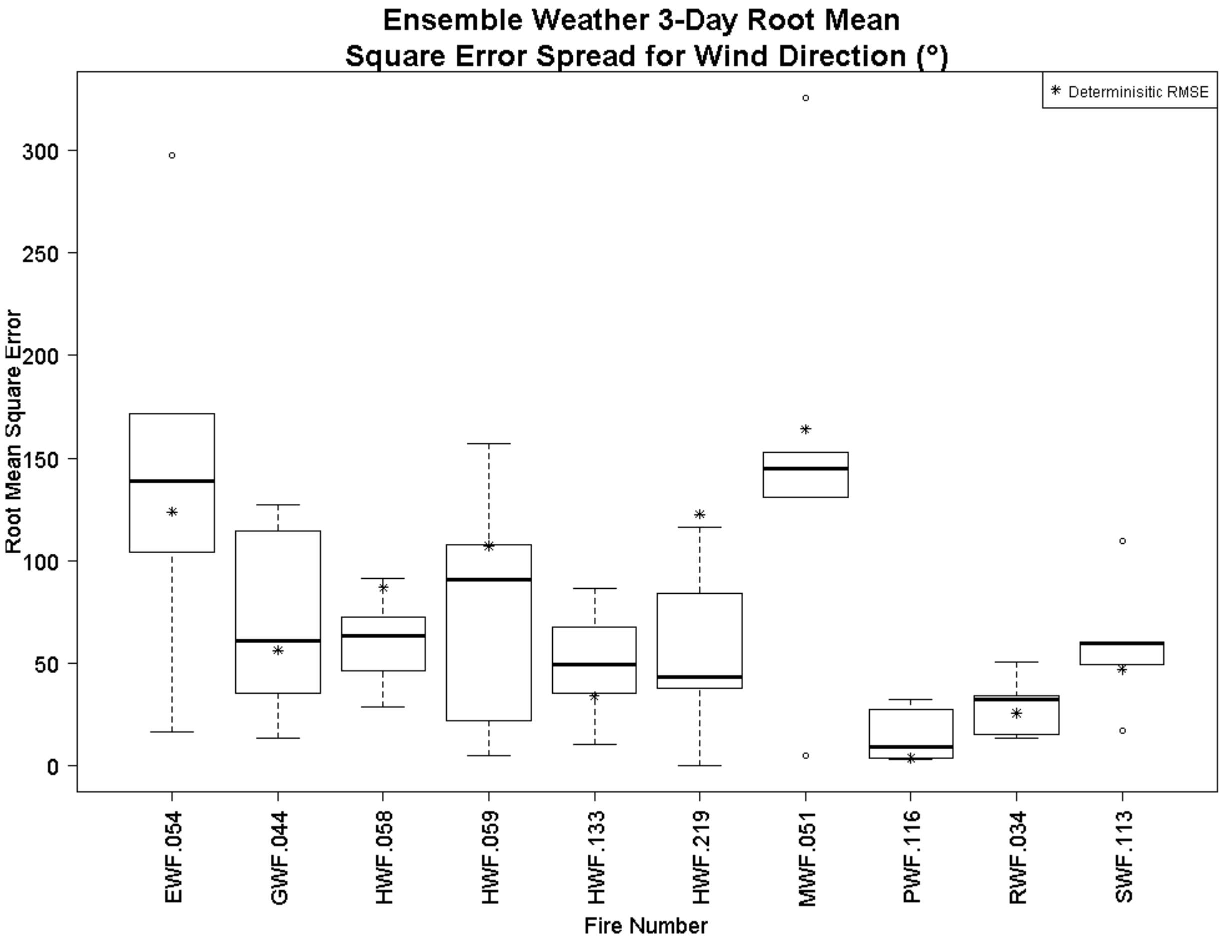

Figure C.2 – Wind Direction RMSE comparison of deterministic and ensemble outputs for all ten fires.

