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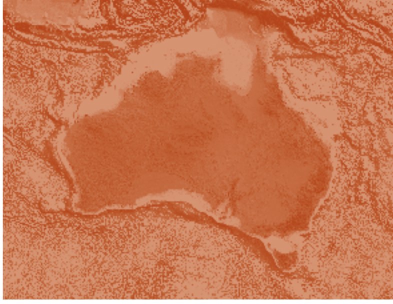

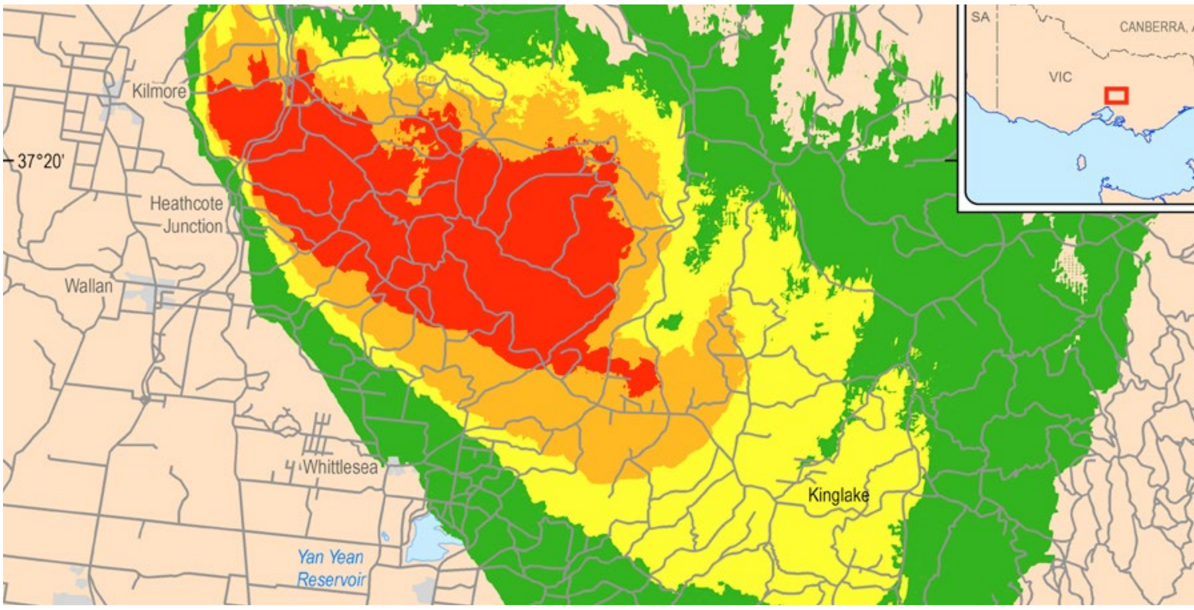

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Acknowledging and Understanding Variability in Simulating Bushfires

Part 1 - Evaluation of FireDST against the Kilmore fire of 7 February 2009

Ian A. French, H. Martine Woolf, Bob P. Cechet, Tina Yang, L. Augusto Sanabria

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GEOSCIENCE AUSTRALIA
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Contents

Audience & Acknowledgements

This document contains scientific information and technical content. It is intended for scientists and emergency services practitioners who have an understanding of the management of bushfires and controlled burns. The results of this work should be interpreted in the context of the study. This report does not give a comprehensive risk assessment of the study area, and should not be used as a basis for decision making about planning or emergency response.

The authors would like to acknowledge the assistance of:

- The Bushfire CRC for funding the FireDST project.
- Dr Jeff Kepert and Dr Robert Fawcett of the Bureau of Meteorology (CAWCR) who supplied the ACCESS weather simulations.
- Derek Ming Onn Chong of the University of Melbourne who modified PHOENIX RapidFire to accept transport layer wind direction and wind speed files.
- Dr Mick Meyer and Dr Martin Cope from C.S.I.R.O Marine and Atmospheric Research who provided the combustion gas profiles that have been used to create the ensemble smoke output.
- All the staff at the Bushfire CRC for supporting the FireDST project team.

Glossary

The following terms and abbreviations have been used throughout this document. Abbreviations that are part of the scenario labels are specified in Appendix B.

Term	Definition
ACCESS	Australian Community Climate and Earth-System Simulator, the Bureau of Meteorology weather model used in this study.
AWS	Automated Weather Station managed by the Bureau of Meteorology to record actual weather.
Boundary Layer	The air layer in the atmosphere that is adjacent to the earth’s surface.
Bushfire CRC BCRC	Bushfire Cooperative Research Centre
Collection District	This is the name given by the Australian Bureau Statistics in the 2006 Census that now is called Statistical Area Level 1 (SA 1). This is generally a population of 200-800 people and an average of 400 people.
CSIRO	The Commonwealth Scientific and Industrial Research Organisation
Ensemble Footprint	The fire shape that is made by including all the ensemble members.
FireDST	The simulation system developed as part of the F.I.R.E.-D.S.T. project.
F.I.R.E.-D.S.T.	Fire Impact and Risk Evaluation Decision Support Tool.
Fire Ensemble	An ensemble refers to a set of different individual fire simulations that have been collected together
Mesh Block	The smallest geographical region published by the Australian Bureau of Statistics. Only limited Census data (total population and dwelling count) are published at this level.
PHOENIX RapidFire	The model developed by the University of Melbourne that provided the core fire spread modelling capability for the FireDST system.
Vulnerability curve	Vulnerability curves are used to specify the probable damage to a building as a function of the hazard. The more the hazard, the more likely the house will be destroyed.

1 Executive Summary

Introduction

In 2011, the Bushfire Cooperative Research Centre (BCRC) funded a multi-agency research project called the Fire Impact & Risk Evaluation Decision Support Tool (F.I.R.E-D.S.T) Project. The project team comprised Geoscience Australia, the Bureau of Meteorology, the University of Melbourne and CSIRO.

The F.I.R.E-D.S.T. project aimed to investigate how uncertainty within fire spread modelling could be examined while assessing the potential consequences (impacts) of an event. FireDST was designed to generate an ensemble of scenarios, that is: different realisations of the potential fire spread based on variations in the conditions in which the fire occurs. Geoscience Australia developed an approach and the tools to meet the following research objectives.

Develop a methodology to assess and visualise the sensitivity of the fire spread to a range of modelling parameters. Demonstrate that this methodology can be used to explore sensitivity of the modelled fire spread to parameters describing the

- surface weather,
- weather conditions in the upper atmosphere,
- fuel conditions, and
- ignition.

Develop a methodology to assess the sensitivity of the estimated numbers of people and buildings exposed to and impacted by fire to a range of parameters determining:

- modelled fire spread, i.e. surface weather, fuel conditions and ignition, and
- vulnerability of buildings.
- Develop a methodology to model the impact of human action on building damage in fires.
- Develop a methodology to assess the sensitivity of modelled smoke movement to the fire spread.

These research questions focus on sensitivity of the modelled fire spread and impact. Sensitivity analysis is a key component of a better understanding of the robustness and error of model outputs. By addressing the questions above, the project aims to achieve the following outcomes.

1. Development of an integrated fire spread and impact assessment methodology and tool.
2. Incorporation of the functionality to explore variability in key parameters as part of an integrated fire spread and impact modelling tool.
3. Demonstration of a product that can provide an ensemble around the modelled fire spread and fire impact, rather than a best estimate. This allows stakeholders to explore the potential benefits of such information, as well as issues around user requirements and adoption.
4. Improved understanding of uncertainty in fire spread and impact modelling through sensitivity analysis of key input parameters.

5. Development of “proof-of-concept” for a system or approach that enables ensemble fire spread modelling, given the right input parameters. This includes an improved understanding of the information and system requirements for such a system.
6. Improved understanding of the information and system requirements for future products based on the methodologies developed by F.I.R.E-D.S.T. This could be either an integrated fire and smoke spread and impact system, or a system quantifying uncertainty around projected fire and smoke spread or impact, or a combination of the two.

Project approach

Answering the research questions and objectives outlined above required the development of a proof-of-concept simulation system, called FireDST. FireDST is a modular system that combines a range of models and inputs from across the project team:

a. New numerical weather prediction model (ACCESS) from the Bureau of Meteorology.
b. Updated PHOENIX RapidFire bushfire simulator from the University of Melbourne.
c. Building and population information based on the Australian building database (NEXIS) from Geoscience Australia and Census information from the Australian Bureau of Statistics.
d. A new building vulnerability model from Geoscience Australia and CSIRO and
e. A smoke and combustion product dispersion model from CSIRO.

The core of the FireDST functionality is its ability to model a fire spread and estimate the fire’s impact. The FireDST system simulates a fire spread based on particular weather, fuel and ignition conditions. It assesses the people and buildings in the fire spread, and models the potential damage to the buildings. One of its distinguishing features is that FireDST was built to generate multiple scenarios of the possible fire. Each instance of the fire is created using a variation in the input conditions (such as slight changes in temperature and wind direction). In doing this, FireDST creates ensembles of fire spread and impact. The ensemble data enables assessment of the sensitivity of the modelled fire spread due to the variations in the input parameters.

FireDST was evaluated by the application of the sensitivity test in three case studies: the Victorian Black Saturday Kilmore fire of 7 February 2009, the south Australia Wangary fire of 10 January 2005 and the New south Wales Mt Hall fire of 24 December 2001.This document evaluates the results of sensitivity tests using FireDST in the first case study, the Black Saturday Kilmore fire of 7 February 2009.

Objective 1 – Assessing and visualising variability in the fire spread

The range of fire spread scenarios within an ensemble was visualised by FireDST in terms of overlap. Ensembles provided key information on the sensitivity of fire spread simulations through the spread of the fire spread envelope. To allow the ensemble fire spread to be interpreted in terms of probability of fire spread, the ensemble would have had to sample the full distribution of the uncertainty in input parameters. This was outside the scope of the project. However, even a ‘naïve’ sensitivity ensemble such as generated in this report gives information on the potential development of an event that cannot be provided by a single deterministic model run. With the correct input, the FireDST system allows consideration of variability in the fire spread modelling during the lifetime of an event.

Objective 1.1 – Sensitivity of fire spread to the surface weather

The F.I.R.E.-D.S.T project aimed to develop a methodology for integrating the individual uncertainties in surface weather parameters into the FireDST system. The methodology was tested by assessing the sensitivity of the fire spread to the surface weather conditions: weather parameters, time interval, wind direction, wind intensity, temperature, humidity and combinations.

The weather was simulated for the conditions during the Kilmore fire in terms of temperature, humidity, wind direction and wind speed. The weather simulations were produced by the Bureau of Meteorology ACCESS Weather model at 0.036^{o,} 0.012^{o} and 0.004^{o} grid spacing (approximately 4000, 1200 and 440 m grid resolution), in time steps of five minutes.

The fire spread modelled by FireDST for the Kilmore fire underestimated the size of the historical event, based on the available reconstruction data. This is likely to be due to underestimated wind speeds in the ACCESS output at all resolutions. An approach to correct the bias in the ACCESS wind strength was developed however it did not solve this issue, although it did improve the accuracy of the modelled fire spread based the 4000 m and 1200 m resolution weather information. Additional correction of the modelled wind to reflect local effects using the 'Wind Ninja' modifiers made further improvements for the fire spread based on weather data at those resolutions. However, the benefit of the local wind modification was not shown for a simulation based on the 440 m weather data. The cause of this was unknown and will need to be the subject of further research.

A series of tests showed evidence of the sensitivity of the modelled fire spread to the following weather parameters: temporal and spatial resolution of the weather model, wind direction, wind intensity, temperature, humidity and timing of the weather patterns. The results also demonstrated that sensitivity of the modelled fire shape to perturbations in key parameters cannot be judged in isolation. The modelled process is also sensitive to interactions between the parameters, caused by the physical processes that drive the fire. When assessing robustness of a fire spread prediction or generating a probabilistic fire spread forecast, this interaction between the input parameters has to be explicitly built into the sampling design of ensembles.

Objective 1.2 – Sensitivity of the fire spread to the weather conditions in the upper atmosphere

Upper level wind speed and direction are key drivers of the spread of embers from the fire. The project aimed to develop a methodology for integrating uncertainties in the wind direction and speed at different altitudes into the FireDST system. The simulation of the atmospheric conditions in the upper atmosphere were generated by the Bureau of Meteorology ACCESS model, which produced the vertical atmosphere at fifty heights (levels) each with 4 km horizontal resolution and time steps of 15 minutes. FireDST includes adaptations to the PHOENIX RapidFire ember transport model.

The results demonstrated that the fire spread showed sensitivity to the strength and direction in upper level wind as supplied in the ACCESS simulated atmosphere. Winds from lower levels in the boundary layer (up to 410 m) produced realistic results for the fire spread, based on comparison with the observed fire spread in the Kilmore event. Fire spread simulations based the conditions between

610 m and 3130 m overestimated the forward rate of spread, resulting in a modelled fire spread that exceeded that observed in the historical event. This indicates that either the modelled winds at those vertical levels were overestimated, or that the ember transport mechanism introduced in PHOENIX RapidFire was too high.

Upwards of 3.6 km into the atmosphere, the wind direction differed significantly from the dominant wind direction in the boundary layer. As a consequence, fire spread simulations based on these winds did not reproduce the direction of the Kilmore event. This suggests that in the actual Kilmore event, winds at heights below 3.6 km played a major role in the ember transport. Note that 3.6 km is under a quarter of the plume height that was observed in the Kilmore event.

Objective 1.3 – Assessing the sensitivity of the fire spread to fuel load

The accuracy of landscape (fuel) characterisation is a major source of uncertainty for fire modelling. This project modelled the sensitivity of fire spread and impact projections from inaccuracies in the fuel load. Scenarios varying the fuel loads were tested based on varying the burning history, and the shape of the fuel regeneration curves. The results showed that the simulated fire spread was sensitive to fuel load, with larger fire spreads for higher fuel loads.

Objective 1.4 – Assessing the sensitivity of the fire spread to ignition

The F.I.R.E-D.S.T project assessed the sensitivity of the fire spread to the location and timing of the ignition. The sensitivity of fire spread to the location of the ignition point is a critical detail in fire modelling since ignition determines the landscape conditions that the fire encounters. The timing of the fire start determines the weather conditions that the fire encounters. The results of the work showed that the modelled fire spread is sensitive to variations in both parameters.

Objective 2 – Estimating ensemble exposure and impact

The ability to generate an inventory of the buildings and people that are exposed to a fire is a fundamental part of an integrated assessment of fire impact modelling. F.I.R.E-D.S.T. implemented a framework for the derivation of exposure associated with fire. A comprehensive database of building and population statistics was developed based on existing information, mainly from Geoscience Australia (NEXIS database) and the Australian Bureau of Statistics 2006 Census. In combination with the fire spread information, FireDST system can quantify and visualise exposure information for either a single fire scenario or different levels of overlap within the fire spread ensemble.

Objective 2.1 – Estimating building loss using a fire spread ensemble

The FireDST system estimates the probability that a building is destroyed by fire, based on the building location and the bushfire characteristics. Building loss information can be directly related to the corresponding area of the ensemble fire spread. The project implemented a set of four vulnerability curves that estimated house loss as a function of radiation and ember density. In order to apply these curves, the FireDST system integrates the large-scale fire spread modelling with a parameterisation of sub-grid scale fire conditions.

The accuracy of using the vulnerabilities to predict house loss for the individual houses in the Kilmore was 55%. Estimated house loss was shown to be sensitive to the choice of vulnerability function. Ideally, vulnerability functions should reflect differences in relevant building characteristics, such as construction type, age, building-code compliance and maintenance level. The vulnerability functions applied in this project did not vary with these characteristics, and could therefore only be expected to attain a limited level of accuracy for individual buildings.

Estimated house loss was also sensitive to the input parameters determining the fire spread. In the Kilmore event, the sensitivity to the fire spread overshadowed the sensitivity to the vulnerability model assumptions.

Objective 3 – Estimating the impact of human action on building damage in fires

The ability of residents to defend their home significantly influences the chances that a building will survive a fire. FireDST implements the new Building Fire Impact Model (BFIM) that captures the impact of human action as part of an integrated fire spread and impact assessment. This model component accounts for factors such as the number of people available to douse spot fires or embers. This module also improves the accuracy of the building damage modelling because it accounts for building-to-building ignition.

The initial results developed with the BFIM for the Kilmore case study showed that the approach was flexible and could be developed to refine the ‘standard’ engineering vulnerability modelling approach such as that in the previous section. At this time, however, the BFIM makes many assumptions that are difficult to validate without extensive observations, and further work is essential to develop a robust version of the model that can be incorporated effectively in a system such as FireDST.

Objective 4 – Assessing the sensitivity of smoke movement to the fire spread

Smoke is a key contributor to bushfire impact, particularly through its consequences for human health. FireDST integrates a model for smoke and combustion product movement in the fire spread modelling. The results of this work demonstrate that the ensemble approach can be extended to modelling of smoke and combustion products. The visualisation of the ensemble smoke products included mapping the intensity in terms of the maximum concentration, as well as the overlapping spread of the gases. The ensemble spread can be interpreted in terms of the sensitivity of the spread and concentration of those products, linked to uncertainty and error in the modelling parameters.

2 Introduction

2.1 Background

Australia needs to develop and use sophisticated fire modelling techniques as an aid in the prevention and mitigation of bushfires (COAG 2002). In 2011, the Bushfire Cooperative Research Centre (BCRC) funded a multi-agency research project called the Fire Impact & Risk Evaluation Decision Support Tool (F.I.R.E-D.S.T.) Project. F.I.R.E-D.S.T. aimed to investigate how uncertainties within fire spread modelling could be incorporated into a more robust assessment of the potential consequences (impacts) of a fire event.

The last few decades have seen the development of numerous computational bushfire spread models. These models include PHOENIX RapidFire (Tolhurst *et al*., 2008) in Australia, FireSite (Finney, 1998), FlamMap (Finney, 2006), WFDSS- FSPro (Wildland Fire Decision Support System- Fire Spread Probability Model) (McDaniel, 2007) in the USA, and Prometheus, the Canadian wildland fire growth simulation model (Tymstra *et al*., 2009). These models project the spread of a fire through the landscape in time. Such models typically assimilate information on the weather, terrain, and fuel load and type. Other models link fire spread to impact on buildings and people.

While fire modelling has advanced significantly, none of the existing fire spread and impact models are perfect. As is the case with any model of a complex phenomenon, there are many uncertainties in the output from fire spread and impact models. These uncertainties are associated with both the model parameterisation and the input data. The model output, typically a single ‘best estimate’ of projected fire spread or impact, conveys limited or no information on the impact of those uncertainties. Understanding the sensitivity of the model output to those uncertainties is essential to assessing the robustness of the projected fire spread and impact. It can help determine the probable range of variation around a modelled ‘best estimate’. The F.I.R.E-D.S.T project developed an approach to assess and visualise the sensitivities of fire spread and impact modelling to those uncertainties in the modelling. Ultimately, the outcomes from this project should contribute to an improved robustness of decisions made on the basis of fire spread and impact modelling outputs.

The F.I.R.E-D.S.T Project comprised five sub-projects, undertaken by the organisations whose name appears in brackets:

Risk Assessment Decision Toolbox (Geoscience Australia)

a. Development of a computational risk assessment framework.
b. Development of a simulation system integrating outputs from the other four sub-projects as well as databases with building and socio-economic information.

Enhancement of fire behaviour modelling (University of Melbourne)

a. Enhancement of the fire spread model PHOENIX RapidFire to incorporate the three-dimensional meteorology.
b. Enhancement of fire suppression within PHOENIX RapidFire.
c. Analysis of vegetation mapping and properties within PHOENIX RapidFire.

Enhancement of weather predictions under extreme conditions (Bureau of Meteorology)

a. Development of a high-resolution numerical weather prediction (NWP) capability for use in natural disaster modelling.

b. Examination of how sub-scale weather phenomena can be parameterised (for NWP).

c. Assessment of the sensitivity of extreme fire behaviour to weather.

Regional and local impacts from bushfire dispersion (CSIRO Marine and Atmospheric Research)

a. Development of a high-resolution smoke dispersion model.

b. Examination of the health impacts of bushfire smoke.

Enhancement of local impacts – vulnerability parameterisation (CSIRO Ecosystem Science)

a. Examination of the impact of the local environment on house survivability.

b. Parameterisation of the vulnerability of houses to hazard (radiation, ember-attack).

The approach followed by the F.I.R.E-D.S.T project implemented a computational risk assessment framework for quantitative bushfire risk assessments (Jones *et al.,* 2012). This approach complied with the National Emergency Risk Assessment Guidelines (NEMC 2010). Figure 2.1 displays the linkages between the research components undertaken by each of the teams. A full description of the project can be found in the Cechet *et al*., 2014. This describes the Geoscience Australia simulation system component, the “proof-of-concept” FireDST system.