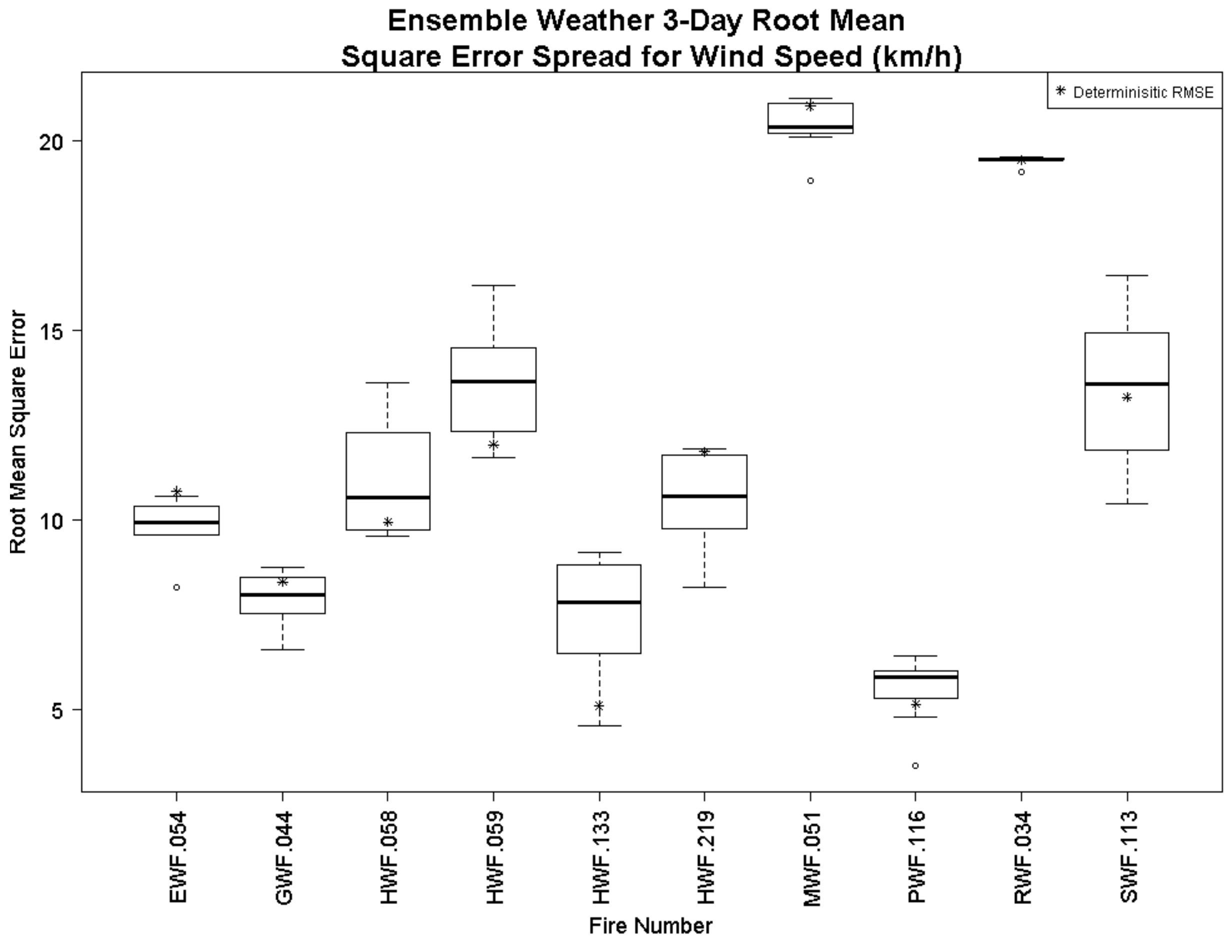

Figure C.3 – Wind Speed RMSE comparison of deterministic and ensemble outputs for all ten fires.

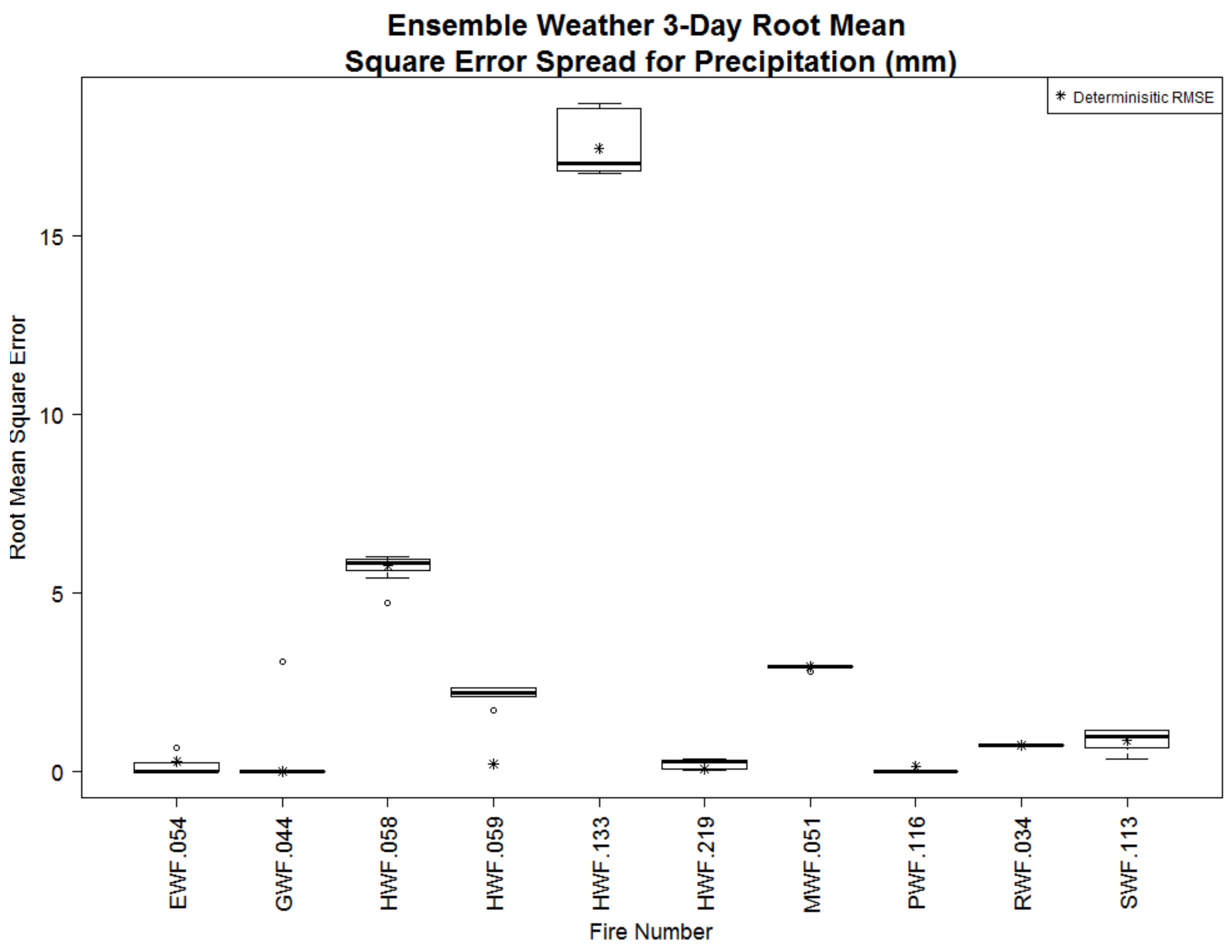

Figure C.4 – Precipitation RMSE comparison of deterministic and ensemble outputs for all ten fires.