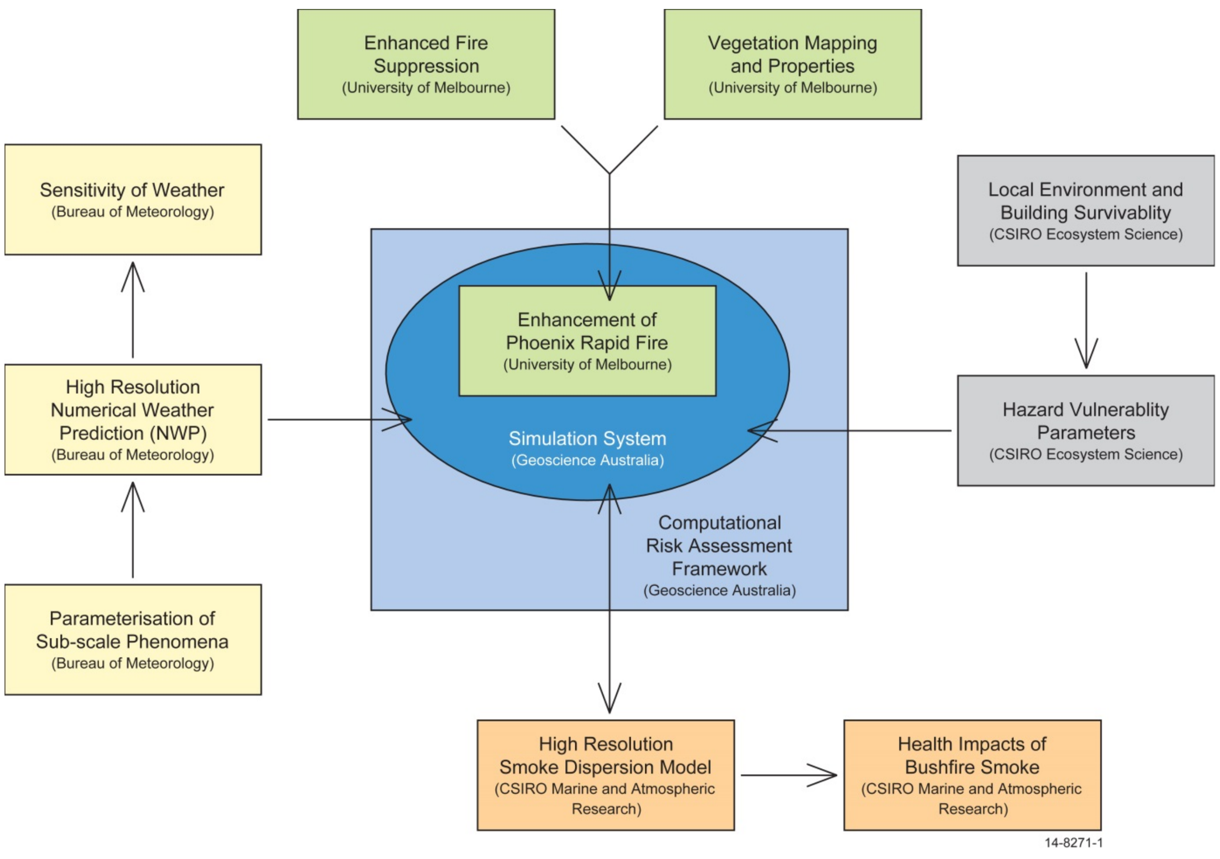


Figure 2.1 Relationship between the F.I.R.E.-D.S.T project components.

2.2 Research objectives

As outlined in the previous section, the primary objective of the F.I.R.E-D.S.T. research was to investigate how uncertainty within fire modelling could be incorporated into an estimate provided by a fire spread and impact model. The FireDST proof-of-concept simulation system was used to explore the sensitivities of fire spread and impact modelling to key parameters in the modelling process. This allowed addressing the following research objectives.

Develop a methodology to assess and visualise the sensitivity of the modelled fire spread to a range of parameters describing:

- surface weather,
- weather conditions in the upper atmosphere,
- fuel load and type, and
- ignition.

Develop a methodology to assess the sensitivity of the estimated numbers of people and buildings exposed to and impacted by fire to a range of parameters determining:

- modelled fire spread, i.e. surface weather, fuel conditions and ignition, and
- vulnerability of buildings.
- Develop a methodology to model the impact of human action on building damage in fires.
- Develop a methodology to assess the sensitivity of modelled smoke movement to the fire spread.

The research described in this report focuses on sensitivity of the modelled fire spread and impact. Sensitivity analysis investigates how outputs from a model or process change when the inputs are varied. Sensitivity analysis is a key component of a better understanding of the robustness and uncertainty of model outputs. A methodology that contributes to improved understanding of the possible range of variability around a 'best estimate' supports a more robust interpretation of those model outputs in a decision making process. It has to be noted that this project did not generate probabilistic fire spread and impact estimates. This would involve quantifying the distribution of the error in the model parameters, and this was beyond the scope of the F.I.R.E-D.S.T. project. However, with that additional information, the methodology used by the FireDST system could be applied directly to generate probabilistic fire spread and impact estimates.

By addressing the questions above, the project therefore achieves the following outcomes.

1. Development of an integrated fire spread and impact assessment methodology and tool.
2. Incorporation of the ability to explore variability in key parameters as part of an integrated fire spread and impact modelling tool.
3. Demonstration of a product that provides a range of fire spread and impact, rather than a deterministic 'single point of truth'. This allows stakeholders to explore the potential benefits of such information, as well as issues around user requirements and adoption.
4. Improved understanding of the drivers of uncertainty in fire spread and impact modelling through sensitivity analysis of key input parameters.

5. Development of “proof-of-concept” for a system or approach that enables full uncertainty modelling, given the right input parameters. This includes an improved understanding of the information and system requirements for such a system.
6. Improved understanding of the information and system requirements for a future operational product based on (part of) FireDST. This could be either an integrated fire and smoke spread and impact system, or a system quantifying uncertainty around projected fire and smoke spread or impact, or a combination of the two.

The FireDST approach was validated in three case studies of historical fires. The case studies were selected based on their range of characteristics in terms of terrain and topography, fire severity and complexity of extreme fire weather.

2.3 Outline of this report

This report describes the results of the case study of the Kilmore East bushfire in Victoria on Black Saturday (February 2009). An overall summary of all the research across the entire project is contained in the F.I.R.E-D.S.T. Final Report (Cechet *et al.,* 2014).

The remainder of this introductory chapter will give more details on the historical Kilmore fire that was used for this case study. Chapter 3 describes the FireDST system that was used to address the research objectives. Chapters 4 to 11 discuss the results of the Kilmore Case Study. The work is broken up in the following components.

Chapter 4 discusses how FireDST enables *assessment and visualisation of the variability in the fire spread.* The FireDST system explores the uncertainties within fire spread and impact modelling. Key to this is to visualise the variability of the fire shape or impacts that reflects those uncertainties.

Chapter 5 discusses how FireDST enables *assessment of the sensitivity of the fire spread to the surface weather.* The project aimed to develop a methodology for integrating uncertainty in surface weather predictions into the FireDST system. The methodology was tested by assessing the sensitivity of the fire spread to surface weather conditions.

Chapter 6 discusses how FireDST enables *assessment of the sensitivity of the fire spread to the weather conditions in the upper atmosphere.* Upper level wind speed and direction are key drivers of the spread of embers from the fire. The project aimed to develop a methodology for integrating uncertainties in the wind direction and speed at different altitudes into the FireDST system.

Chapter 7 discusses how Fire DST enables *assessment of the sensitivity of the fire spread to fuel parameters.*

Chapter 8 discusses how Fire DST enables *assessment of the sensitivity of the fire spread to variation in ignition.*

Chapter 9 discusses *estimating the number of buildings and people exposed to the fire spread.*

Chapter 10 discusses the methodology used for *estimating house loss using a fire spread ensemble.*

Chapter 11 discusses an approach for *estimating the impact of occupant action on building damage in fires.* The ability of residents or fire-fighters to defend buildings significantly influences the chances that a home will survive a fire. The project aimed to model the impact of human behaviour as part of an integrated fire spread and impact assessment.

Chapter 12 discusses how FireDST *assess the sensitivity of smoke movement to the fire spread.* Smoke is a key component of bushfire impact, particularly through its consequences for human health. This project aimed to quantify the variability in smoke movement modelling as part of an integrated fire spread and impact assessment.

Chapter 13 discusses the main conclusions from the Kilmore case study against the original objectives of the work.

2.4 The 2009 Kilmore fire

A reconstruction of the Kilmore fire on 7 February 2009 has been detailed in a draft report for the Victorian Department of Sustainability and Environment (Gellie *et al.,* 2012). This draft report and associated data has been provided by the Victorian Government Department of Sustainability and Environment (DSE) for use by the project team for FireDST project purposes only. The Kilmore fire is detailed from pages 98 to page 125 in that report. This reconstruction is used in all modelled fire comparisons.

This section provides a brief outline of the 7 February 2009 Kilmore fire. The context of the Kilmore fire as described in Gellie *et al.,* (2012) is:

"The Kilmore East Fire is estimated to have started at 1145 hours following a power line failure at power pole 38 on the Pentadeen power line north of Saunders Road in Kilmore East (Victorian Bushfires Royal Commission, 2010). The fire crossed the Hume Highway, passing to the north of the township of Wandong as it moved towards Mount Disappointment. From there, the fire travelled in a south-easterly direction until 1745 on 7 February, when a cool change arrived on the fire ground, transforming the eastern flank into a 50-km-long head fire moving towards the communities of Clonbinane, Kinglake, Strathewen, Steels Creek and Dixon Creek. Before the end of the day, the fire burnt through an estimated 86,965 ha, resulting in 119 fatalities, 232 casualties."

ARC-GIS shape files were provided as part of the reconstruction report and the reconstructed fire isochrones were used in all simulation shape comparisons. Figure 2.2 to Figure 2.5 provide an outline of the major stages of the Kilmore fire.

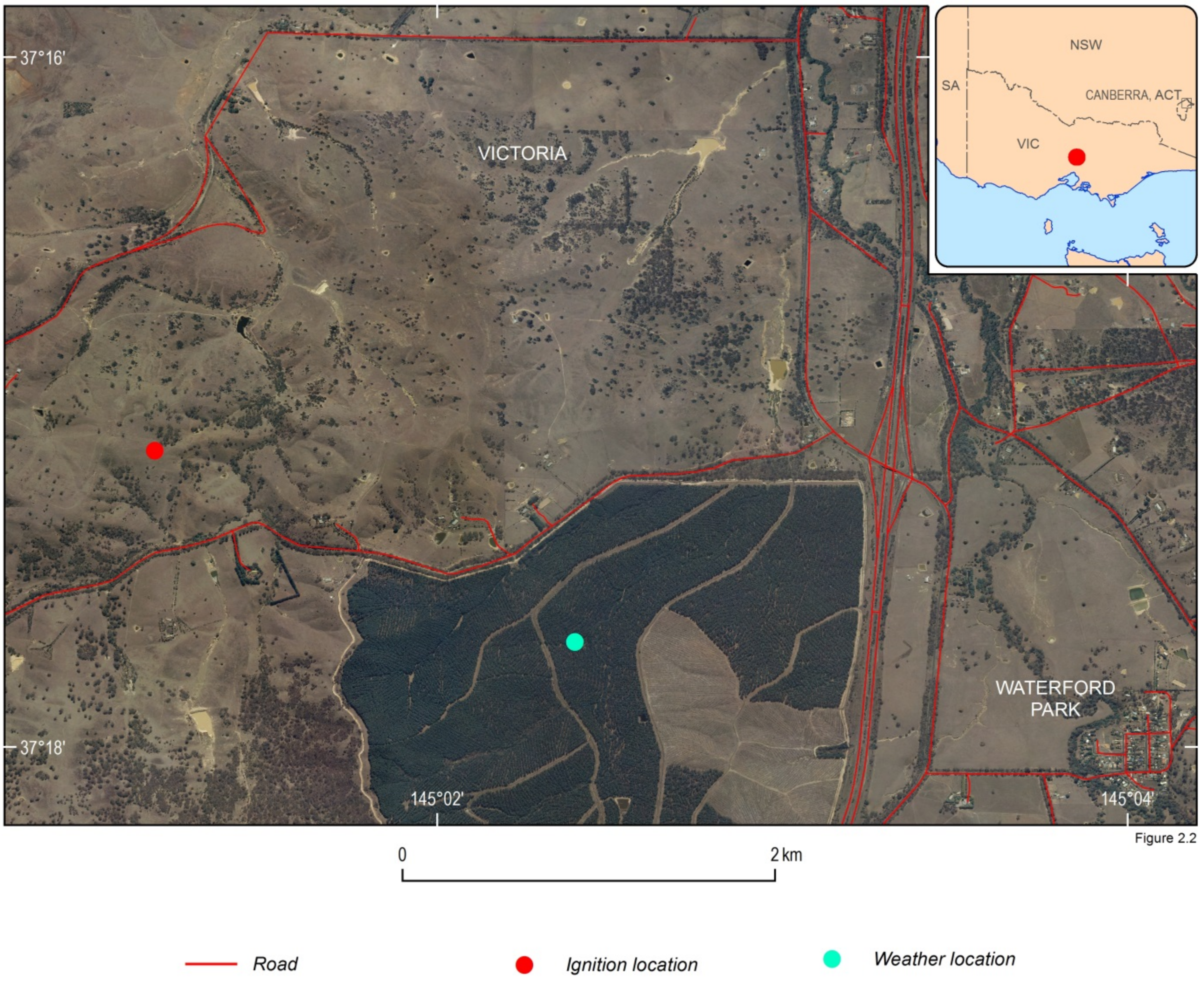


Figure 2.2 Kilmore fire ignition location.

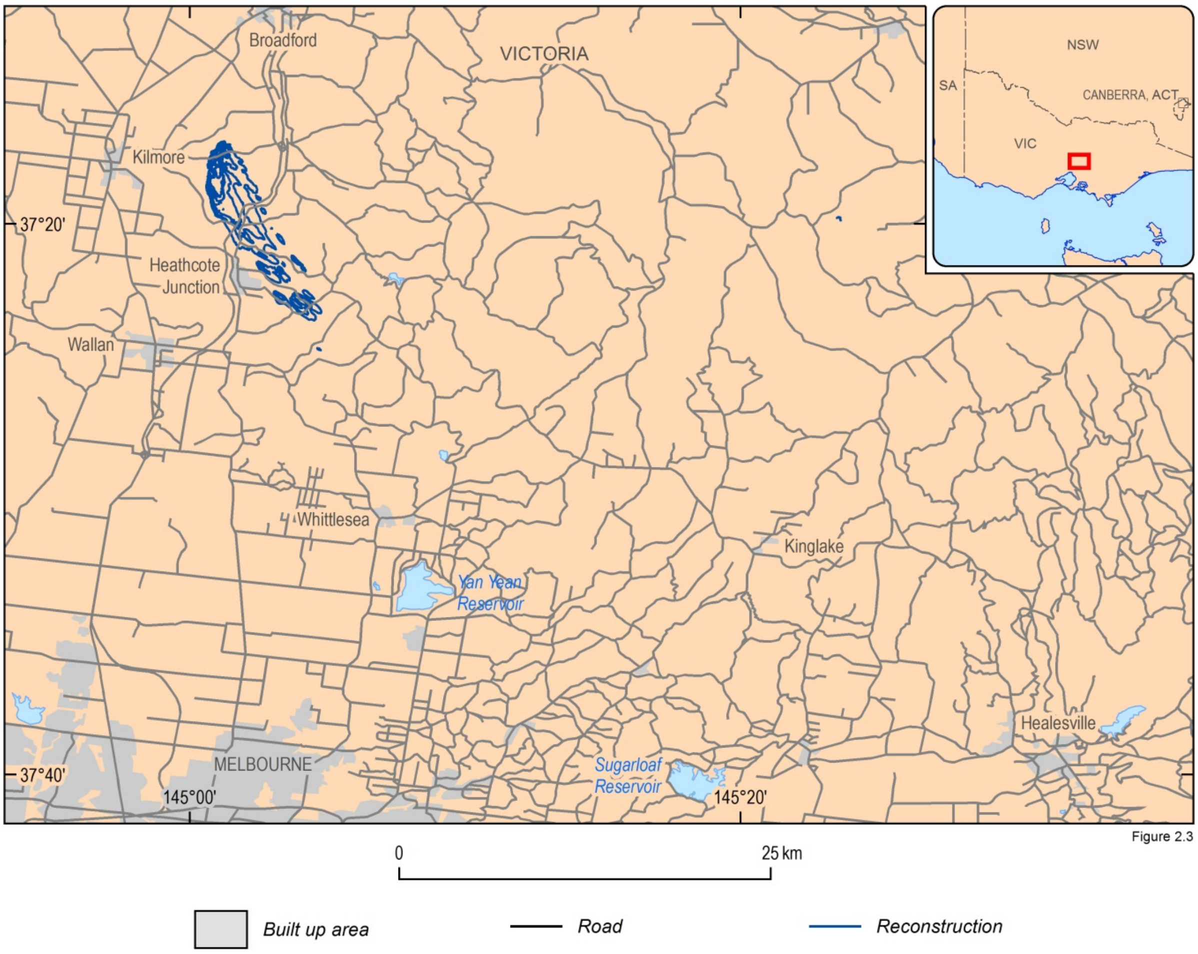


Figure 2.3 Reconstructed progress of the Kilmore fire as it progressed to 15:00 to the north of Wandong/Heathcote Junction (isochrones source Gellie et al., 2012).

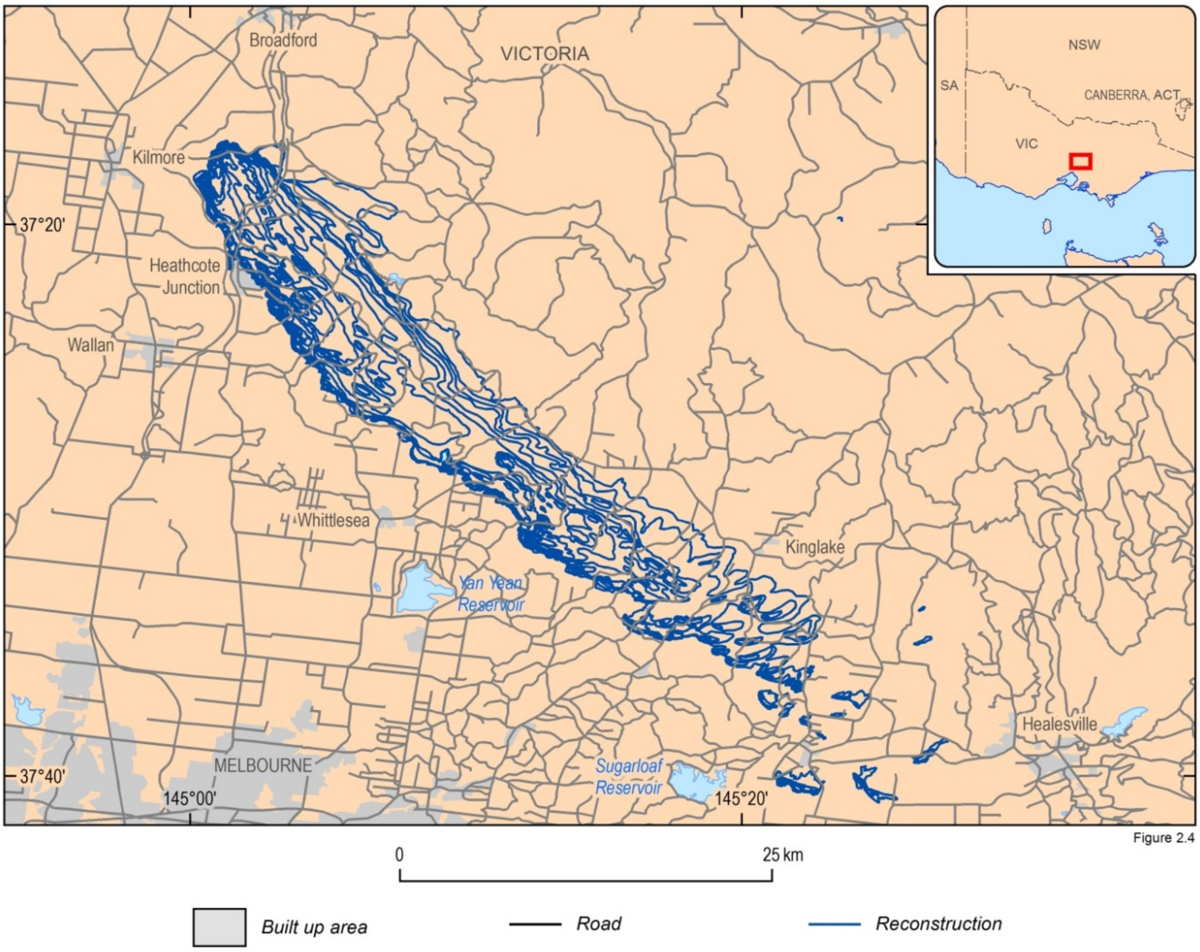


Figure 2.4 Reconstructed progress of the Kilmore fire as it progressed to 18:00 hours on 7 February 2009 (isochrones source Gellie et al., 2012).

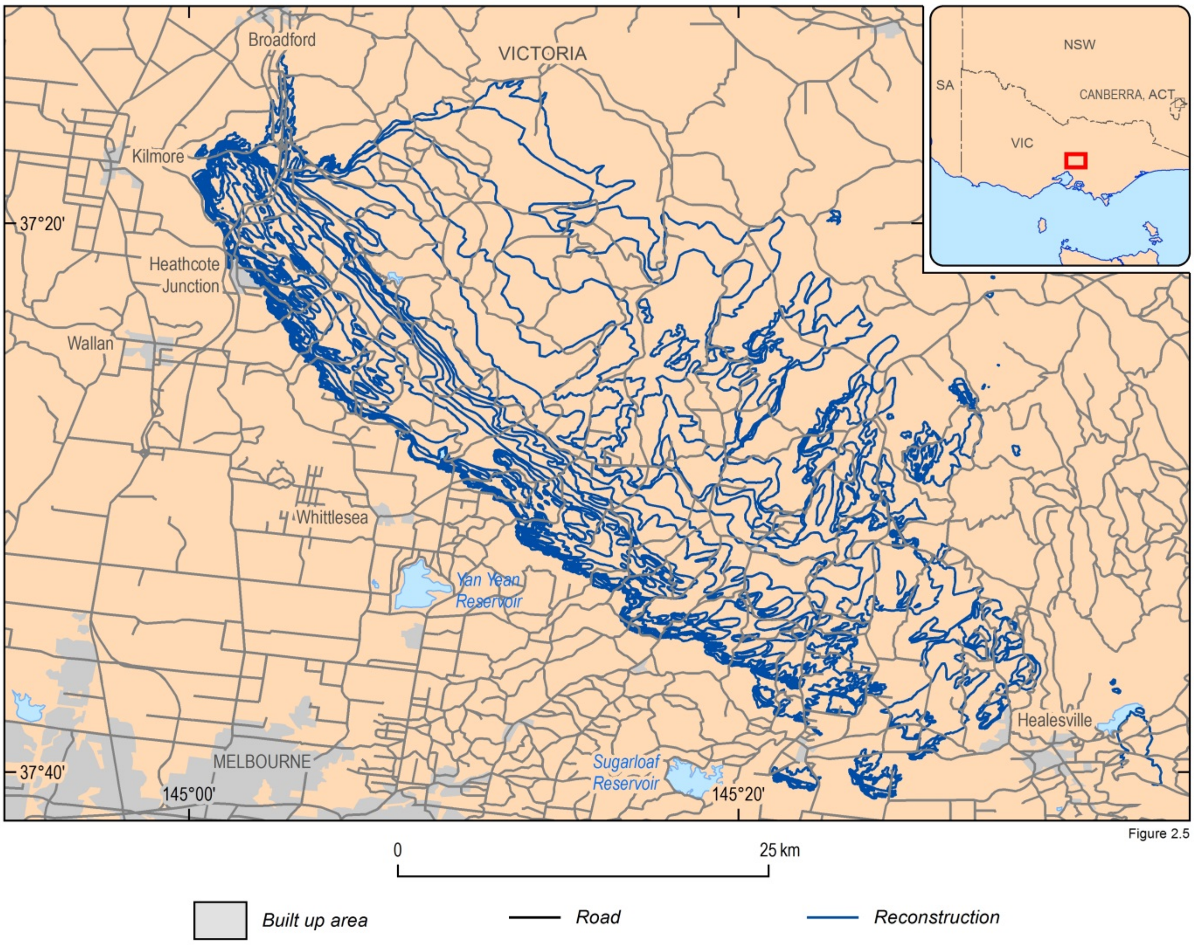


Figure 2.5 Reconstructed progress of the Kilmore fire from 1800 to 2130 – showing the wind direction change (isochrones source Gellie et al., 2012).