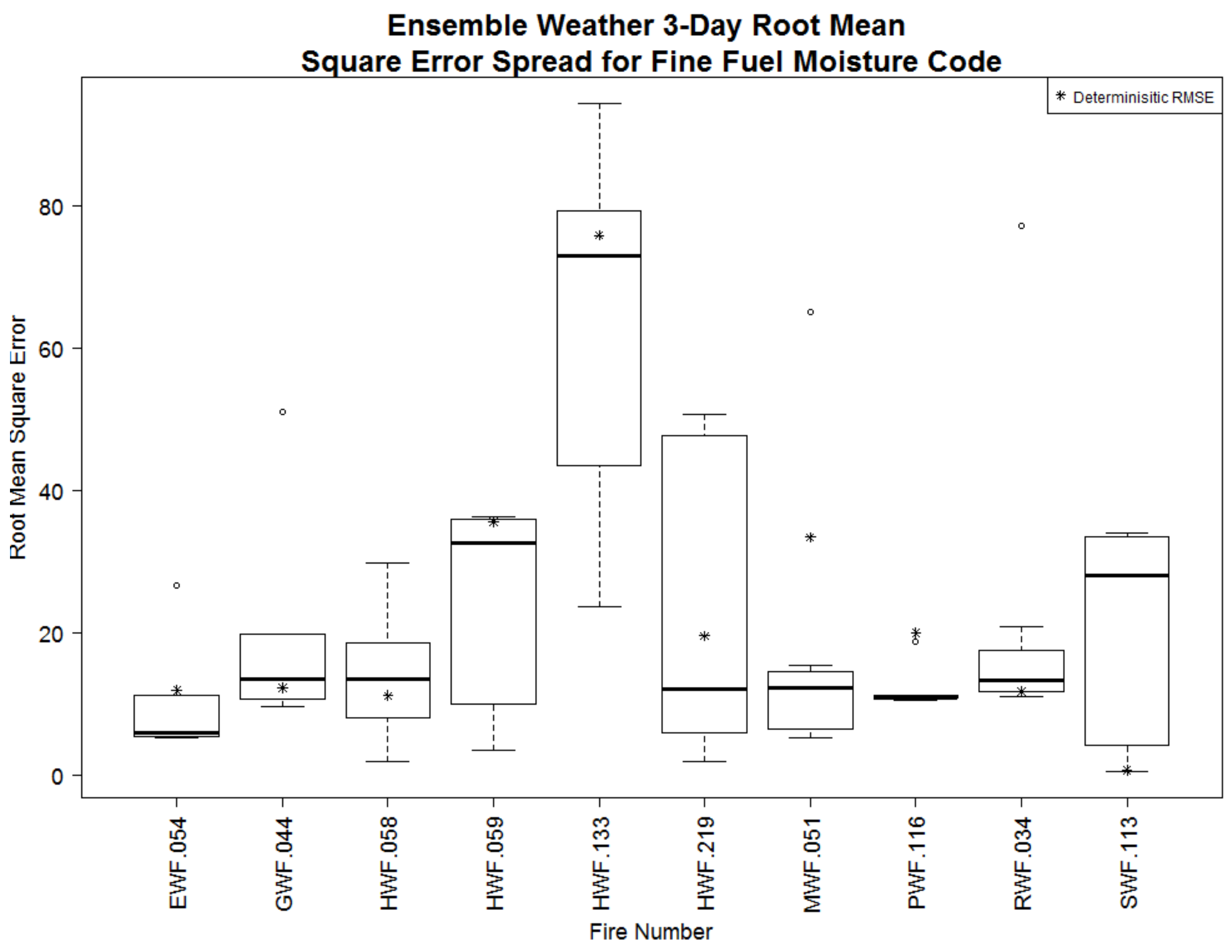

Figure C.5 – Fine Fuel Moisture Code RMSE comparison of deterministic and ensemble outputs for all ten fires.

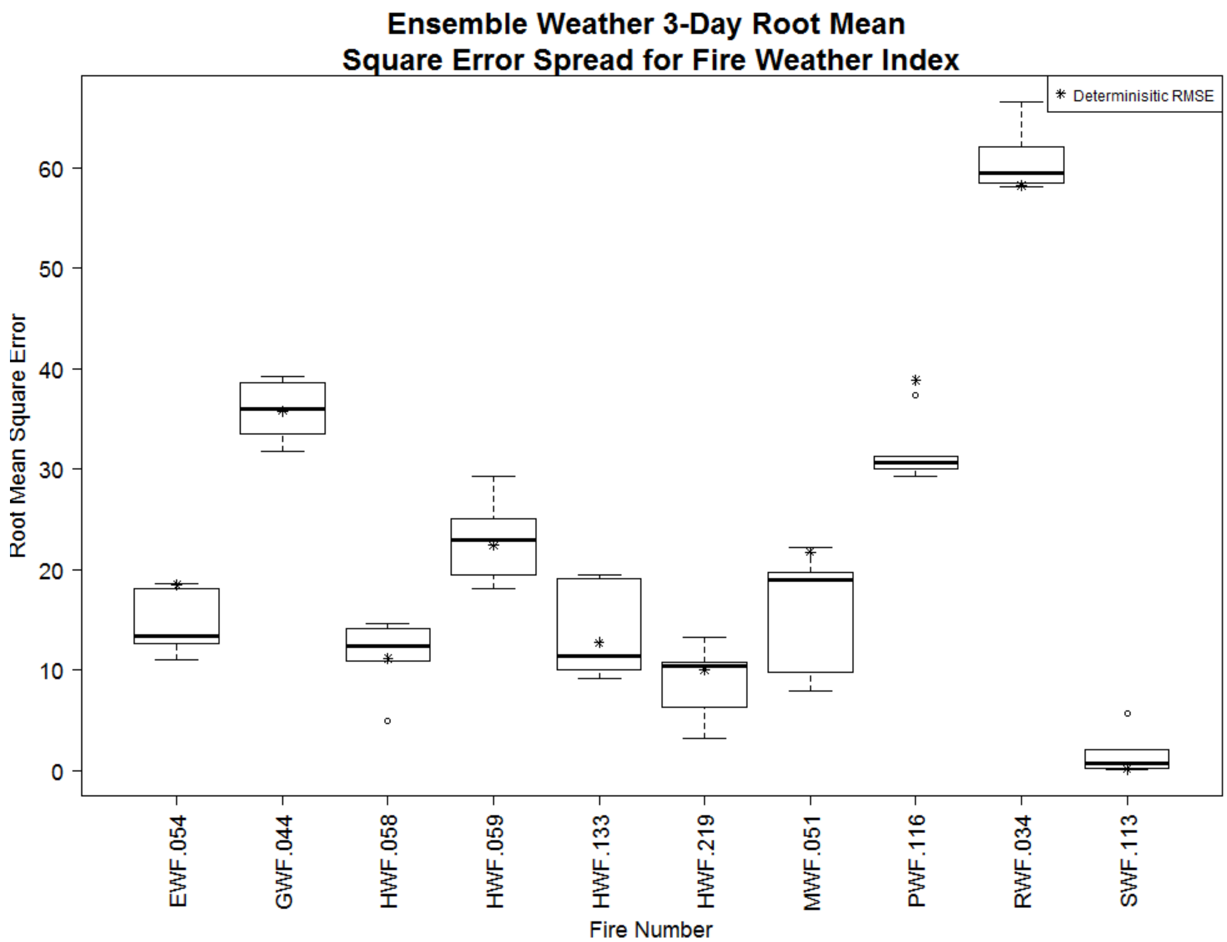

Figure C.6 – Fire Weather Index RMSE comparison of deterministic and ensemble outputs for all ten fires.