3 The FireDST system

The development of the proof-of-concept FireDST system represents a key achievement of the F.I.R.E-D.S.T Project. The FireDST system integrates the project's research components and enables the research objectives to be addressed (see Section 2.2). This section discusses FireDST and its inputs and outputs. Later chapters examine each of the research questions in turn.

The core of the FireDST functionality is built around its ability to model a fire spread and estimate the fire's impact. One of FireDST's distinguishing features is its ability to generate multiple scenarios of possible fire spread. FireDST creates 'ensembles' of fire spread scenarios by applying variations to the modelling input parameters or modelling assumptions.

Figure 3.1 displays the information flow in the FireDST system. The next sections give more detail on the system.

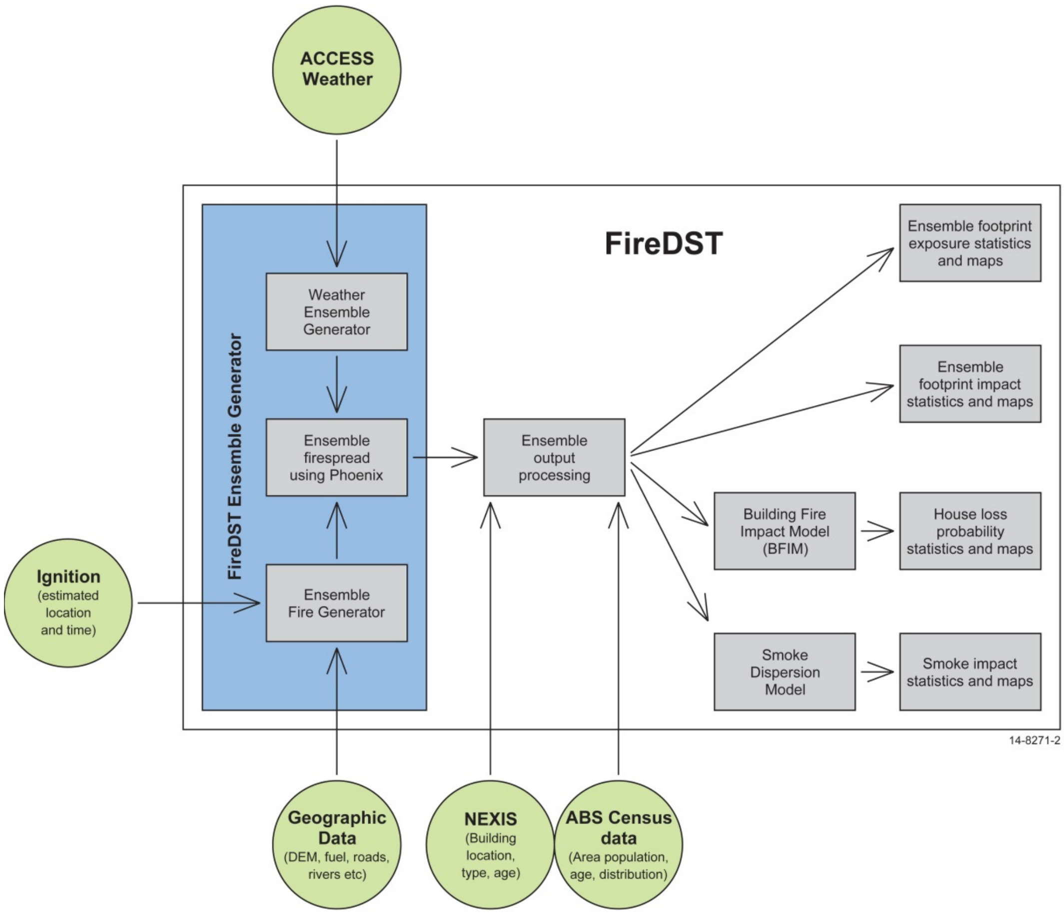


Figure 3.1 Information flow in FireDST.

3.1 FireDST input information

This section briefly describes the nature and source of the input data for FireDST. To model the fire spread, the system ingests information on the location and timing of a fire's ignition as well as the fuel and the weather at the time of the fire (see Figure 3.1). To model the impact of the fire, the system requires information on the exposed assets. This information is stored by FireDST in three input databases (shown outside the largest dashed box at the bottom of Figure 3.1), Geographic Data (vegetation and fuel type), and exposure data, based on NEXIS and ABS census data.

The Bureau of Meteorology supplied information on the meteorology during the Kilmore event, based on a weather model run for the conditions at the time. The Bureau of Meteorology numerical weather prediction model is known as ACCESS (Australian Community Climate and Earth-System Simulator) (Puri, 2011). ACCESS files are currently produced nationally at twelve km resolution with hourly time steps every six hours. A set of files is produced for the temperature, humidity, wind speed and wind direction at ten metre height. For this case study, research ACCESS files were specifically generated for a 48 hour period from 11am on 6/2/2009 at grid resolutions $0.036^{o,}$ 0.012^{o} and 0.004^{o} (which is approximately 4000m, 1200 m and 440m) at five minute time steps. In addition the Bureau of Meteorology provided extra research information about the conditions in the atmosphere i.e. wind speed and wind direction at 50 different altitudes in the atmosphere were modelled for the 4000 m resolution ACCESS simulation at 15 minute intervals.

The geographic information ingested by FireDST can be split into two categories: data for the fire spread simulator PHOENIX RapidFire (Tolhurst *et al*., 2010) and data for the visualisation of the output maps. PHOENIX RapidFire input data includes a vegetation database (10 m grid), disruptions database(10 m grid), asset database (10 m grid), digital elevation model (DEM 100 m grid) and fire history database (10 m grid). Most of this information was supplied for the Kilmore case study by the University of Melbourne.

The visualisation data consists of ArcGIS shape files that show items such as roads, rivers, railways and lakes. This information was supplied electronically by Geoscience Australia from their 250K map series (www.ga.gov.au). The information allowed the visualisation of the fire simulations and ensembles in the context of the Kilmore region.

Ignition location and timing was sourced from the Kilmore fire reconstruction report (Gellie *et al.,* 2012).

The exposure database in FireDST contains information on all assets that are exposed to the fire, that is, people and buildings. Geoscience Australia supplied building information sourced from the National Exposure Information System (NEXIS) (Nadimpalli, 2007; Canterford, 2011). Population statistics were extracted from the 2006 Australian Bureau of Statistics Census at the Collection District reference level and allocated as an average to all the individual houses in that collection district. This information was then used to calculate exposure and loss statistics for the ensemble.

3.2 FireDST Information flow - overview

The FireDST approach of creating multiple scenarios for a single event is implemented by the Ensemble Generator, comprising the Weather Ensemble Generator and the Ensemble Fire Generator (Figure 3.2). An ensemble refers to a set of different individual fire scenarios, in this context exploring potential variation in the parameters that specify the fire conditions. The Weather Ensemble Generator creates a set of different weather scenarios, referred to as the weather ensemble. It is based on permutations of the originally supplied weather. The Fire Ensemble Generator creates an ensemble of different fire spread scenarios. The fire spread scenarios in the ensemble are based on variations of the specified ignition location, ignition time, vegetation, and the weather permutations created by the Weather Ensemble Generator.

For each scenario in the ensemble, the fire spread is simulated using the PHOENIX RapidFire fire spread model. The complete process is described in more detail in the next section. Once FireDST has simulated an ensemble of fire spread scenarios, there is a variety of ways of viewing the ensemble fire spread information either as a map or statistics. FireDST can display statistics and maps of residents and structures exposed to the ensemble fire spread. The system also analyses the potential fire impact at the building level using a newly developed system, the Building Fire Impact Model (BFIM). The BFIM is described in more detail in Appendix E.

Finally, a FireDST ensemble (including the individual fires) can be passed to a numerical model that models the atmospheric spread of gaseous fire combustion materials such as smoke, ozone, particles smaller than 2.5 microns (PM 2.5) , Nitrogen monoxide (N0) and carbon dioxide (CO2) (supplied by CSIRO Marine & Atmospheric Research). The CSIRO model and results are described in the final report (Cechet *et al.,* 2014). Individual fire outputs of the CSIRO model are overlayed to produce ensemble maps that show the spatial distribution of the concentration of the various products of bushfire combustion as well as the impacted population. This type of information could potentially assist in managing public health warnings and the movement of people and emergency service teams. The ensemble view of the smoke combustion products is generated in a similar way to the generation of the ensemble fire spread (see Chapter 11).

3.3 FireDST Ensemble Generator

This section describes how FireDST creates an ensemble view of the selected fire scenarios using the Weather Ensemble Generator, the Fire Ensemble generator, the fire spread simulator PHOENIX RapidFire and the Ensemble View Generator (Figure 3.2).

3.3.1 Weather Ensemble Generator

The Weather Ensemble Generator (Figure 3.2) varies the weather conditions to produce different weather scenarios. The permutation is based on simple rules, for example: increasing wind speeds by five metres per second, or increasing the temperature by two degrees. More complex weather scenarios are created using combinations of varied humidity, temperature, and wind speed or wind direction parameters.

The resultant weather ensemble is stored by the FireDST system as a set of alternative weather files. Storage allows different combinations of weather to be used by the Ensemble Fire Generator. In this case study, the weather ensembles were generated by perturbing the historical conditions for the Kilmore fire, as specified in the ACCESS files provided by the Bureau of Meteorology. The variability used to generate the ensembles for this case study was based on an initial assessment of the likely range; within that range the probability distribution was assumed to be ‘flat’ (all values have equal probability). Chapters 5 and six discuss the generation of ensembles by the FireDST Weather Ensemble Generator for the surface weather (Chapter 5) and the conditions in the vertical atmosphere (Chapter 6).

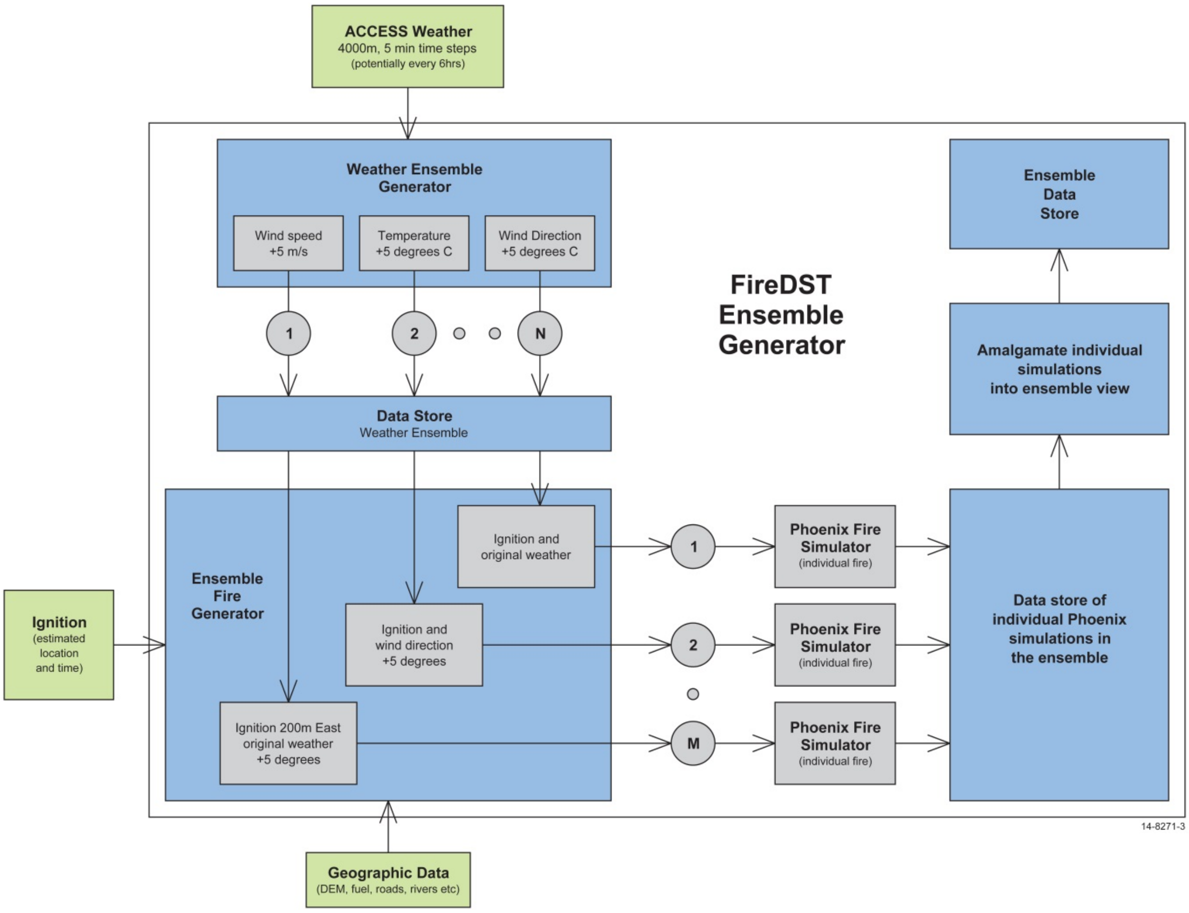


Figure 3.2 The FireDST Ensemble Generator.

3.3.2 Ensemble Fire Generator

Analogous to the perturbation of the weather, the Ensemble Fire Generator creates an ensemble of scenarios by varying the ignition point parameters. The case study described in this report created an ensemble by varying the historical ignition point and time for the Kilmore fire. As above, the range of perturbations used in this case study were based on an initial assessment of likely range of error of the parameters; within that range the probability distribution was assumed to be ‘flat’ (all values had equal probability).

The FireDST Ensemble Fire Generator can also perturb the vegetation conditions by varying fuel load and curing parameters. All these scenarios can be modelled separately and have to be combined with a set of weather from the Weather Ensemble Data Store. The Ensemble Fire Generator creates a specific PHOENIX RapidFire input file defining the combinations of parameters to be used in the individual simulation. This input file allows further modification of wind speed based on the local terrain/topography using the Wind Ninja system (Forthofer *et al.*, 2009).

3.3.3 Fire spread simulation

For each of the individual scenarios in the ensemble, FireDST simulates the fire spread using PHOENIX RapidFire V4.0 (Tolhurst *et al.*, 2010). This requires spatial information, including a vegetation grid (10 m resolution supplied by the Victorian Department of Sustainability and

Environment), the digital elevation model (100 m grid resolution), areas where roads have decreased the amount of fuel in a cell, and fire history database (180 m resolution all supplied by The University of Melbourne). Chapter 7 provides more details on the spatial information and examines the sensitivity of fire spread and impact to this information.

The V4.0 PHOENIX RapidFire model includes a module which simulates the impact of suppression by emergency services teams that “attack” the flanks at the back of the fire in equal proportion on each flank. The impact of the suppression module could potentially amplify or mask the sensitivity of the fire spread modelling as length of the flanks will differ between scenarios. To enable like-for-like comparison across scenarios in an ensemble, the suppression component was deactivated in FireDST. Therefore, none of the results reported in this document consider suppression activities in the fire spread modelling.

3.3.4 Ensemble View Generator

The FireDST Ensemble Generator takes all the individual fire spread simulation results for the ensemble and produces an ensemble footprint of the complete collection of simulations in the ensemble. This shows the range of locations that will be burnt, based on the scenarios in the fire ensemble. This ensemble footprint is computed by overlaying the individual simulated fire spread extents. Figure 3.3 shows an example of how an ensemble burn extent is derived from four fire shapes. Initially, locations within each fire shape are allocated a value of one; locations outside the shape are set to zero. Two shapes are combined by summing the location values. Thus, locations where both fires overlapped are assigned a value of two, areas where the fires did not overlap are set to one, and locations that did not burn in either simulation are given a value of zero. The process is repeated for all the fire shapes in the ensemble. The percentage overlap in the final shape is calculated by converting the numbers in the overlap shapes to a percentage of the total number of fires in the ensemble. The percentage shape is then displayed as ESRI ArcGIS shape files in percentage intervals (e.g. increments of 5%, or 10%, or 25%).

The FireDST system can display the ensemble view at various steps through the simulated timeframe (to identify the fire progression) and at different percentage bins. Chapter 4 discusses assessment and visualisation of ensemble fire spread for the Kilmore fire.

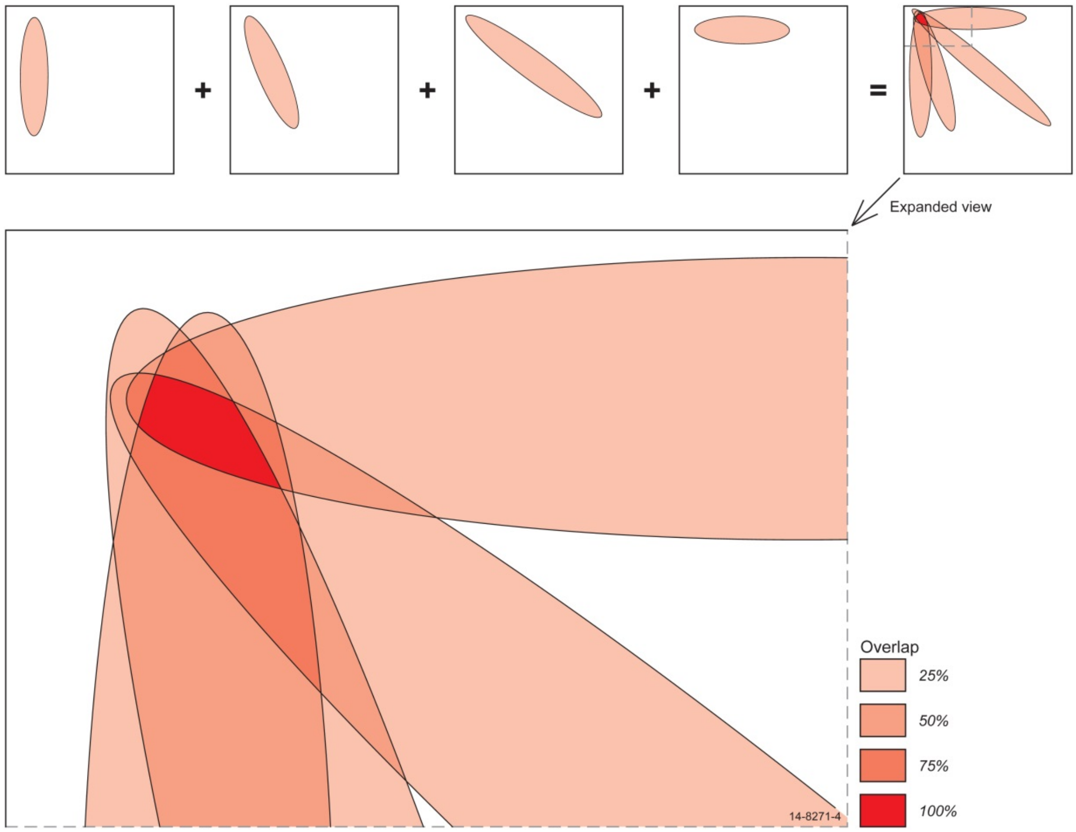


Figure 3.3 Example of how an ensemble shape footprint extent is produced. The polygons show the fire spread of individual simulations.

3.4 FireDST system implementation

This section provides a brief overview of the software implementation of the proof-of-concept FireDST system. FireDST is constructed using Python 2.6.2, PHOENIX RapidFire v4.0 and ArcGIS V10.0.

All components (shown in Figure 3.1) except the Weather Ensemble Generator were developed on the MicroSoft Windows XP platform. The choice of platform was imposed by PHOENIX RapidFire, which is written in .NET, with limited or no option of running it on other platforms. The FireDST Ensemble Main Control Panel (Figure 3.4) manages the interaction with the user, and there is no direct interaction between the user and PHOENIX RapidFire or any other components of FireDST.

The FireDST Weather Ensemble Generator was developed for the Unix Ubuntu system. This decision was driven by the choice to use the Unix-based package NCO Tools to manipulate the ACCESS NetCDF Weather files. The output weather ensemble files are then transferred to the Microsoft Windows XP system as input into FireDST.

When FireDST is started, the user is asked to select a case study and then an ensemble of scenarios that make up an ensemble fire spread. Then FireDST opens and displays a main control panel, a visual control panel and the ArcGIS view of the ensemble (Figure 3.4). The main output for FireDST is delivered in ArcGIS (version 10.0) as this was a common platform in emergency service agencies.

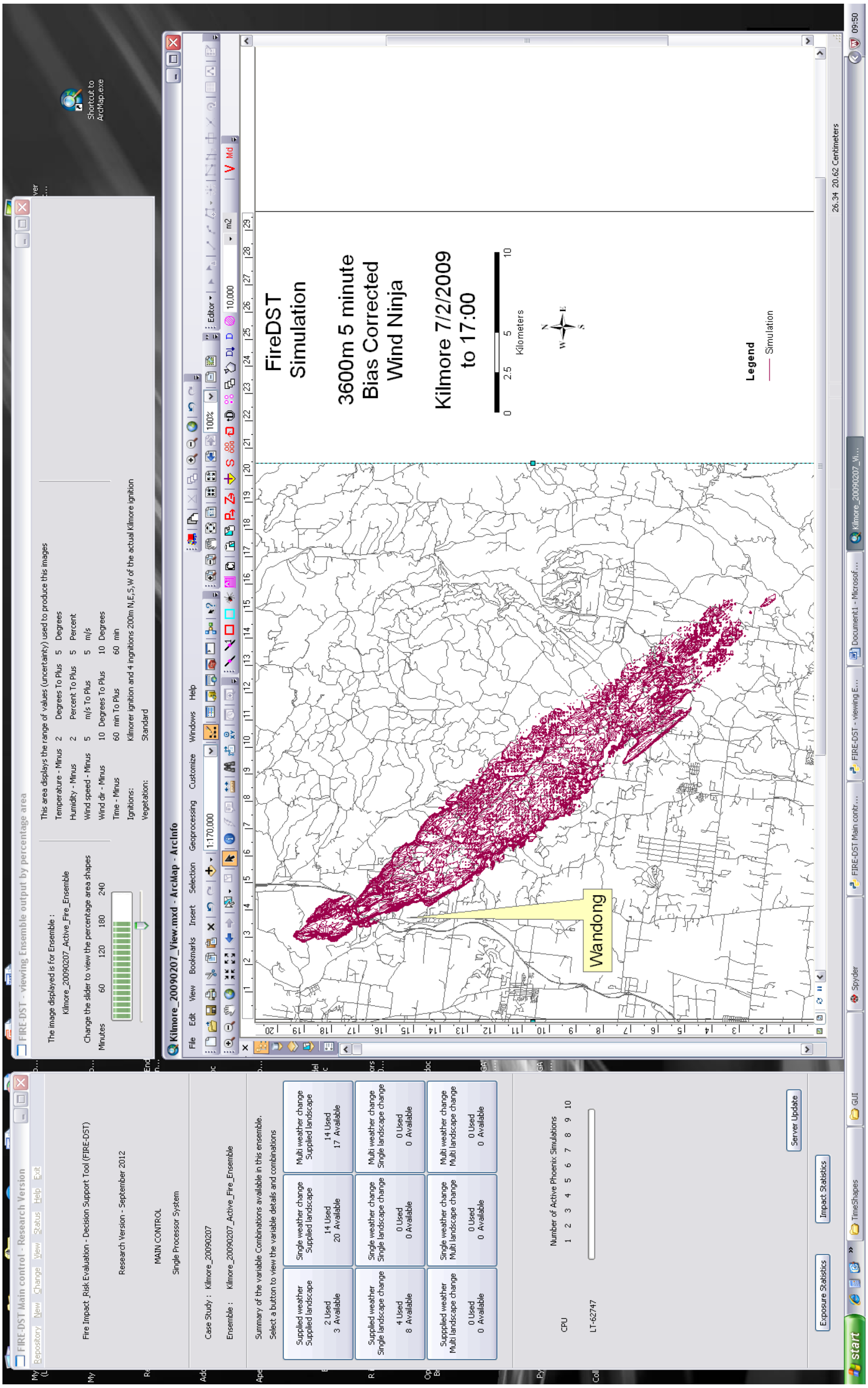


Figure 3.4 Full screen layout for FireDST.

The FireDST main control panel (Figure 3.4) maintains the standard Windows XP look and feel, with the main functions appearing in the menu bar at the top of the window. The nine large buttons in the centre of the FireDST main control panel (Figure 3.5) allow the user to select what simulations are included in the ensemble. The nine functions provide an efficient way to manage the complex number of individual simulations that can form an ensemble. The functions allow the user to change the ensemble contents or create a new ensemble.

The exposure statistics and impact statistics functions produce statistics for the current ensemble's footprint.

Top row (left to right)

Button 1 – Supplied ACCESS Weather simulations and supplied landscape

Button 2 – Single Change in Weather and supplied Landscape

Button 3 – Multiple changes in weather and supplied landscape

Middle row (left to right)

Button 4 – Supplied weather and single change in landscape

Button 5 – Single change in weather and single change in landscape

Button 6 - Multiple changes in weather and single change in landscape

Bottom row (left to right)

Button 7 - Supplied weather and multiple changes in landscape

Button 8 – Single weather change and multiple changes in landscape

Button 9 - Multiple changes in weather and multiple changes in landscape

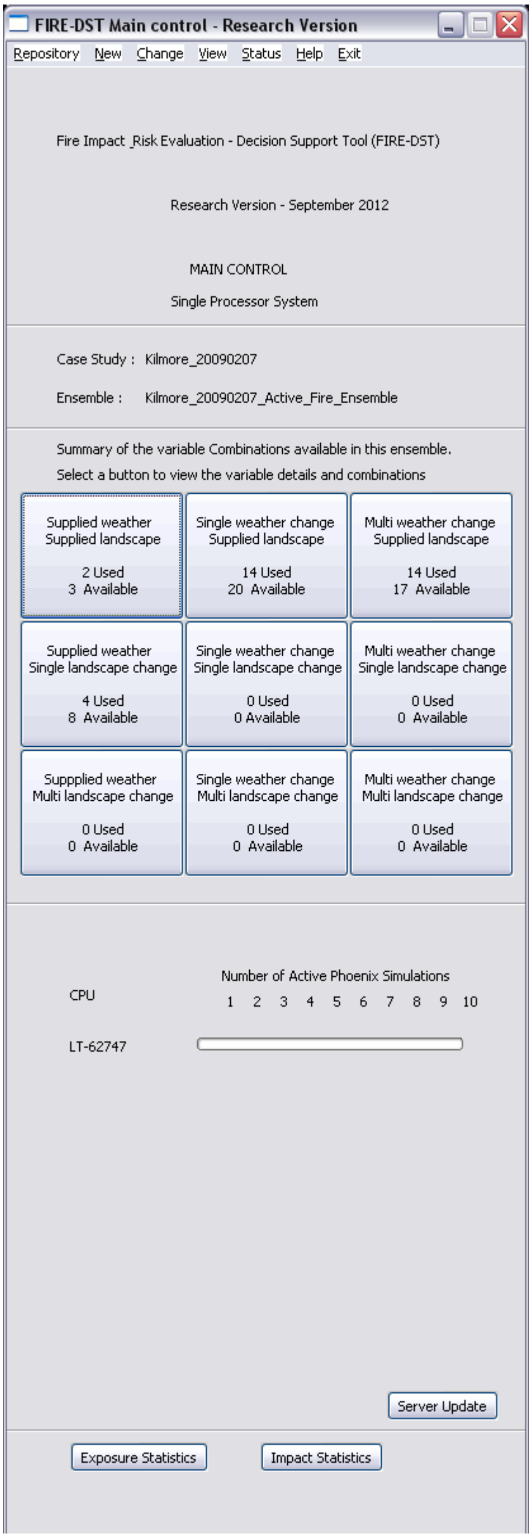


Figure 3.5 FireDST Main Control Panel.

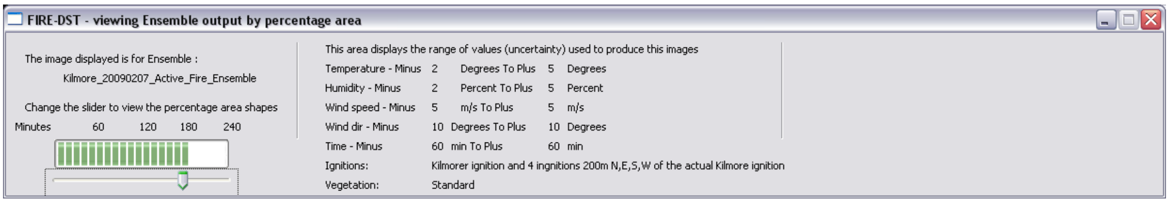


Figure 3.6 Viewing ensemble control panel.

Once an ensemble is selected a window appears that controls the visualisation of the ensemble (Figure 3.6). This window contains a slider that allows the user to step the ensemble through time in increments of 60 minutes up to four hours ahead of the start time of the simulation. The window also displays the outer bounds of the parameters used in the ensemble.

3.5 FireDST research code

The F.I.R.E-D.S.T project was funded by the Bushfire CRC. The FireDST research code produced in this project is included as a deliverable of the project and can be accessed on request through the Bushfire CRC.

The following chapters discuss the research questions outlined in Section 2.2. An overall summary of all of research for each of the project teams is contained in the F.I.R.E-D.S.T Final Report (Cechet *et al.,* 2014).

4 Assessing and visualising variability in the fire spread

4.1 Objective

FireDST was designed to generate an ensemble of scenarios, that is: different realisations of the potential fire spread based on variations in the conditions in which the fire occurs. The output from FireDST can be used to assess the sensitivity of simulated fire spread to the conditions surrounding the fire, for example meteorology or the fuel conditions. A system such as FireDST is an essential part of the ability to investigate uncertainty into fire spread modelling. This chapter investigates how to visualise the variability in the ensemble fire spread.

The work described in this chapter used the Kilmore 2009 fire as a case study for:

- Developing the techniques to create an ensemble simulation of bushfire spread.
- Creating a “proof-of-concept” system for the generation, management, and analysis of ensemble fire spread and impact.
- Understanding the potential benefits of ensemble fire spread modelling.

For a full uncertainty analysis, the variability would be determined by the probability distribution of the error in particular parameters. This fell out of the scope of this study.

4.2 Methodology

4.2.1 Background

As described in the Introductory chapter of this report, the last few decades has seen the development of computerised bushfire spread models that produce a single simulation of the fire spread. These models include PHOENIX RapidFire (Tolhurst *et al*., 2008) in Australia, FireSite (Finney, 1998), FlamMap (Finney, 2006), WFDSS- FSPro (Wildland Fire Decision Support System- Fire Spread Probability Model) (McDaniel, 2007) in the USA, and Prometheus, the Canadian wildland fire growth simulation model (Tymstra *et al*., 2009). All are able to assimilate information on the environmental and meteorological conditions to compute the progress of the fire as a single graphical output.

FireDST is a “proof-of-concept” system that generates an ensemble of scenarios by perturbations in the input parameters to the fire spread model. The resulting ensemble fire spread summarises the variability in the predicted fire spread, specifying for each location in what proportion of the scenarios it was burnt. Mapping the ensemble fire spread illustrates the sensitivity of the fire spread to the variation of the input parameters used to create the ensemble. With the correct input parameters, the ensemble fire spread represents the probability that a location will be burnt.

This chapter discusses the method that was developed to visualise the ensemble output information in more detail.

4.2.2 Method

The methodology to create fire spread ensembles using the FireDST Ensemble Generator is described in Chapter 2. In this case study, the fire spread ensemble was a set perturbation range in the input parameters. As described in Chapter 2, the ensemble members are considered to be equally likely. Where a location is burnt in all scenarios in the ensemble, the ensemble fire spread scenario is 100 percent; where it is burnt in some but not all scenarios, the location value is proportionally lower.

4.3 Results and Discussion

4.3.1 Ensemble visualisation

Figure 4.1 shows one ensemble of 30 scenarios for the Kilmore fire. The fire spread footprint is displayed in intervals of 25 percent coincidence of the individual scenarios (see Appendix B for detail). The next section compares the ensemble and the reconstruction of the historical fire spread.

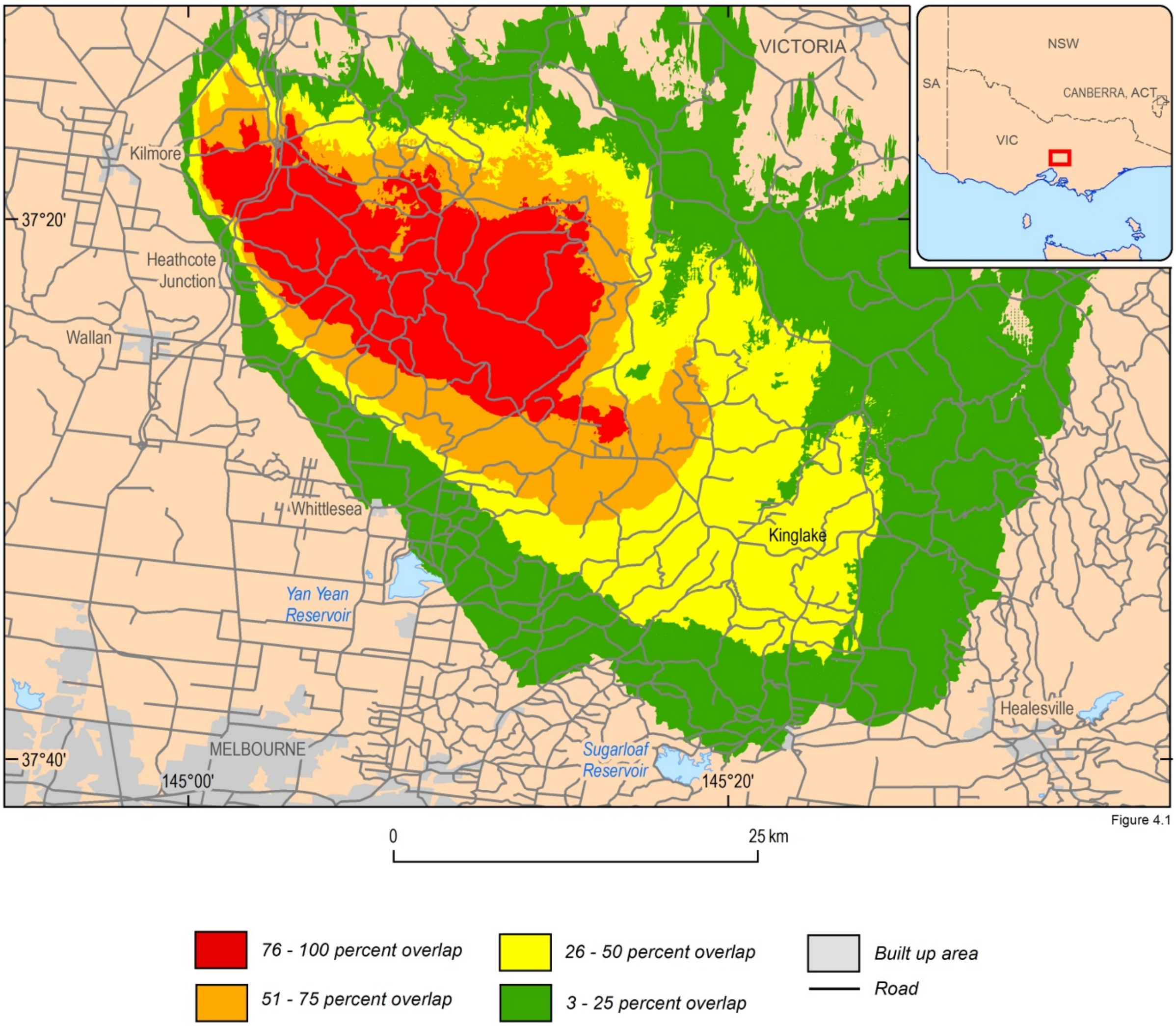


Figure 4.1 An ensemble view of the Kilmore fire using a 30 member ensemble to 9:45 PM (10 hours after ignition).

4.3.2 Comparison of ensemble and reconstruction

The Kilmore fire of 7 February 2009 was studied post fire in great detail due to the Coroner's inquest and the Victorian Bushfire Royal Commission. A reconstruction of the fire is described briefly in Chapter 2. There is not a good match between modelled and historical fire spread if the fire spread for the 2009 Kilmore event is modelled deterministically, i.e. as a single model run based on the conditions at the time the fire occurred. This is likely to be due to uncertainties and inaccuracies in the parameter estimates of those historical conditions (as discussed in Chapters 5 and 6), as well as the internal parameterisation of the fire spread.

Figure 4.2 displays the reconstructed fire scar at 15:50 (3:50PM) against the 30 member ensemble fire spread for that time. The fire reconstruction falls within the range of the ensemble fire spread. This provides some validation that the FireDST approach to creating the ensemble, as well as the range of parameter values used to generate it can lead to realistic results.

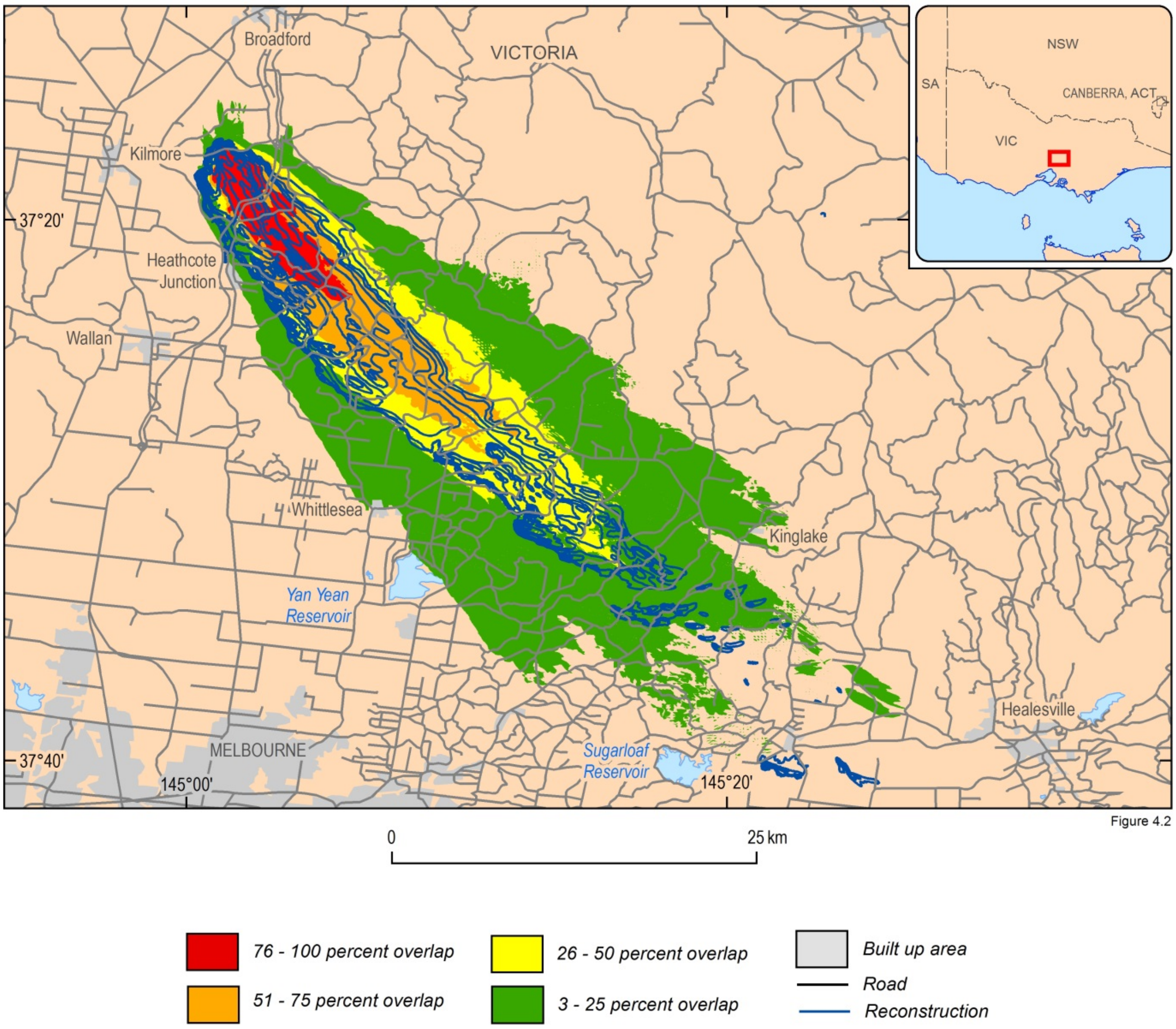
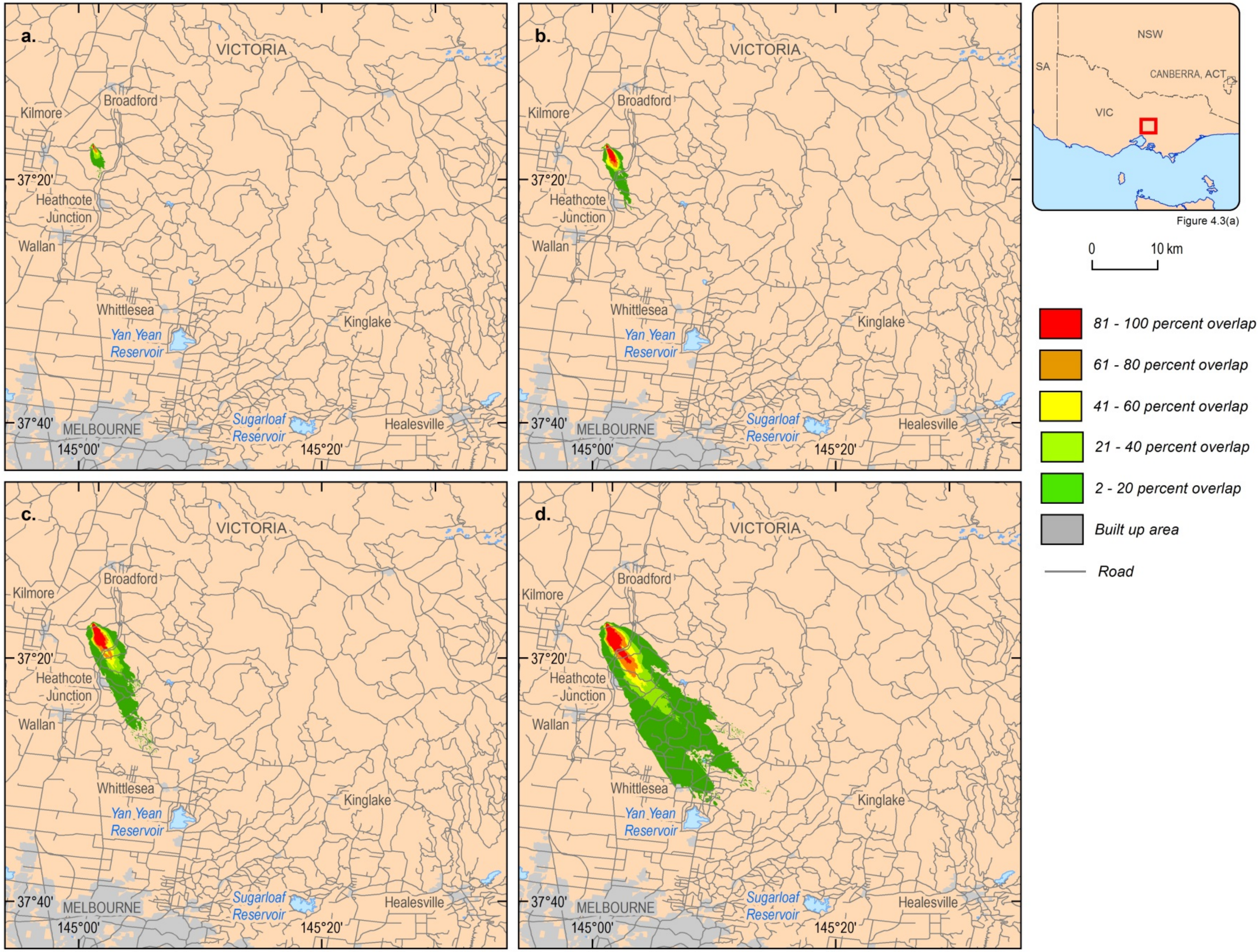


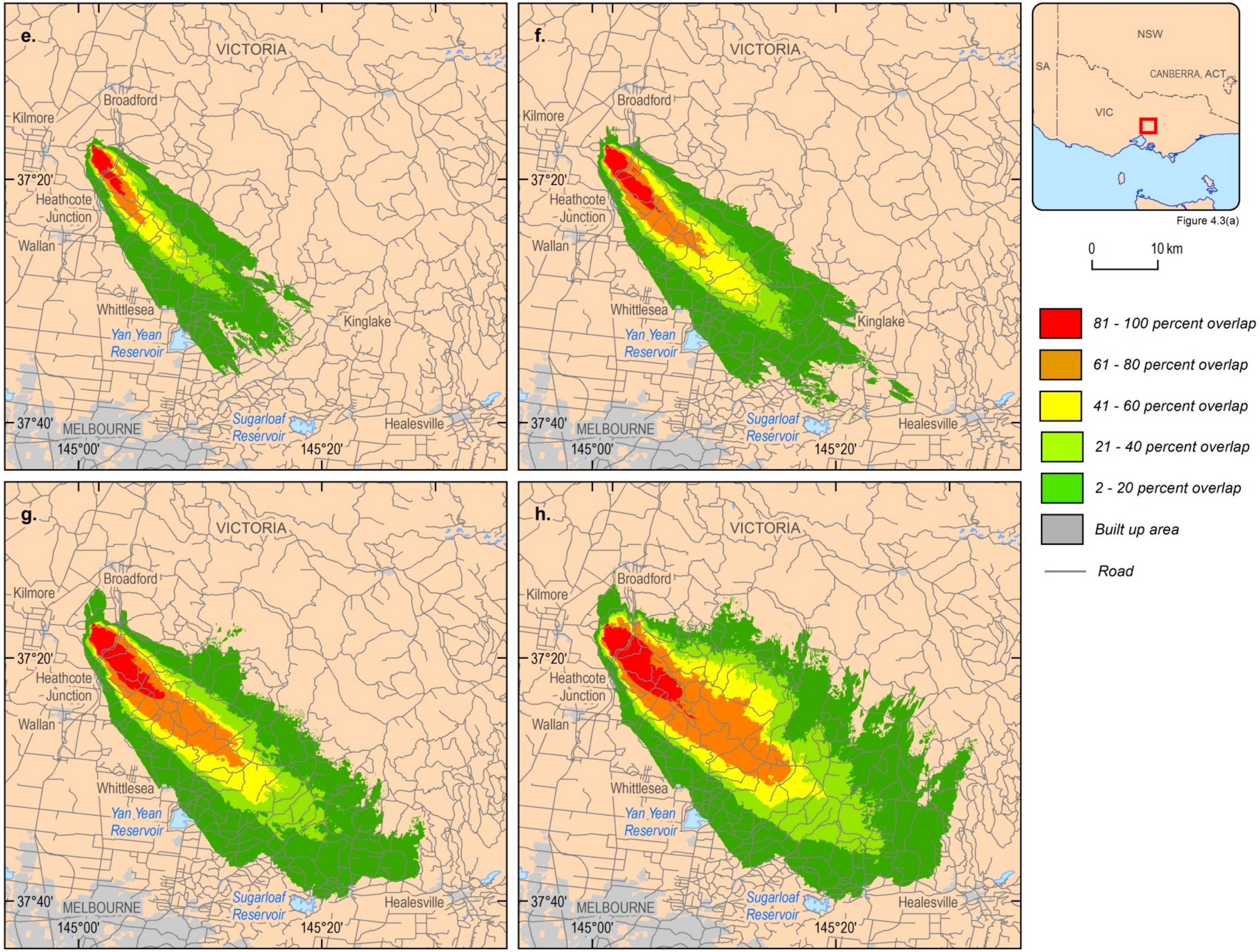
Figure 4.2.Ensemble footprint for the Kilmore fire overlayed with the reconstruction of the Kilmore fire to 3:50PM.

4.3.3 Ensemble visualisation through time

FireDST can display the ensemble spread at selected time intervals. Figure 4.3 displays hourly time step ensemble output for the 30 member ensemble fire shape shown in Figure 4.1. Figure 4.3 demonstrates that the range of predicted fire spread increases between ensemble members as time progresses. This reflects incremental impact over time of the different parameters on the fire spread.



a.
b.
c.
d.
VICTORIA
Broadford
Kilmore
37°20'
Heathcote
Junction
Wallan
Whittlesea
Yan Yean
Reservoir
Kinglake
37°40'
MELBOURNE
Sugarloaf
Reservoir
Healesville
145°00'
145°20'
NSW
SA
CANBERRA, ACT
VIC
Figure 4.3(a)
0
10 km
81 - 100 percent overlap
61 - 80 percent overlap
41 - 60 percent overlap
21 - 40 percent overlap
2 - 20 percent overlap
Built up area
Road


e.
f.
g.
h.
VICTORIA
Broadford
Kilmore
37°20'
Heathcote Junction
Wallan
Whittlesea
Yan Yean Reservoir
Kinglake
37°40'
MELBOURNE
Sugarloaf Reservoir
Healesville
145°00'
145°20'
NSW
SA
CANBERRA, ACT
VIC
Figure 4.3(a)
0
10 km
81 - 100 percent overlap
61 - 80 percent overlap
41 - 60 percent overlap
21 - 40 percent overlap
2 - 20 percent overlap
Built up area
Road

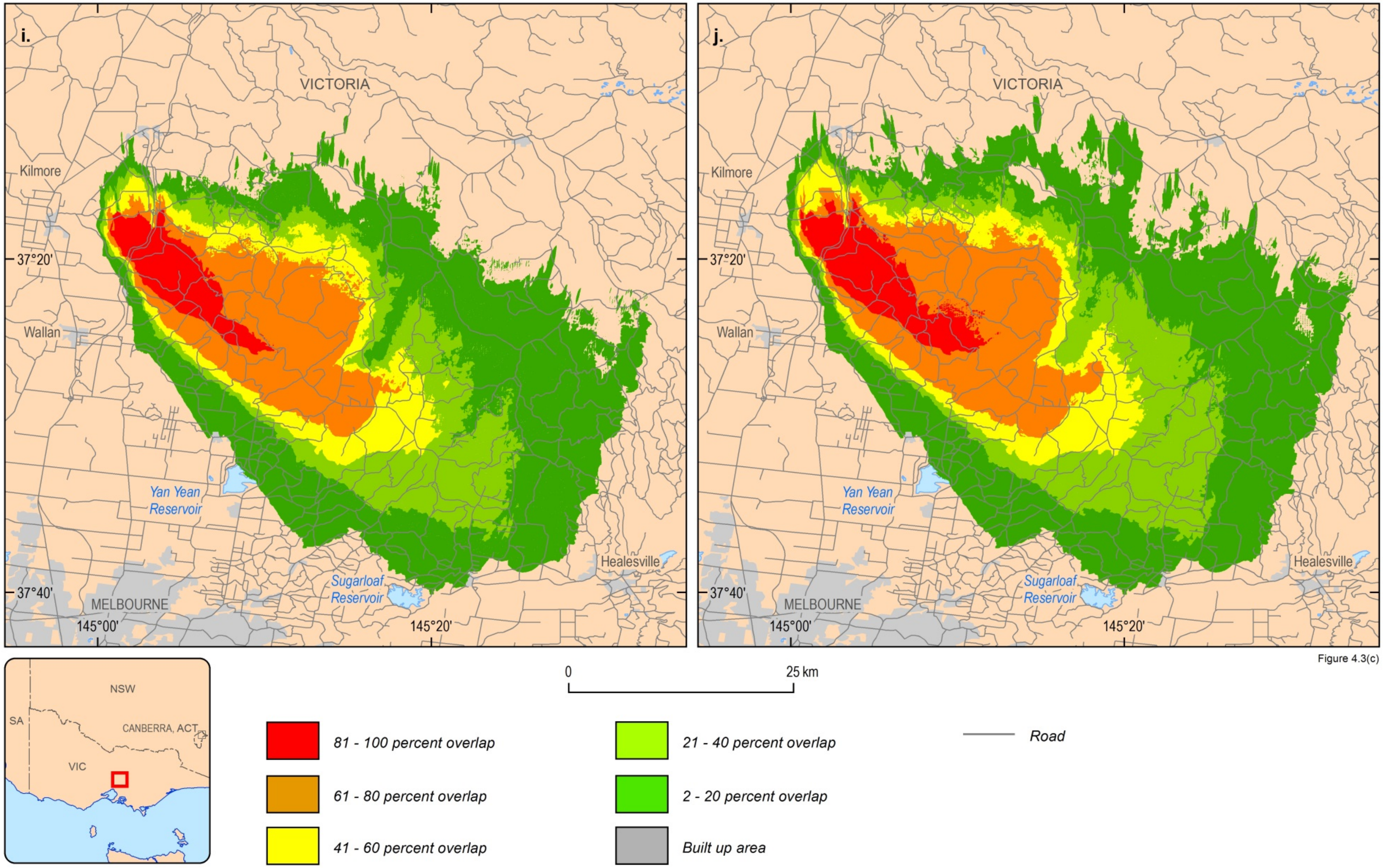


Figure 4.3 Ensemble views hourly through time of the potential fire spread.

4.3.4 Ensemble fire spread – sensitivity to input range

Figure 4.4 and Figure 4.5 demonstrate how ensemble information contributes to an understanding of the sensitivity of fire spread modelling. Both figures show the ensemble fire spread, generated by sampling two scenarios in temperature (Figure 4.4) and wind speed variability (Figure 4.5), respectively. The size of the difference between the scenarios is an indication of the sensitivity of the modelled fire spread to the perturbation of the input parameters. For example, Figure 4.4 shows the that the fire spread is not very sensitive to a change in temperature, as using an ensemble with +/- five degrees produces only a slightly smaller shape that using +/- ten degrees. In context of the event, this is not too surprising because the temperatures on the 7/2/2009 were already extreme (Cechet *et al.,* 2014) and there had been an extremely long duration of days with high temperatures prior to the 7/2/2009.

In comparison, Figure 4.5 however shows that the fire spread was sensitive to a wind speed change, as the difference between the scenarios is relatively large. This sensitivity was shown particularly when the fire entered the National Park where the terrain was more varied. The +/- five meters per second ensemble shape is about half the +/- ten meters per second ensemble shape at 14:45 and yet at 15:45 they more similar. This result probably reflects that PHOENIX RapidFire is sensitive to wind speed in grassland (first part of the fire) but is less sensitive to wind speed in forest (as it crossed the south westerly portion of the National Park).

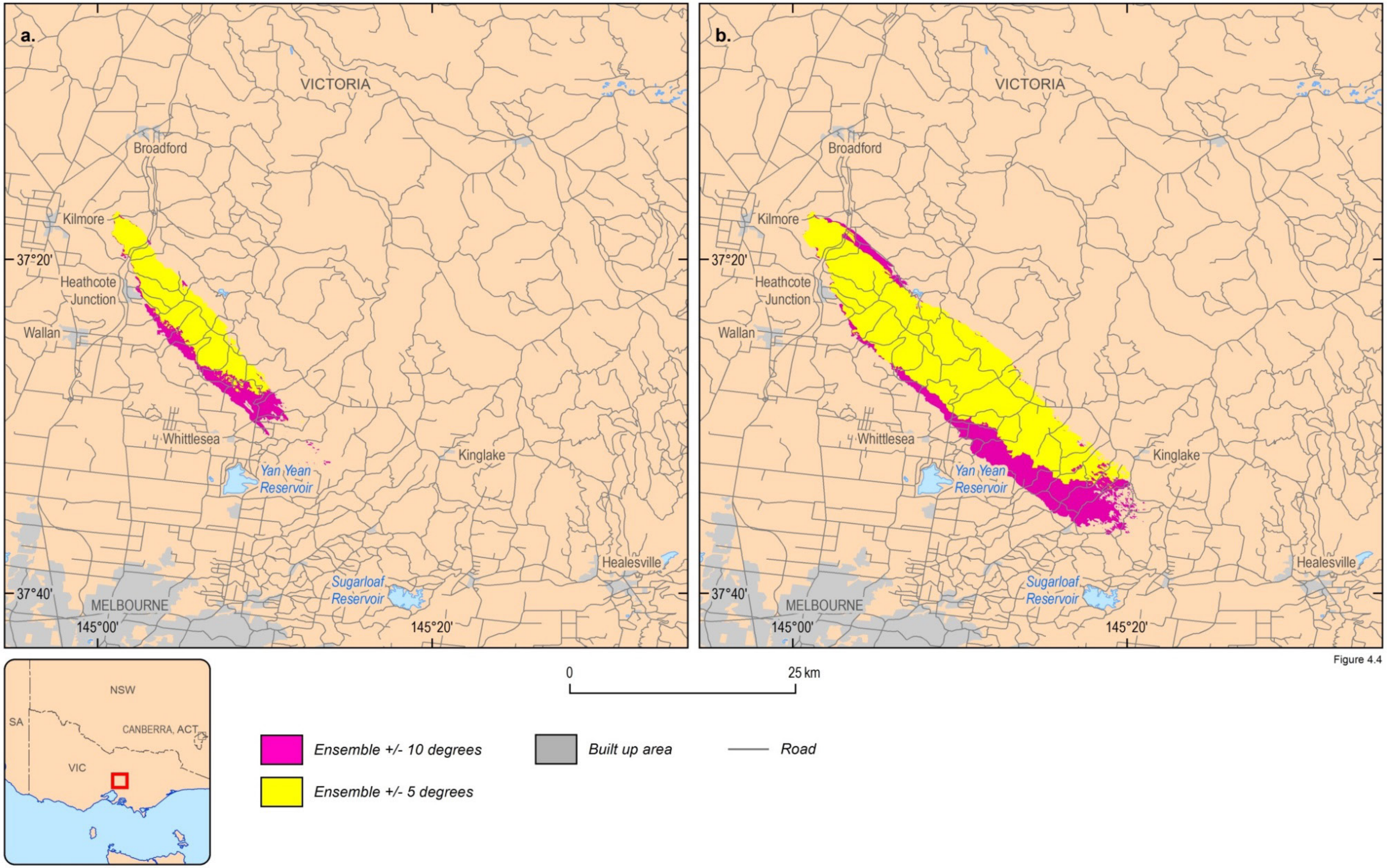


Figure 4.4 Sensitivity of the ensemble envelope to ranges in temperature at two different time steps (a)15:45 and (b) 17:45

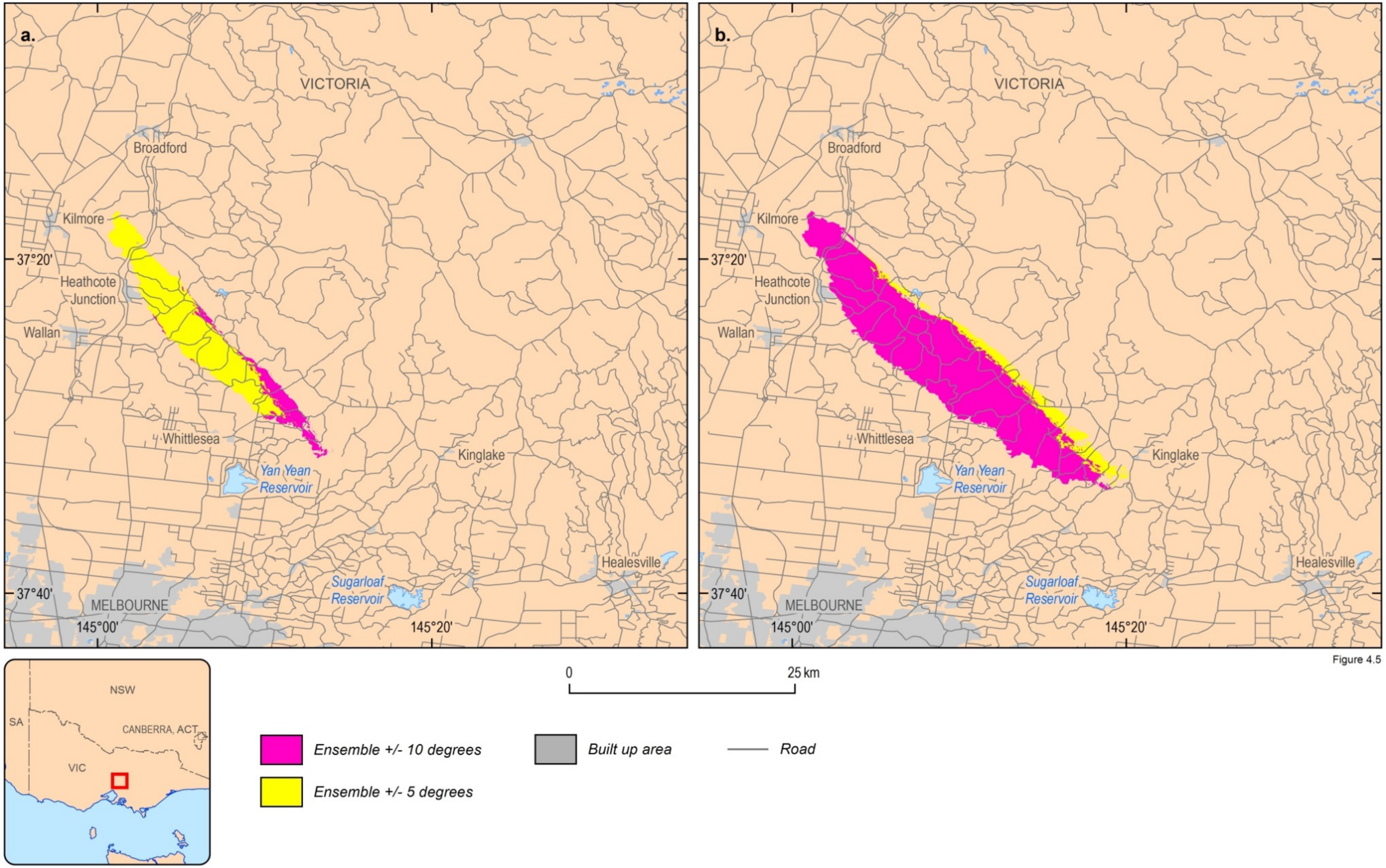


Figure 4.5 Sensitivity of the ensemble envelope to ranges in wind speed at two different time steps (a)15:45 and (b) 17:45

This last example demonstrates that sensitivity of model fire spread can change, depending on the weather conditions, the landscape in which the fire develops, and the particular ability of the code to represent the complex interactions between the fire and those elements. A better understanding of the sensitivity of model output for a range of conditions provides an indication of the variability of robustness of the model output. Considering a ‘worst case’ scenario, such as shown in Figure 4.5 could prompt different decisions based on ensemble output than single ‘best estimates’. Finally, understanding model sensitivity can help prioritise areas of further development, as will be demonstrated throughout this report.

At this point, the scenarios in the FireDST ensemble are weighted equally. In order to allow the ensemble fire spread to be interpreted in terms of *probability* fire spread, this method will have to sample the full distribution of the uncertainty in input parameters, rather than the limited perturbations applied here. This means the parameter perturbations that generate the ensemble scenarios should cover the range and frequency of the uncertainty in those parameters. For example, an error in the temperature forecast of 5 degrees might be 90% probable while a temperature variation of 10 degrees might have a 0.01% probability. Note that uncertainties can change as an event develops: as new information becomes available, uncertainties may decrease, or uncertainties may increase as a weather pattern changes. This can alter the range of simulations in an ensemble during an event.

4.4 Conclusions and Future Work

The objective of the work described here was to develop a methodology to assess and visualise the variability in the ensemble fire spread. An ensemble fire spread simulation can be constructed based on any number of individual simulations or simulation scenarios. The ensemble fire spread is computed as the percentage of overlap of the component ensemble scenarios.

This chapter gives an initial demonstration of a potential benefit of understanding sensitivity and uncertainty through an ensemble approach. Based on the reconstructed conditions, it was not possible to recreate the fire spread for the 2009 Kilmore event as a single model run based on the conditions at the time the fire occurred. However, the reconstruction of the Kilmore event does fall within the ensemble envelope based on limited perturbation of the input parameters, showing that the FireDST approach can lead to realistic results.

The size of the ensemble fire spread envelope is representative of the sensitivity of the fire spread modelling to variability in the input parameters. The results in this chapter and further in this report show that sensitivity itself depends on the conditions in which the fire develops. Understanding the model sensitivity allows a user to attach due consideration to the variability of model outcomes. Ultimately, this reduces the risk of over-interpreting inaccurate model results.

The FireDST output should not be interpreted as a true probabilistic fire spread, as the range and frequency of the parameters used to create the scenarios is unrepresentative of the true uncertainty in the simulation process. Nevertheless, the results presented here demonstrate the following outcomes are achieved:

FireDST can provide ensemble fire spread information that validates reasonably well against historical observations. Furthermore,

FireDST ensembles provide key information on the sensitivity and robustness of fire spread simulations through the spread of the fire spread envelope.

Even a ‘naïve’ sensitivity ensemble such as generated in this report gives information on the potential development of an event that cannot be provided by a single deterministic model run.

In conclusion, the results discussed in this chapter demonstrate that Fire DST can provide valuable information on the sensitivity in the fire spread modelling. Moreover, with the correct input, it allows integrating uncertainty into the fire spread modelling. In either form, the FireDST capability improves the ability to interpret the outputs of a fire spread model.

4.4.1 Future Work

A key focus of future work should include specifying the uncertainty in the various FireDST parameters, and building this into the Ensemble Generator. This would allow generation of a fully probabilistic fire spread ensemble that could be interpreted in terms of uncertainty of the outcome of an event.

Business analysis of the potential application of ensembles in an operational (or other applied) context would impose a number of requirements on the options to “interact” with ensemble information. For example, this could flag the need to sub-select, add or exclude specific scenarios from an existing ensemble as an event unfolds or additional information becomes available. Further work would have to determine efficient ways of including such information without compromising the validity of the results.

5 Assessing sensitivity of the fire spread to the surface weather

5.1 Objective

Fire spread, and fire spread modelling, is sensitive to the weather, in particular to variation in the wind speed (Cechet *et al*., 2014). It is important for users of fire spread models to understand the sensitivity of the outputs to potential uncertainties in the weather inputs. The PHOENIX RapidFire fire spread model used in FireDST is parameterised to be driven by surface (at 10 m height) weather conditions, and this is the focus of this chapter. Chapter 6 focuses on potential sensitivity to weather conditions in the higher layers of the atmosphere.

The objective of this chapter is to assess the sensitivity of the fire spread model to the surface weather by:

- Demonstrating the methodology used by the FireDST Weather Ensemble Generator to create an ensemble that samples variability in the supplied surface weather parameters.
- Demonstrate the resulting sensitivity of the fire spread modelling to the perturbations in surface weather.

FireDST produces fire simulations using ACCESS weather files rather than the standard PHOENIX RapidFire weather input that is based on historical Automated Weather Station (AWS) readings. To conduct this work, the University of Melbourne team produced a version of PHOENIX RapidFire that was able to read the ACCESS netCDF weather files.

The research described here used the standard ACCESS surface weather files supplied by the Bureau of Meteorology. Analysis of the sensitivity of the fire spread modelling to the spatial resolution of the weather files was conducted by the University of Melbourne. The outcome of this research is covered in Cechet *et al.,* (2014).

5.2 Methodology

5.2.1 Input Data

The Bureau of Meteorology's numerical weather prediction system, ACCESS (Australian Community Climate and Earth-System Simulator) (Puri, 2011) provided four netCDF format files for the temperature, humidity, wind speed and wind direction at ten metre height. These files represent the standard weather forecast for the forty eight hours from 11am on 6/2/2009 at grid resolutions 0.036^{o,} 0.012^{o} and 0.004^{o} (which are approximately 4000m, 1200 m and 440m) at five minute time steps.

The FireDST Weather Ensemble Generator perturbs weather conditions in the ACCESS files and uses these to create an ensemble fire spread. The Weather Ensemble Generator creates a modified netCDF file for each weather variable setting in the range. Changes are applied equally across the whole grid. For instance, a user creates a scenario with a temperature decrease of 2°C. The decrease is applied equally to all the temperatures in the file and there is no location sensitive nature to these changes. If the supplied temperature at 2pm is 32°C at Melbourne airport and 43°C at Kilmore, then that particular scenario specifies that the temperature for 2pm at Melbourne airport is 30°C and 41°C at Kilmore.

FireDST imposes a few restrictions to ensure that scenarios generated have physical relevance when sampling potential bushfire scenarios. For example, the humidity cannot be set to 0 percent and the temperature cannot go below 0°C.

Six tests were used to test the ability of FireDST to generate an ensemble that samples a range of weather conditions (Table 5.1). These tests also demonstrated sensitivity of the simulated fire spread to the surface weather parameters and are described together with a sample result in the following sections.

Table 5.1 Weather perturbations for Kilmore generated by the FireDST Weather Ensemble Generator

Parameter	Unit	Range	Comment
ACCESS Grid Resolution	meters	4000,1200,440	Supplied
Time interval	Minute	5,15,30,60	Only 5 minute was supplied
Wind Direction	Degrees	+/- 20	Clockwise from north
Wind Intensity (speed)	m/s	+/- 20	
Temperature	^{o}C	+/-10	
Humidity	%	+/- 5	

The real weather will have variations in all of these parameters at once and so FireDST was also tested with various combinations of these parameters. For example a scenario was produced with the temperature increased by 2 degrees, the humidity down by one percent and the wind speed increased by two m/s.

For each of the scenarios in the respective weather ensembles, the simulated fire shape was compared with the Kilmore reconstruction fire shape. All landscape and environmental conditions were kept constant.

The following sections show a single example result for each test.

5.2.2 Bias correction of the ACCESS Wind Speed

The Bureau of Meteorology conducted a verification of the ACCESS model against their Automated Weather Station (AWS) network. This verification found that there was good correlation for temperature, humidity and wind direction. However the wind speeds were continually underestimated by as much as 20% (Cechet *et al.,* 2014).

A simple manual procedure was undertaken to calculate wind speed bias correction factors. The factors were computed as the difference between the ACCESS model wind speed values and selected automated weather station wind speed for different wind directions. Bias factors were calculated at each weather station (See Appendix A) then averaged to obtain a single bias correction factor. Not all weather stations were used to compute the bias correction factor, as some stations were either not well exposed (shielded) or did not represent the speed up in some wind directions. The bias correction factors do not take into account the differences in topography.

The Weather Ensemble Generator was modified to apply the correction factors to all the wind speed values in the supplied ACCESS wind speed file. The wind speed bias correction factors for the Kilmore event at each ACCESS file resolution are given in Table 5.2.

Table 5.2 Kilmore fire wind speed bias correction

Dir.	Angle segment (Degrees)	4000 m grid resolution	1200 m grid resolution	440 m grid resolution
N	338 – 22	1.28	1.23	1.23
NE	23 - 67	1.0	1.0	1.0
E	68 – 112	1.0	1.0	1.0
SE	113 - 157	1.0	1.0	1.0
S	158 – 202	1.08	1.05	1.05
SW	203 – 247	1.15	1.1	1.1
W	248 – 292	1.35	1.33	1.33
NW	293 – 337	1.54	1.47	1.47

5.2.3 Further correction of the ACCESS Wind Speed by using wind multipliers

Bias correction (above) is a very simple process and does not take into account variation in the topography. Topography effects are included in the supplied ACCESS weather model, but at a relatively large scale. The topography used by ACCESS (Table 5.3) has a grid resolution that matches the grid resolution of the ACCESS files (so the 4000 m ACCESS weather has used a 4000 m topographic grid).

Table 5.3 Different digital elevation models used in FireDST.

Model	4000 m grid resolution	1200 m grid resolution	440 m grid resolution
ACCESS	1.0 m height every 4000 m	1.0 m height every 1200 m	1.0 m height every 440 m
Wind Ninja	1.0 m height every 100 m	1.0 m height every 100 m	1.0 m height every 100 m

PHOENIX RapidFire can use the Wind Ninja[1] wind modifier system, in which the terrain is resolved on a 100 metre grid. The higher resolution terrain should allow more accurate reflection of modifications in wind speed and direction by the terrain. The effect of using the Wind Ninja wind modifiers was tested by running the same simulations using the same weather with and without using Wind Ninja.

[1] http://www.firelab.org/research-projects/physical-fire/145-windninja

5.3 Results and Discussion

5.3.1 Sensitivity of fire spread to resolution of the ACCESS weather grid

Figure 5.1, 5.2 and 5.3 show the simulation shape for the ACCESS weather files for the Kilmore fire at three grid resolutions, 4000, 1200 and 440m. Irrespective of grid resolution, all simulations underestimated the size of the fire compared to the reconstruction of the historical Kilmore fire. The Bureau of Meteorology attributed this to the fact that ACCESS modelled lower wind speeds than those recorded at several automated weather stations during the event. For the Kilmore case study, ACCESS wind speeds were found to have a negative bias of up to 20% (Kepert *et al.,* 2013, Cechet *et al.,* 2014). The results of the bias correction are discussed in the next section.

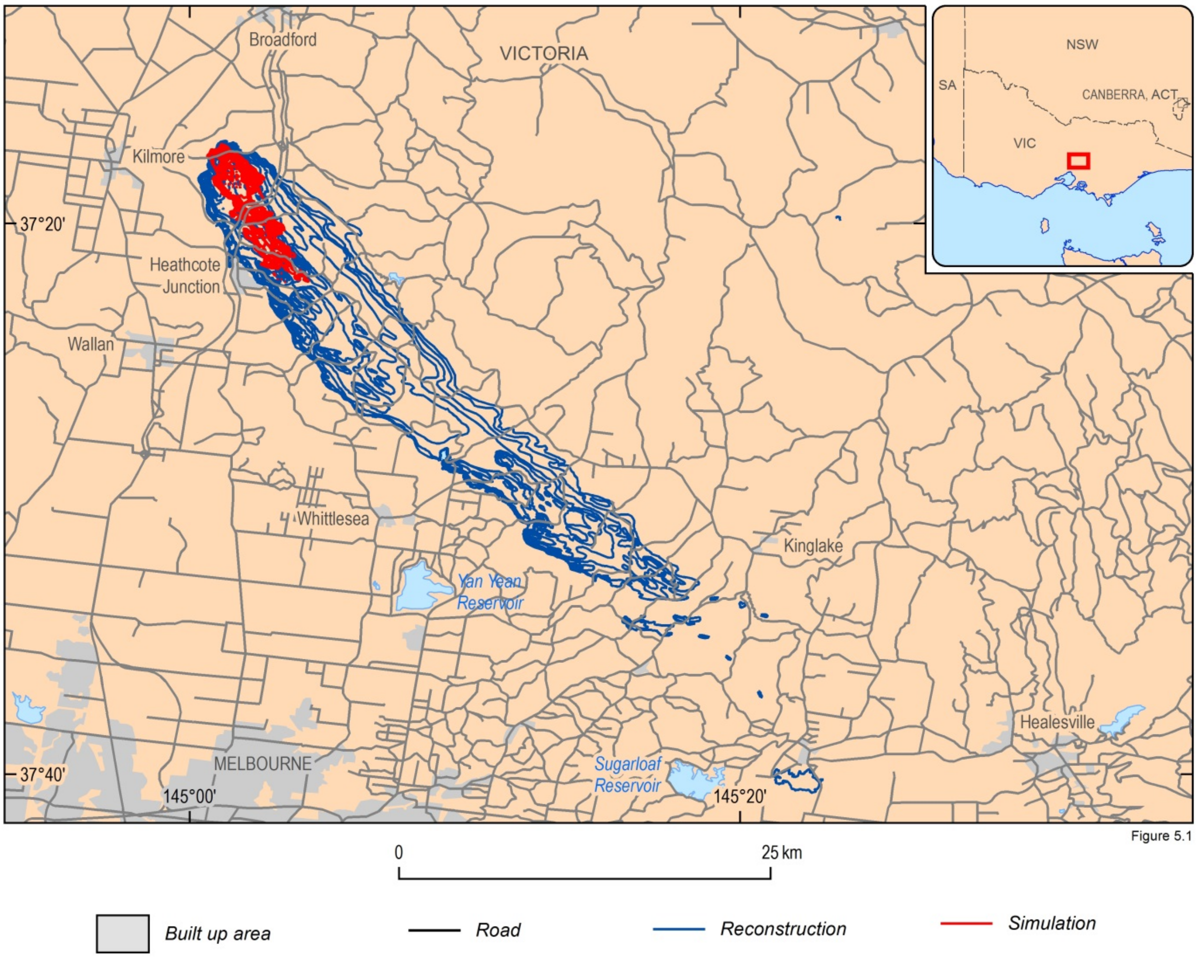


Figure 5.1 Supplied ACCESS 4000 m five minute Simulation (red) of Kilmore Fire to 1730 with the reconstruction (blue).

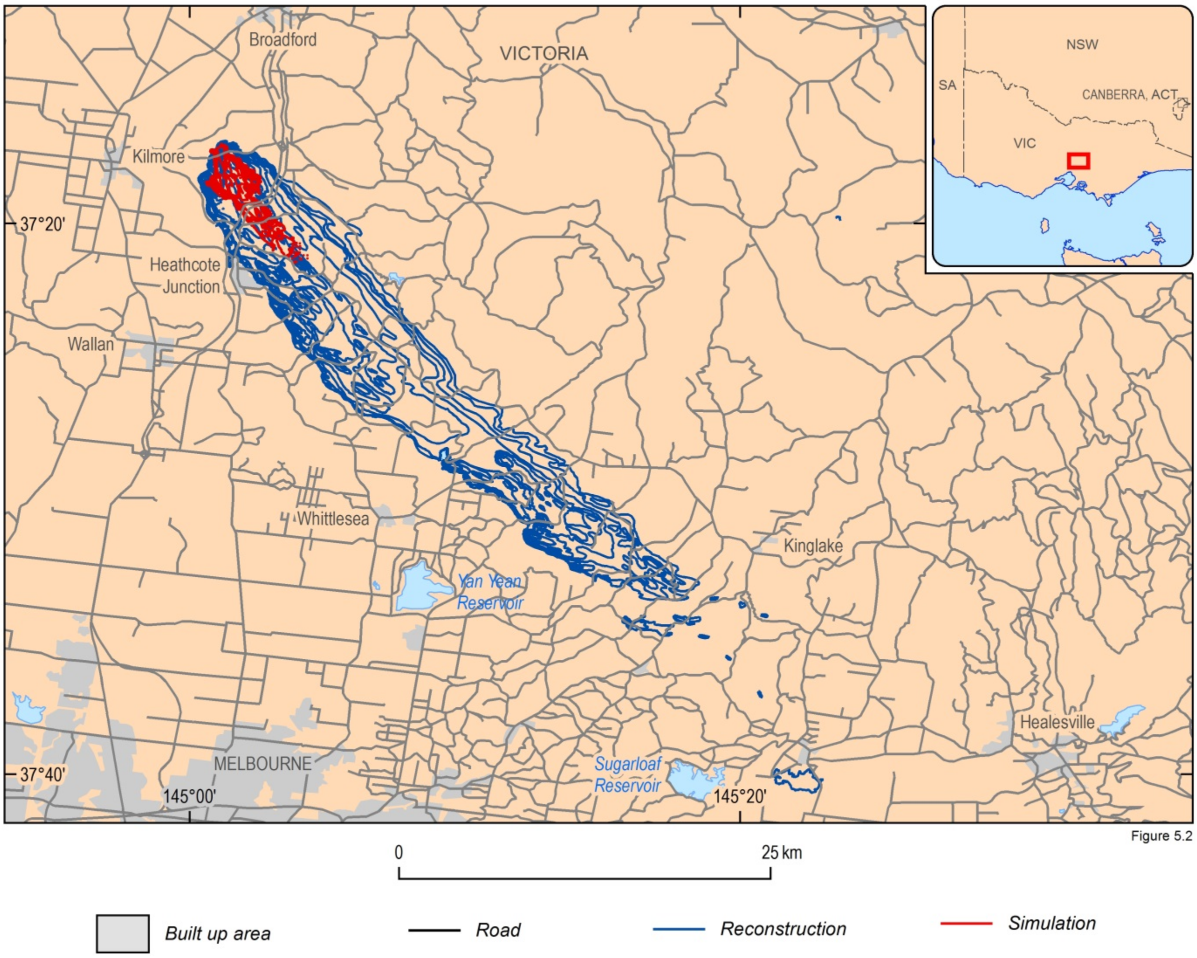


Figure 5.2 Supplied ACCESS 1200 m five min Simulation (red) of Kilmore Fire to 17:30 with the reconstruction (blue).

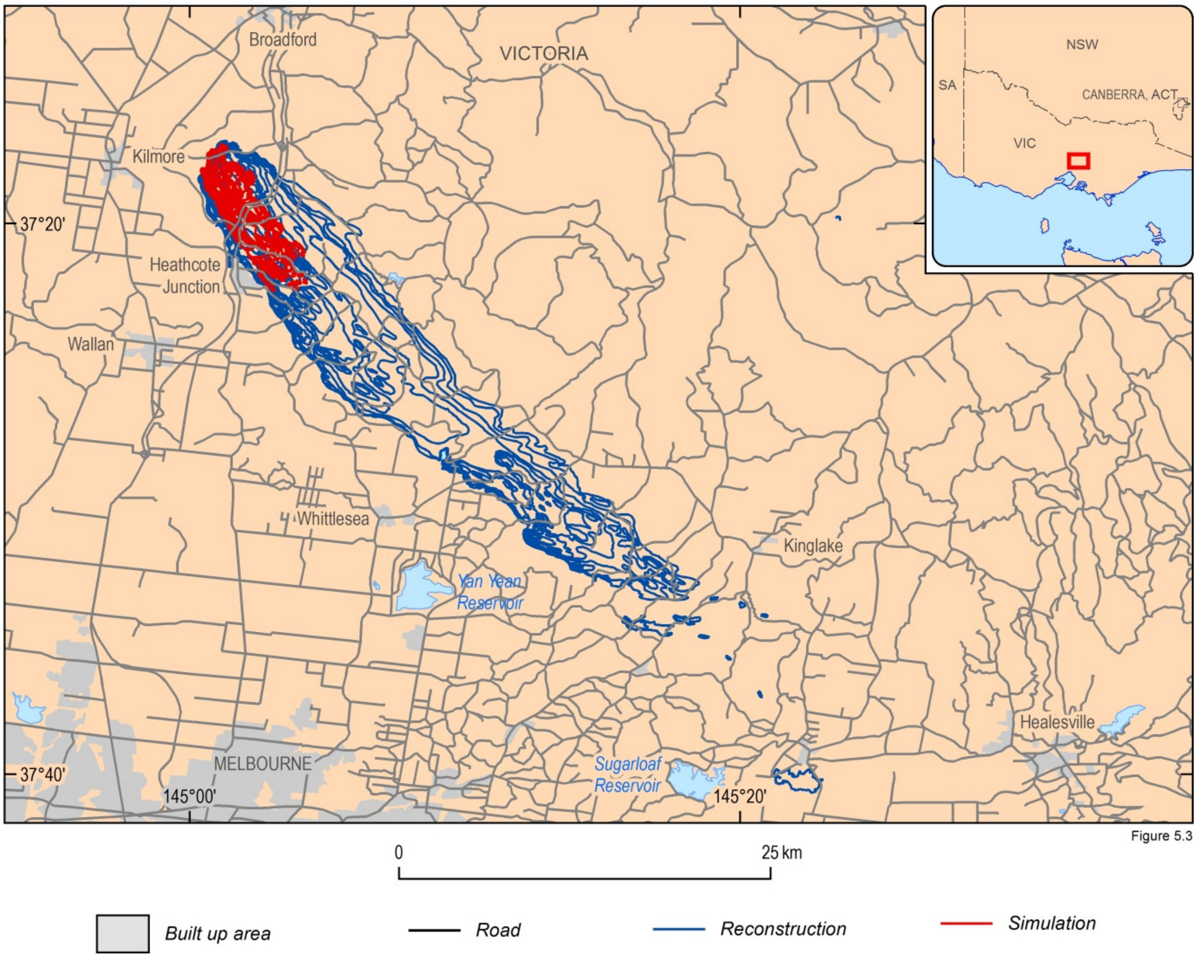


Figure 5.3 Supplied ACCESS 440 m five minute Simulation (red) of Kilmore Fire to 17:30 with the reconstruction (blue).

5.3.1.1 Bias correction of wind strength

Figure 5.4 to Figure 5.6 show the impact of the bias correction on the fire simulation for each resolution of ACCESS file. At 4000 m, bias correction of the wind resulted in the fire spread being overestimated (Figure 5.4). At 1200 m and 440 m resolutions the bias correction increased the fire spread area. Nevertheless, despite the bias correction (at 1200 and 440m), the modelled fire spread did not attain an equivalent shape to the reconstruction of the historical event. This indicates that a 'global' or uniform approach to bias correction of the wind speed over the whole landscape is insufficient to correct the underestimation of the actual fire spread. It is probable that there needs to be an additional bias correction factor that takes into account the variability in the terrain and vegetation. The next section discusses the results following modification of the wind with the local wind modifiers.

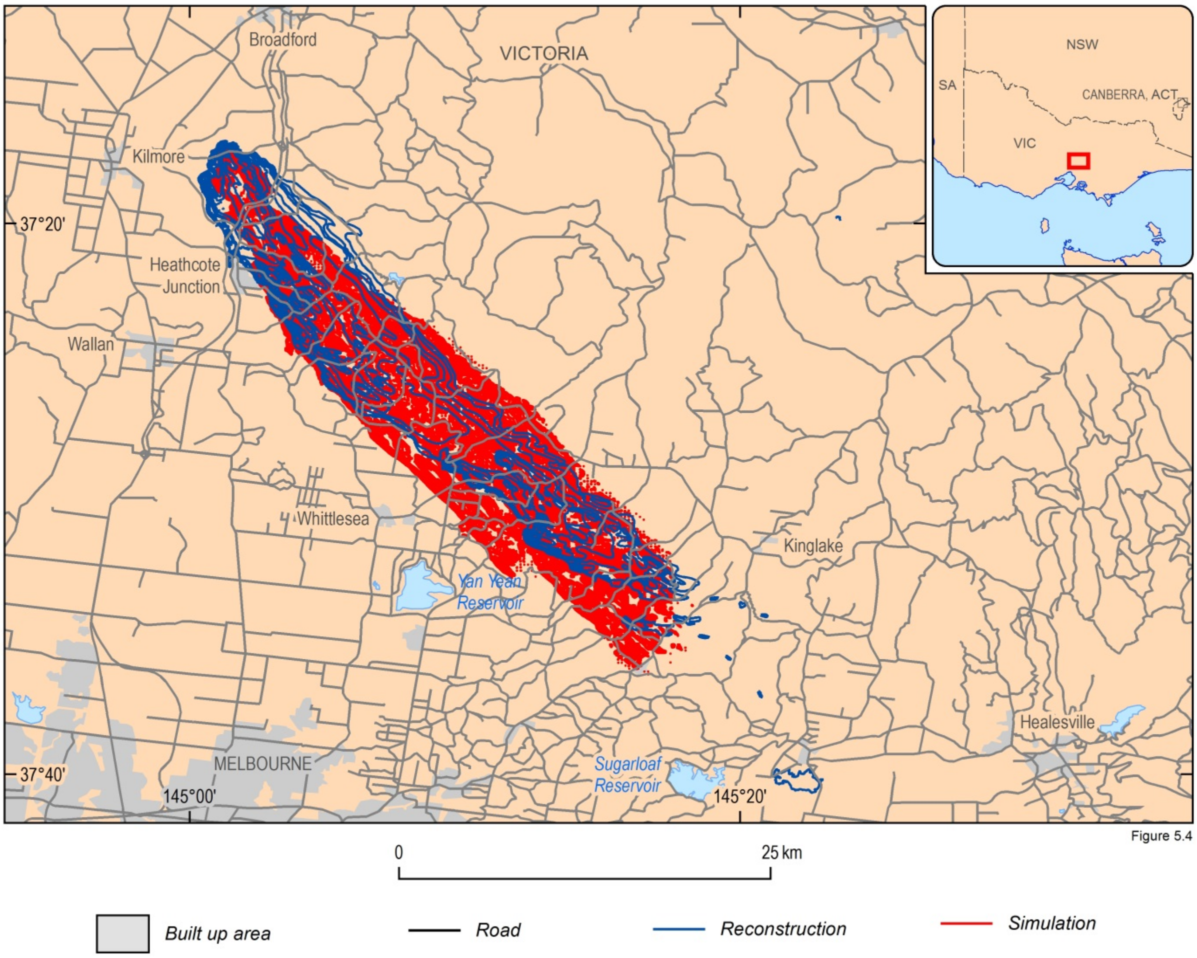


Figure 5.4 4000 m five minute bias corrected simulation (red) with Kilmore Fire reconstruction (blue).

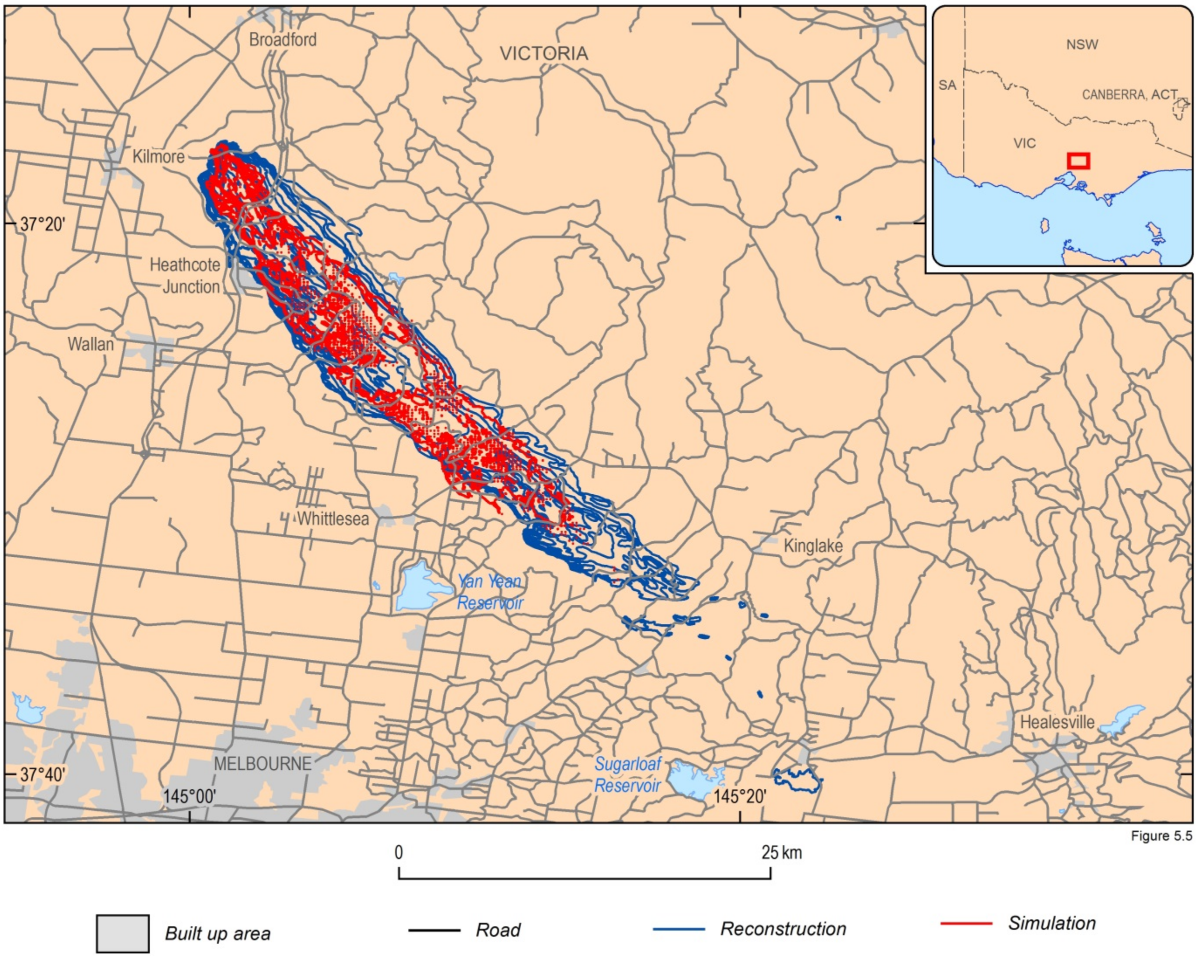


Figure 5.5 1200 m 5 minute bias corrected simulation (red) with Kilmore fire reconstruction (blue).

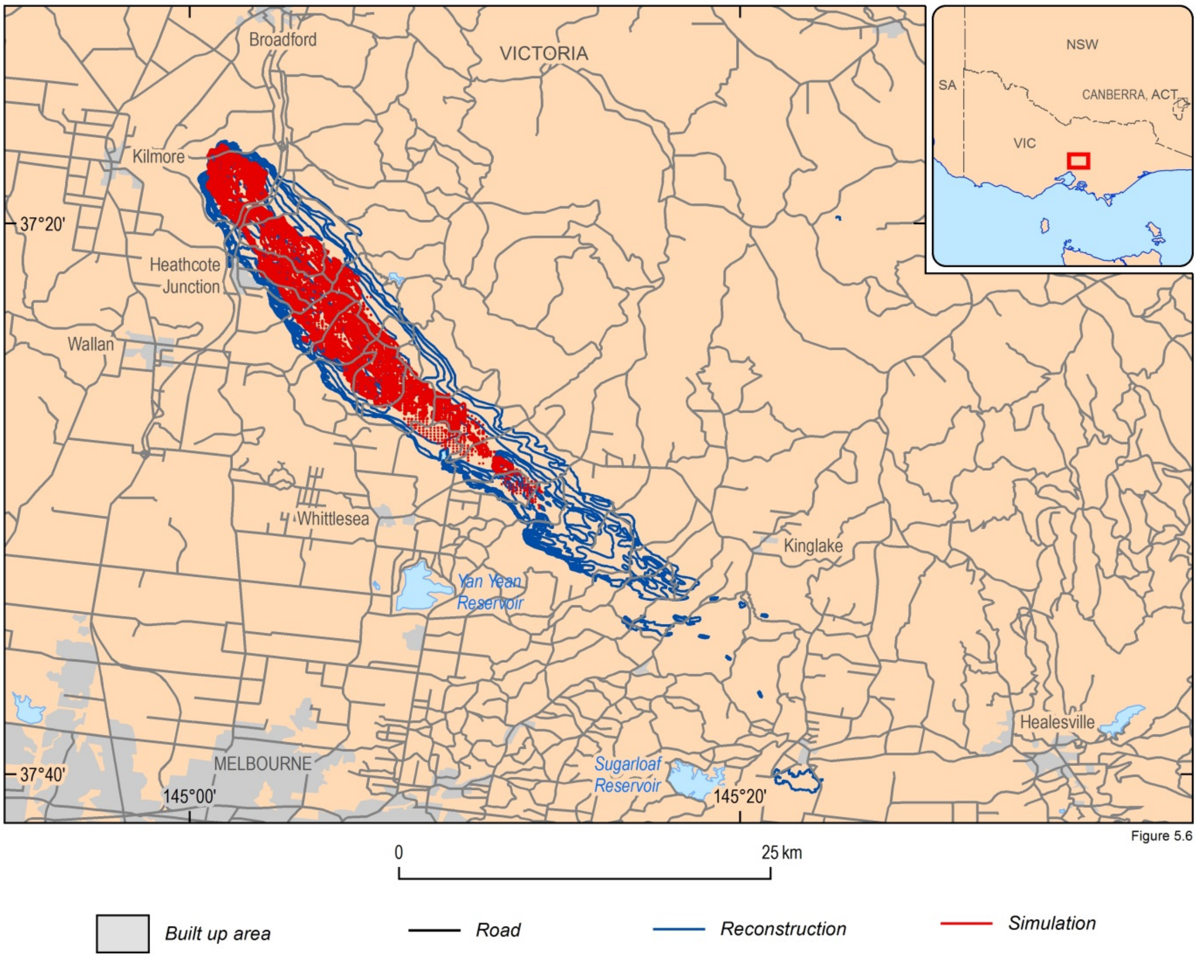


Figure 5.6 440 m five minute bias corrected simulation (red) with Kilmore fire reconstruction (blue).

5.3.1.2 Effect of the introduction of local wind modifiers

The introduction of global bias correction factors for wind speed did not result in a better match between the simulated fire spread and the reconstruction of the historical event. This section discusses the impact of further correcting the wind strength and direction for local effects of topography.

Figure 5.7(4000 m) and Figure 5.8(1200 m) show the simulation based on surface wind speed and direction generated by winds modified with Wind Ninja modifiers. Compared with Figure 5.4 the 4000 m Wind Ninja simulation (Figure 5.7) had slimmed and become more accurate in fire area. The 1200 m Wind Ninja simulation (Figure 5.8) has increased in area and nearly matches the reconstruction.

The simulated shape in Figure 5.9(for 440 m grid) did not increase in size, indicating that the introduction of the Wind Ninja modifiers had little effect at 440 m resolution. This could be because the localised wind effects parameterised by Wind Ninja on a 100 m DEM are already captured by ACCESS using the 440 m DEM.

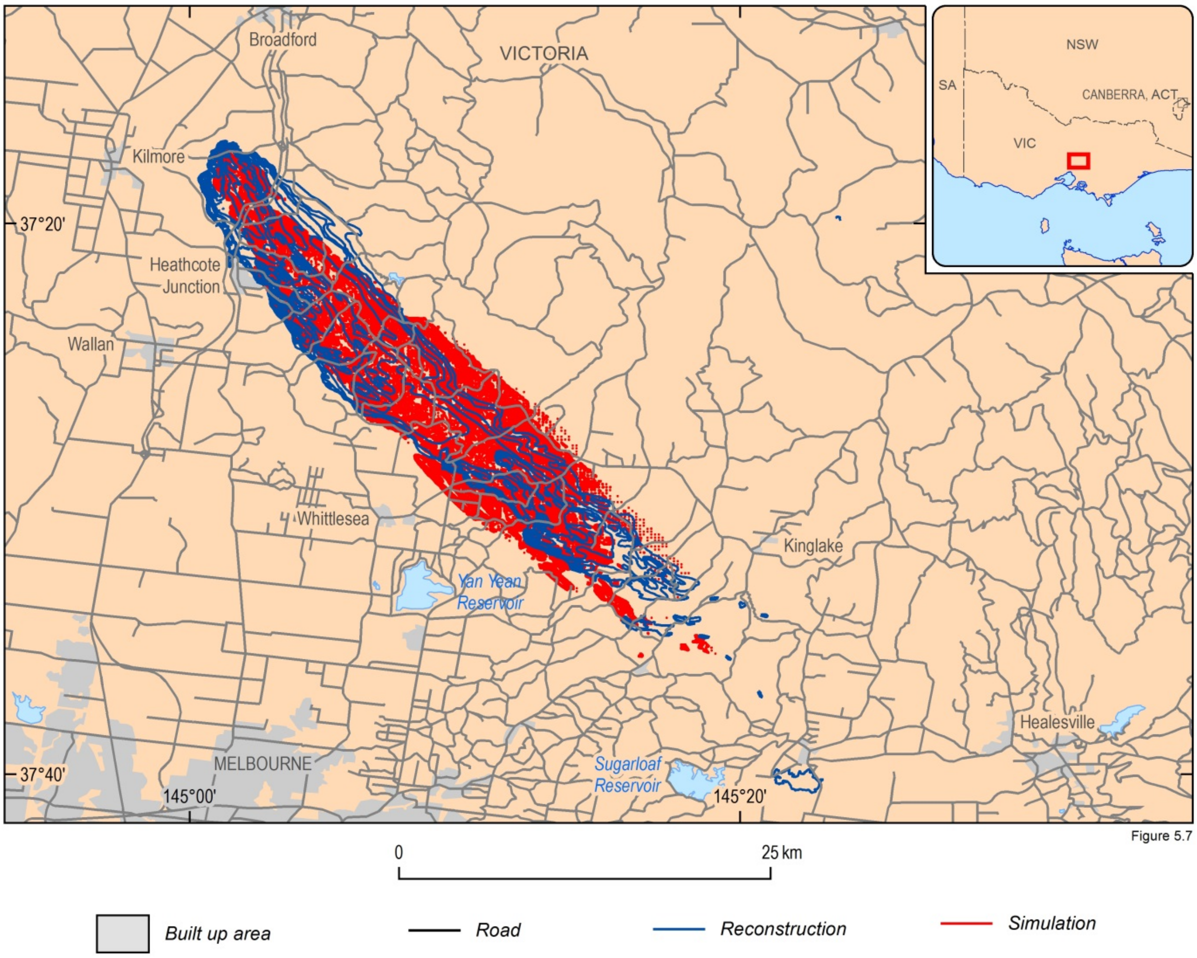


Figure 5.7 4000 m bias corrected Wind Ninja five minute time step (red)) with Kilmore Fire reconstruction (blue).

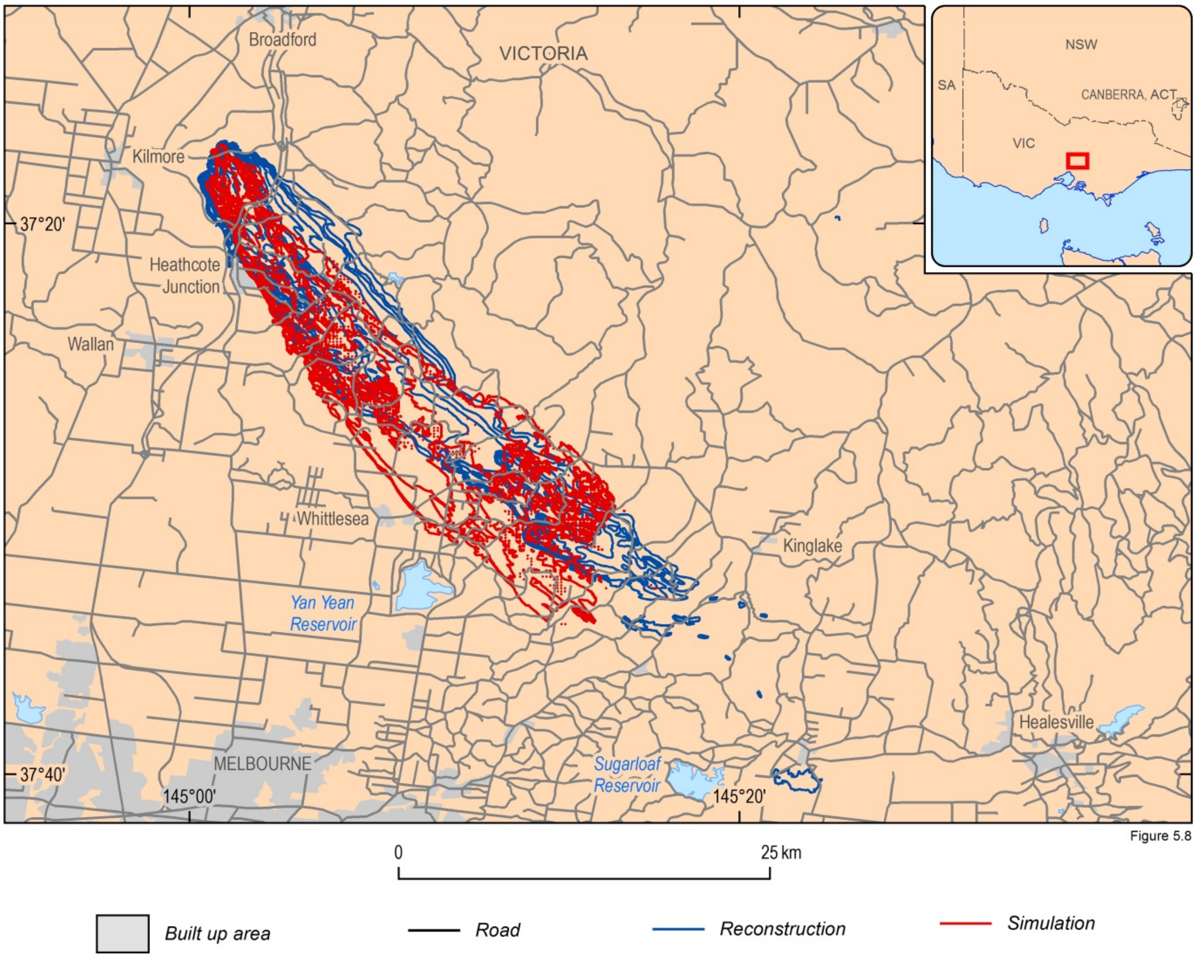


Figure 5.8 1200 m bias corrected Wind Ninja five minute time step (red)) with Kilmore Fire reconstruction (blue).

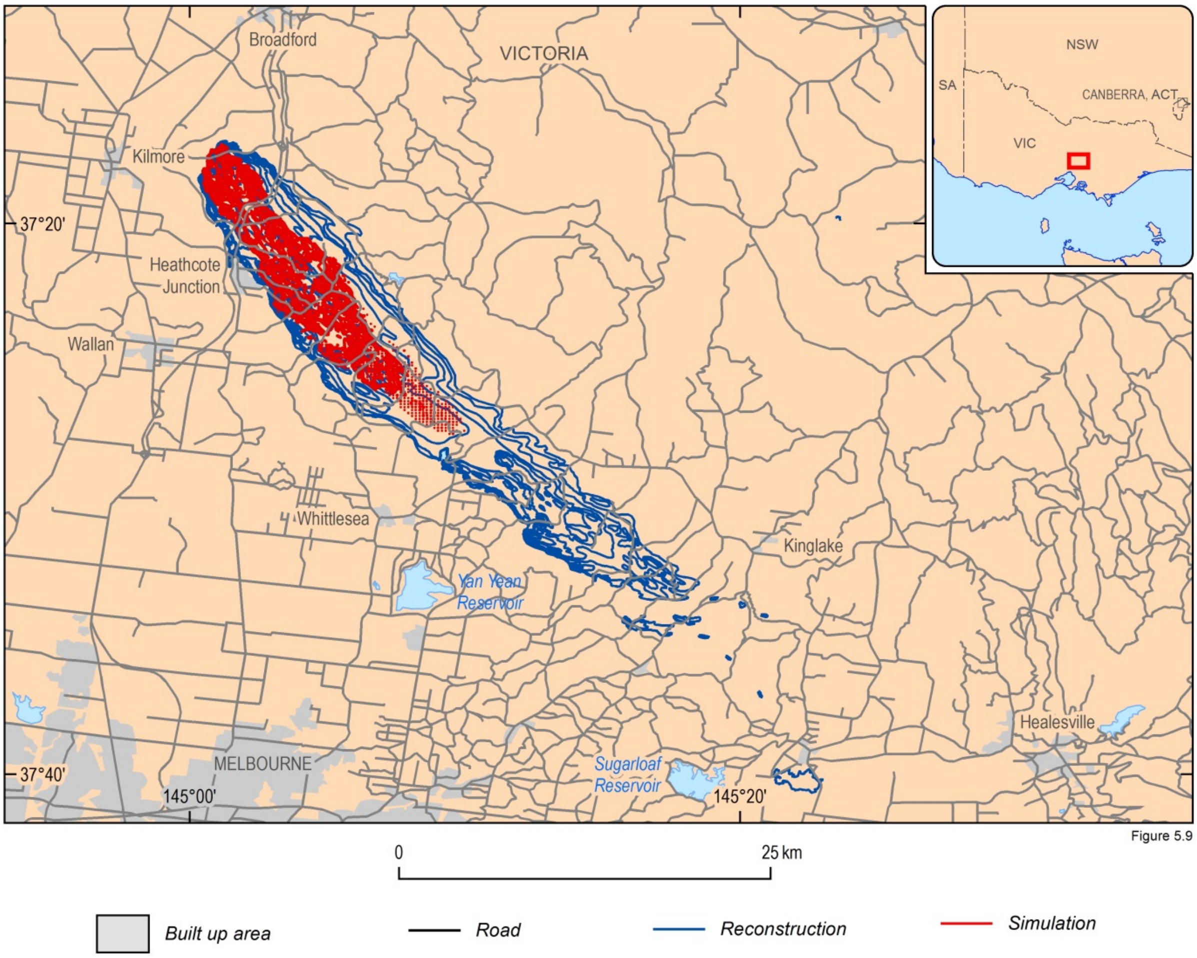


Figure 5.9 440 m bias corrected Wind Ninja 5 minute time step (red)) with Kilmore Fire reconstruction (blue).

5.3.2 Sensitivity to time interval

The ACCESS weather files specified the weather at five minute time intervals. FireDST simulations were produced based on weather specified at 15, 30 or 60 minute intervals, respectively. Simulations were performed for all spatial resolutions of weather files (4000 m, 1200 m and 440 m). Figure 5.10 to 5.12 show the results of simulations with the respective time intervals.

The simulation (for 4000 m and 1200 m) based on five minute time intervals produced fire spreads where the area and length were the most consistent with the reconstructed fire shape. With increasing time intervals, the amount of weather information available to the simulation is reduced. This was reflected by the decreasing match of the simulations using 15, 30 and 60 minute time intervals.

The 440 m resolution simulations showed unexpected behaviour. The simulations based on weather at 15, 30 and 60 minute time interval data produced more accurate shapes than the original five minute simulation (Figure 5.12). Only retaining weather at particular time steps was expected to lead to a decreasing match, as was the case for the larger spatial resolution files due to loss of resolution. This result suggests that the underestimation of the fire spread shape at 440 m with 5 minute time steps is likely to be caused by other factors than the wind speed, and may be related to factors in PHOENIX RapidFire model dynamics. Further research into this phenomenon was beyond the scope of the project.

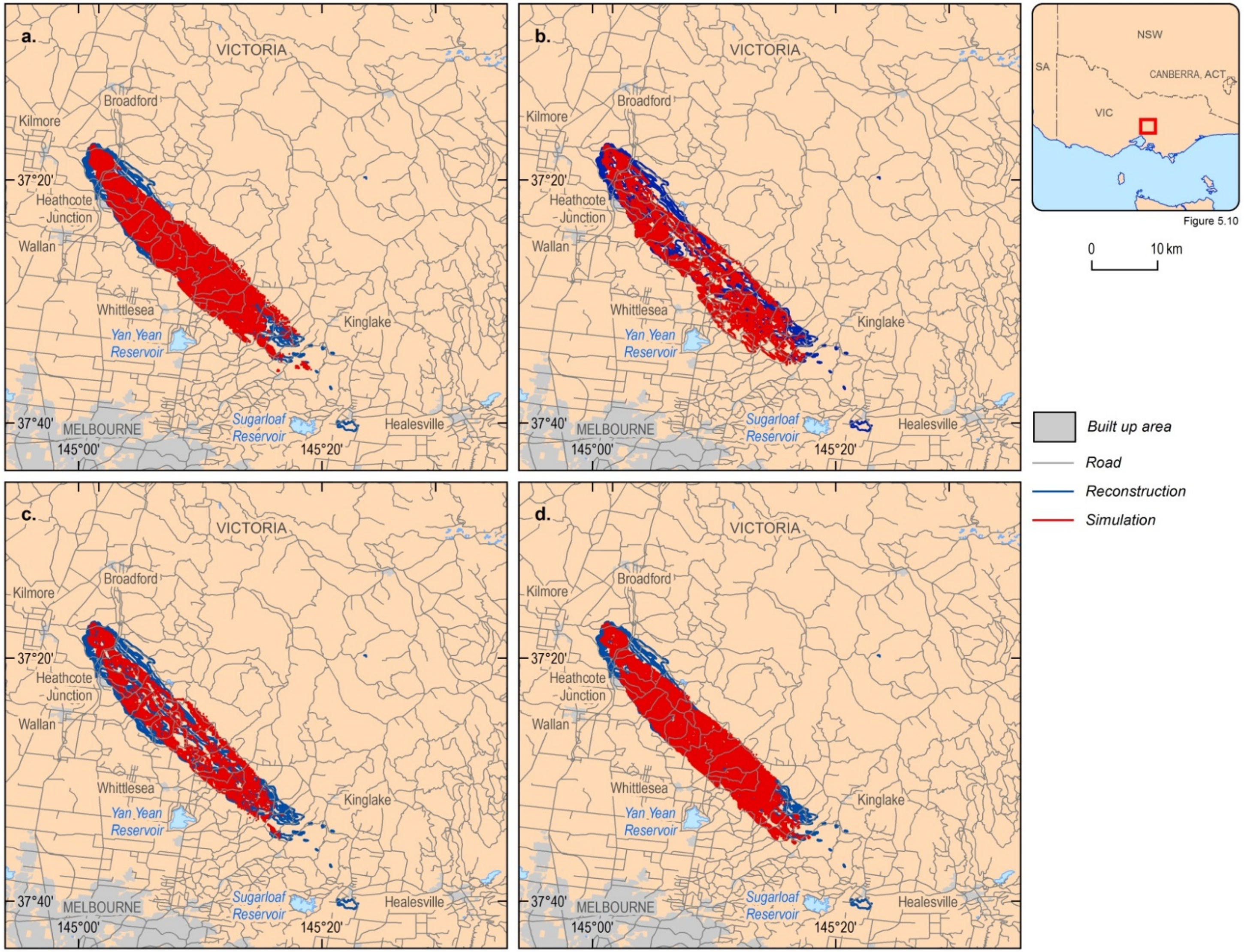


Figure 5.10 4000 m comparison (red)) with Kilmore fire reconstruction (blue) to 17:30 using 5, 15, 30 and 60 minute input weather data.

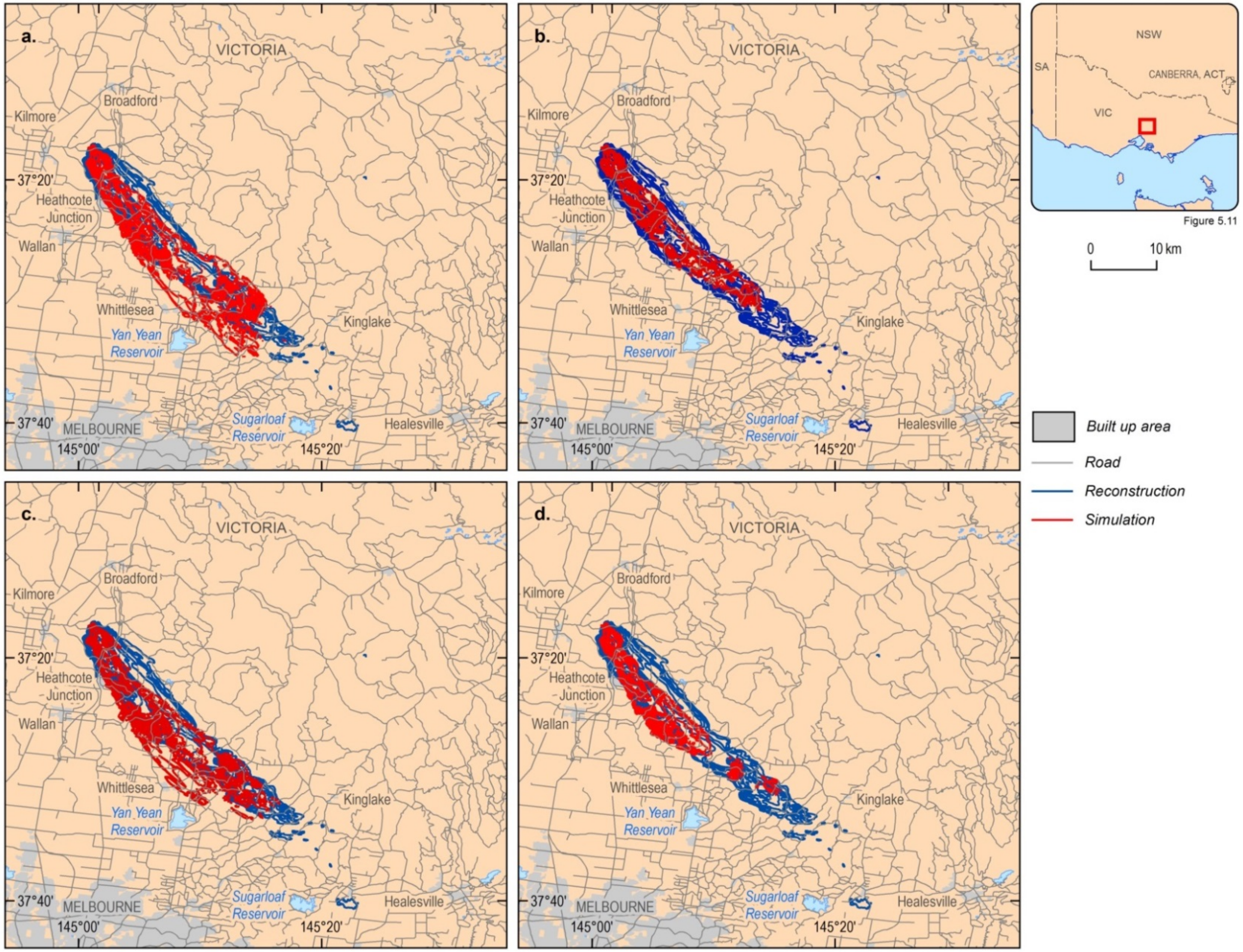


Figure 5.11 1200 m bias corrected time step comparison (red)) with Kilmore fire reconstruction (blue) to 17:30 using 5, 15, 30 and 60 minute input weather data.

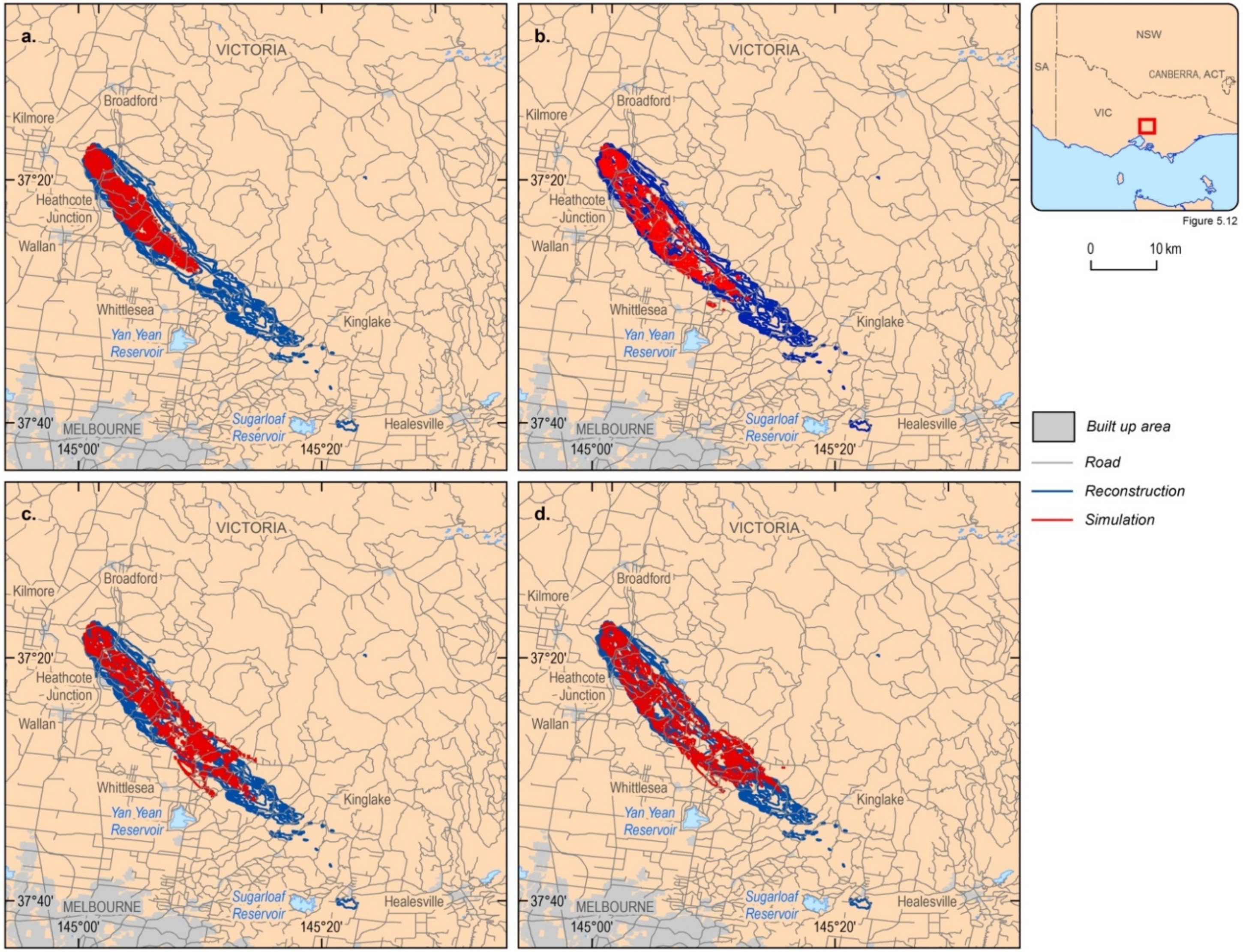


Figure 5.12 440m bias corrected time step comparison (red)) with Kilmore fire reconstruction (blue) to 17:30 using 5, 15, 30 and 60 minute input weather data.

5.3.3 Sensitivity to wind direction

Figure 5.13 and 5.14 show two direction shifts in the wind speed (-/+ 10 degrees, respectively). The figures demonstrate a marked change in the direction of the simulated fire as a result of the perturbed wind direction, indicating significant sensitivity.

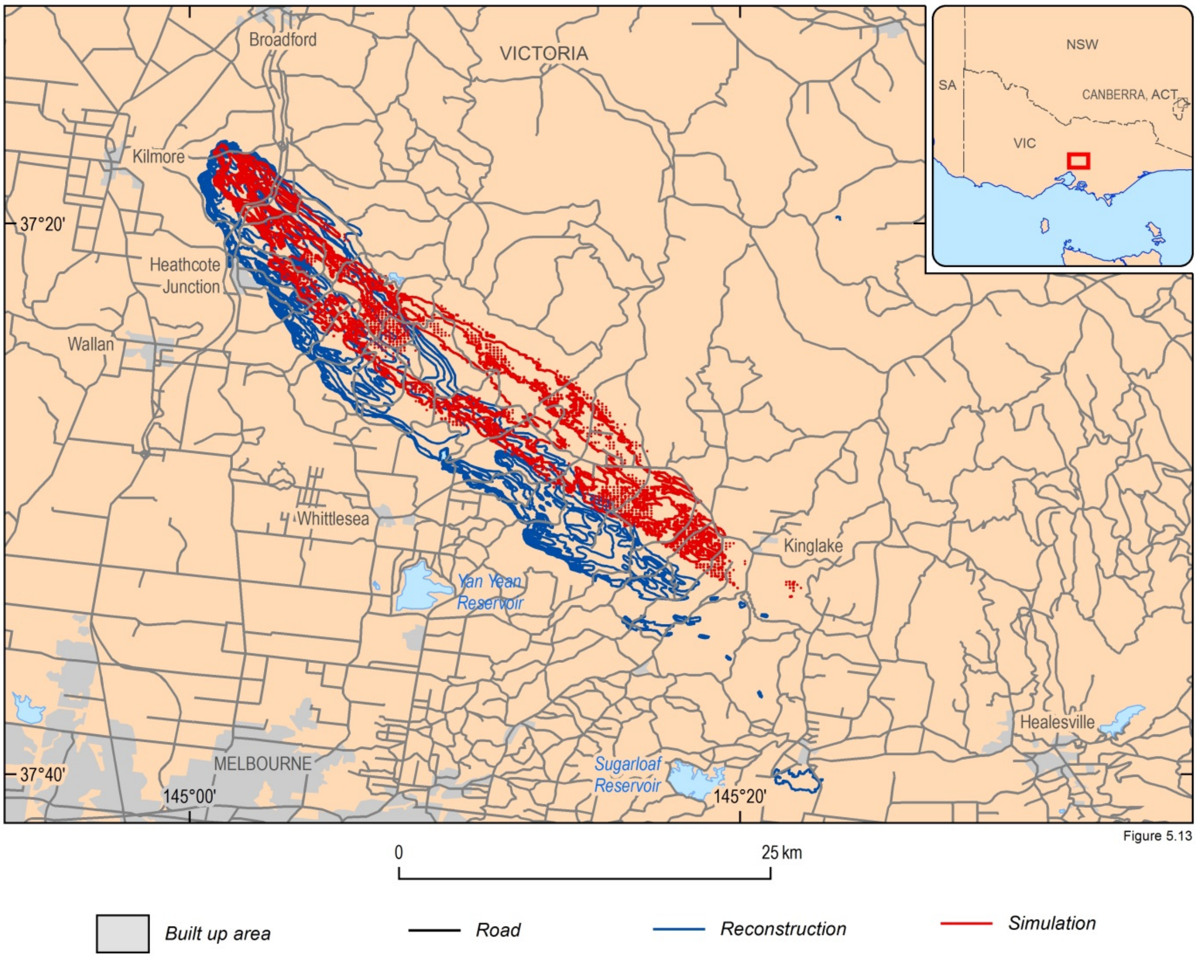


Figure 5.13 4000 m 5 minute bias corrected wind speed with wind ninja minus 10 degrees (red) with Kilmore fire reconstruction (blue) to 17:30.

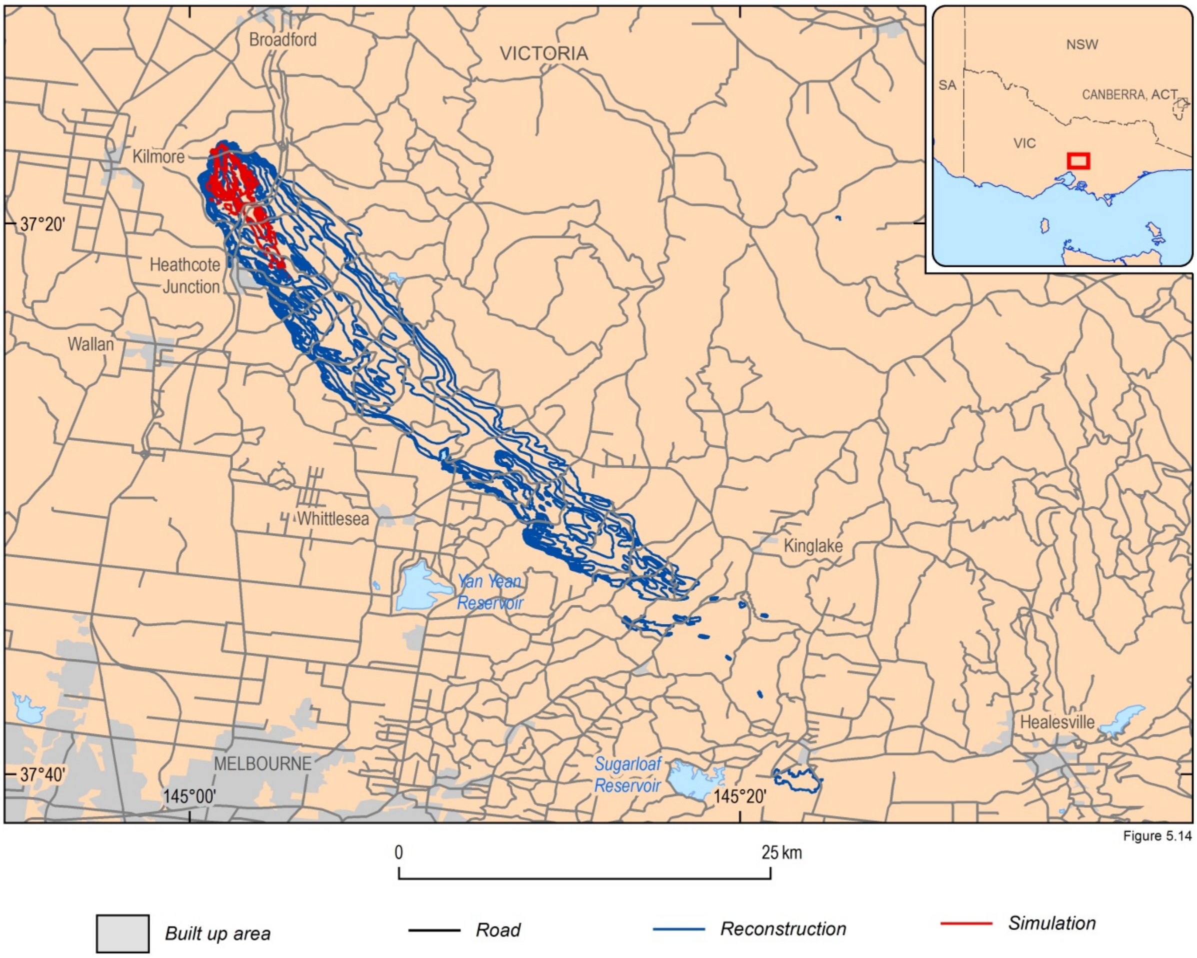


Figure 5.14 4000 m 5 minute bias corrected wind direction plus 10 degrees (red) with Kilmore fire reconstruction (blue) to 17:30.

5.3.4 Sensitivity to wind intensity

To demonstrate the ability of FireDST to reflect the sensitivity of fire spread to wind intensity, two intensity perturbations are displayed in Figure 5.15 (all wind speeds minus 5 metres per second) and Figure 5.16 (all wind speeds plus 5 metres per second). The difference in fire spread between the two figures shows that the fire spread is sensitive to the variation in wind speed.

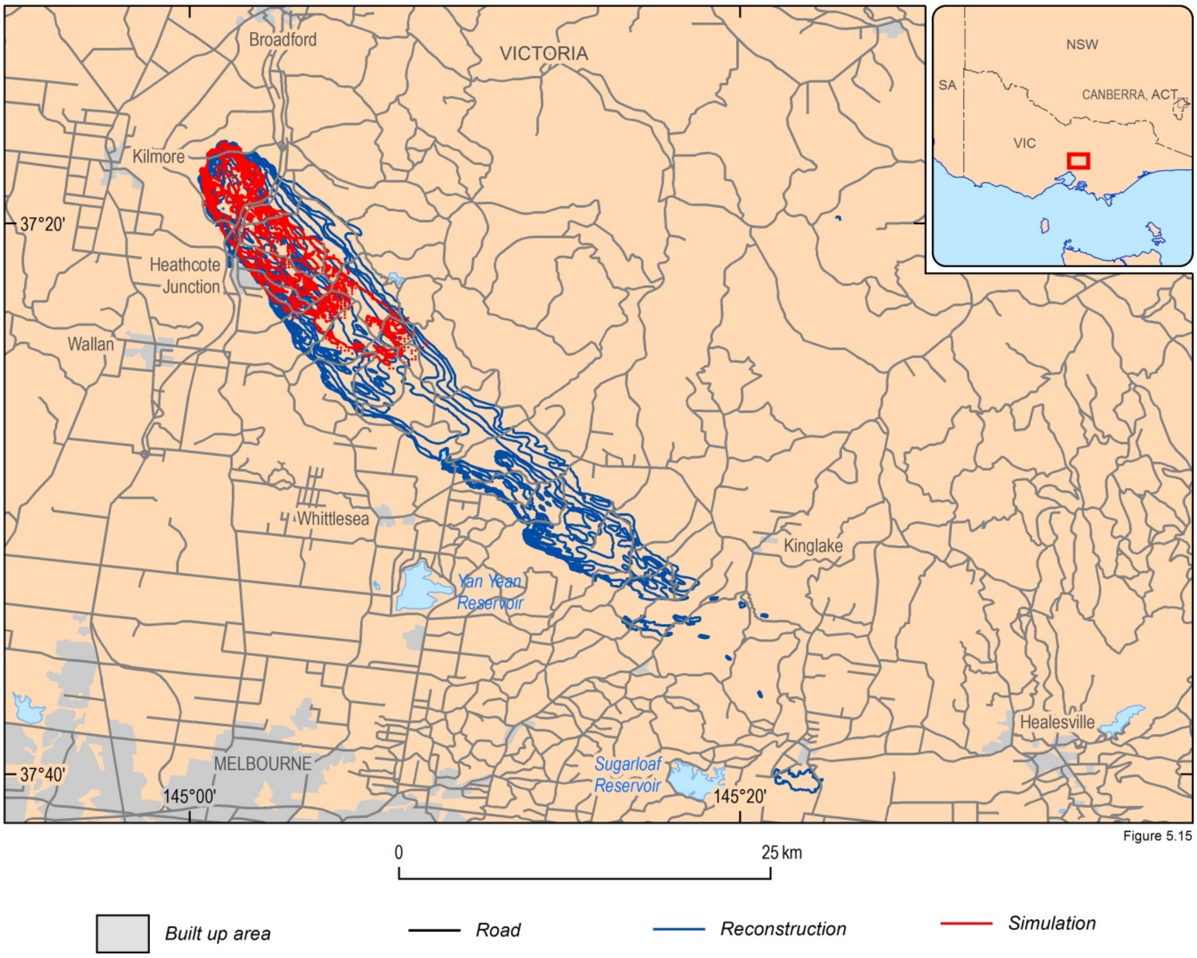


Figure 5.15 4000 m 5 minute bias corrected wind speed minus five m/s (red) with Kilmore fire reconstruction (blue) to 17:30.