AppendixD

Complete Prometheus Report Output

Prometheus Fire Growth Model (Version 6.0.0 (64-bit))

FGM File Name: F:\Data_From_EC\grib\prometheus\20140919\PWF-116.fgm

Date of Report: 28/04/2015 11:33:35

Scenario Inputs:

Name: Member_00

Start Time: September 19, 2014 13:00:00

End Time: September 21, 2014 18:00:00

Ignitions:

PWF-116

Active Grids and Patches:

Southern D1

greenup_INT1U

North East Of the Fire

SW of Fire

Primary Weather Stream:

117.0_55.9_Member_00

Weather Streams:

117.0_55.9: 117.0_55.9_Member_00 [September 19, 2014 00:00:00] - [September 21, 2014 23:59:59]

117.1_56.0: 117.1_56.0_Member_00 [September 19, 2014 00:00:00] - [September 21, 2014 23:59:59]

117.1_55.9: 117.1_55.9_Member_00 [September 19, 2014 00:00:00] - [September 21, 2014 23:59:59]

117.0_56.0: 117.0_56.0_Member_00 [September 19, 2014 00:00:00] - [September 21, 2014 23:59:59]

117.1_55.8: 117.1_55.8_Member_00 [September 19, 2014 00:00:00] - [September 21, 2014 23:59:59]

117.0_55.8: 117.0_55.8_Member_00 [September 19, 2014 00:00:00] - [September 21, 2014 23:59:59]

116.9_56.0: 116.9_56.0_Member_00 [September 19, 2014 00:00:00] - [September 21, 2014 23:59:59]

116.9_55.9: 116.9_55.9_Member_00 [September 19, 2014 00:00:00] - [September 21, 2014 23:59:59]

116.9_55.8: 116.9_55.8_Member_00 [September 19, 2014 00:00:00] - [September 21, 2014 23:59:59]

Comments:

Simulation Settings:

Propagation:

Display Interval: 01:00:00

Maximum Calculation Time Step: 01:00:00

Maximum Time Step during Acceleration: 00:02:00

Distance Resolution (Grid Cells): 1.00

Perimeter Resolution (Grid Cells): 1.00

Smoothing Factor: 0.00

Number of Starting Vertices: 16

Stop Fire Spread at Data Boundary: False

Breaching On: True

FBP:

Acceleration On: True

BUI Effect On: True

Terrain Effect On: True

Green-up On where NODATA or no grid exists: True

FMC Settings:

FMC (%) Override: False

Elevation (m) where NODATA or no grid exists: -1.0

Fire Weather Interpolation: True

Apply spatial interpolation to FWI System values: False

Calculate FWI System values from spatially interpolated weather: True

Apply history to FWI System values affected by patches or grids: False

Burning Conditions:

Enable Burning Conditions: True

Date	Start	End	FWI >	WS >	RH <
2014/09/19	0	23	10	0.00	90
2014/09/20	0	23	10	0.00	90
2014/09/21	0	23	10	0.00	90

Landscape Properties:

Grid Information:

Cell Size (m): 100.0

Columns and Rows: 1000 x 1000

Grid Size: 100.00 km x 100.00 km

Location of Lower Left Corner:

55.445210°,-117.744196°

Elevation Statistics (m):

Min: 305.0

Max: 774.0

Mean: 614.0

Median:618.0

FMC Settings:

FMC (%) Override: False

Elevation (m) where NODATA or no grid exists: 618.0

Time Zone Settings:

Time Zone: MDT Mountain Daylight Time -6:00:00

Landscape Grids:

Projection: F:\Data_From_EC\grib\prometheus\20140919\prom_clip-116.9768_55.909183\fbp.prj

FBP Fuel Grid: F:\Data_From_EC\grib\prometheus\20140919\prom_clip-116.9768_55.909183\fbp.asc

Elevation Grid: F:\Data_From_EC\grib\prometheus\20140919\prom_clip-116.9768_55.909183\elevation.asc

Fuel Patches:

Landscape FBP Fuel Type Patch:

Polygon FBP Fuel Type Patch:

Name: Southern D1

From: --- All Fuels ---

To: D-1 Leafless Aspen

Area: (36.615 ha)

Name: North East Of the Fire

From: Vegetated Non-Fuel

To: C-2 Boreal Spruce

Area: (1388.758 ha)

Name: SW of Fire

From: Vegetated Non-Fuel

To: D-1 Leafless Aspen

Area: (479.685 ha)

Weather Patches and Weather Grids:

Weather Patches:

Weather Grids:

Fuel Breaks:

Ignitions:

Name: PWF-116

Start Time: September 19, 2014 13:00:00

Ignition Type: Point (55.909180°,-116.976800°)

Weather Streams:

Weather Station:

Name: 117.0_55.9

Coordinates: 55.900000°,-117.000000°

Elevation: 638.0 m

Name: 117.0_55.9_Member_00

Start Date: September 19, 2014 00:00:00

End Date: September 21, 2014 23:59:59

Yesterday's Daily Starting Codes:

FFMC: 86.2

DMC: 43.7

DC: 792.4

Precipitation (13:01 - 23:00): 0.0 mm

Today's Hourly Starting Code:

FFMC: 79.1

@ Hour: 17

Diurnal Parameters:

Temperature:

Alpha: -0.770

Beta: 2.800

Gamma: -2.200

Wind:

Alpha: 1.000

Beta: 1.240

Gamma: -3.590

Method of Hourly FFMC Calculation:

Van Wagner

Weather Station:

Name: 117.1_56.0

Coordinates: 56.000000°,-117.100000°

Elevation: 587.0 m

Name: 117.1_56.0_Member_00

Start Date: September 19, 2014 00:00:00

End Date: September 21, 2014 23:59:59

Yesterday's Daily Starting Codes:

FFMC: 86.2

DMC: 44.2

DC: 784.5

Precipitation (13:01 - 23:00): 0.0 mm

Today's Hourly Starting Code:

FFMC: 85.4

@ Hour: 17

Diurnal Parameters:

Temperature:

Alpha: -0.770

Beta: 2.800

Gamma: -2.200

Wind:

Alpha: 1.000

Beta: 1.240

Gamma: -3.590

Method of Hourly FFMC Calculation:

Van Wagner

Weather Station:

Name: 117.1_55.9

Coordinates: 55.900000°,-117.100000°

Elevation: 638.0 m

Name: 117.1_55.9_Member_00

Start Date: September 19, 2014 00:00:00

End Date: September 21, 2014 23:59:59

Yesterday's Daily Starting Codes:

FFMC: 86.3

DMC: 43.8

DC: 782.4

Precipitation (13:01 - 23:00): 0.0 mm

Today's Hourly Starting Code:

FFMC: 81.6

@ Hour: 17

Diurnal Parameters:

Temperature:

Alpha: -0.770

Beta: 2.800

Gamma: -2.200

Wind:

Alpha: 1.000

Beta: 1.240

Gamma: -3.590

Method of Hourly FFMC Calculation:

Van Wagner

Weather Station:

Name: 117.0_56.0

Coordinates: 56.000000°,-117.000000°

Elevation: 593.0 m

Name: 117.0_56.0_Member_00

Start Date: September 19, 2014 00:00:00

End Date: September 21, 2014 23:59:59

Yesterday's Daily Starting Codes:

FFMC: 86.2

DMC: 45.0

DC: 783.6

Precipitation (13:01 - 23:00): 0.0 mm

Today's Hourly Starting Code:

FFMC: 84.2

@ Hour: 17

Diurnal Parameters:

Temperature:

Alpha: -0.770

Beta: 2.800

Gamma: -2.200

Wind:

Alpha: 1.000

Beta: 1.240

Gamma: -3.590

Method of Hourly FFMC Calculation:

Van Wagner

Weather Station:

Name: 117.1_55.8

Coordinates: 55.800000°,-117.100000°

Elevation: 620.0 m

Name: 117.1_55.8_Member_00

Start Date: September 19, 2014 00:00:00

End Date: September 21, 2014 23:59:59

Yesterday's Daily Starting Codes:

FFMC: 86.6

DMC: 44.3

DC: 785.3

Precipitation (13:01 - 23:00): 0.0 mm

Today's Hourly Starting Code:

FFMC: 73.8

@ Hour: 17

Diurnal Parameters:

Temperature:

Alpha: -0.770

Beta: 2.800

Gamma: -2.200

Wind:

Alpha: 1.000

Beta: 1.240

Gamma: -3.590

Method of Hourly FFMC Calculation:

Van Wagner

Weather Station:

Name: 117.0_55.8

Coordinates: 55.800000°,-117.000000°

Elevation: 635.0 m

Name: 117.0_55.8_Member_00

Start Date: September 19, 2014 00:00:00

End Date: September 21, 2014 23:59:59

Yesterday's Daily Starting Codes:

FFMC: 86.5

DMC: 44.1

DC: 796.3

Precipitation (13:01 - 23:00): 0.0 mm

Today's Hourly Starting Code:

FFMC: 71.0

@ Hour: 17

Diurnal Parameters:

Temperature:

Alpha: -0.770

Beta: 2.800

Gamma: -2.200

Wind:

Alpha: 1.000

Beta: 1.240

Gamma: -3.590

Method of Hourly FFMC Calculation:

Van Wagner

Weather Station:

Name: 116.9_56.0

Coordinates: 56.000000°,-116.900000°

Elevation: 592.0 m

Name: 116.9_56.0_Member_00

Start Date: September 19, 2014 00:00:00

End Date: September 21, 2014 23:59:59

Yesterday's Daily Starting Codes:

FFMC: 86.1

DMC: 42.7

DC: 766.7

Precipitation (13:01 - 23:00): 0.0 mm

Today's Hourly Starting Code:

FFMC: 83.7

@ Hour: 17

Diurnal Parameters:

Temperature:

Alpha: -0.770

Beta: 2.800

Gamma: -2.200

Wind:

Alpha: 1.000

Beta: 1.240

Gamma: -3.590

Method of Hourly FFMC Calculation:

Van Wagner

Weather Station:

Name: 116.9_55.9

Coordinates: 55.900000°,-116.900000°

Elevation: 646.0 m

Name: 116.9_55.9_Member_00

Start Date: September 19, 2014 00:00:00

End Date: September 21, 2014 23:59:59

Yesterday's Daily Starting Codes:

FFMC: 86.1

DMC: 42.9

DC: 771.6

Precipitation (13:01 - 23:00): 0.0 mm

Today's Hourly Starting Code:

FFMC: 78.4

@ Hour: 17

Diurnal Parameters:

Temperature:

Alpha: -0.770

Beta: 2.800

Gamma: -2.200

Wind:

Alpha: 1.000

Beta: 1.240

Gamma: -3.590

Method of Hourly FFMC Calculation:

Van Wagner

Weather Station:

Name: 116.9_55.8

Coordinates: 55.800000°,-116.900000°

Elevation: 639.0 m

Name: 116.9_55.8_Member_00

Start Date: September 19, 2014 00:00:00

End Date: September 21, 2014 23:59:59

Yesterday's Daily Starting Codes:

FFMC: 86.4

DMC: 42.7

DC: 781.5

Precipitation (13:01 - 23:00): 0.0 mm

Today's Hourly Starting Code:

FFMC: 71.0

@ Hour: 17

Diurnal Parameters:

Temperature:

Alpha: -0.770

Beta: 2.800

Gamma: -2.200

Wind:

Alpha: 1.000

Beta: 1.240

Gamma: -3.590

Method of Hourly FFMC Calculation:

Van Wagner

Modified FBP Fuel Types: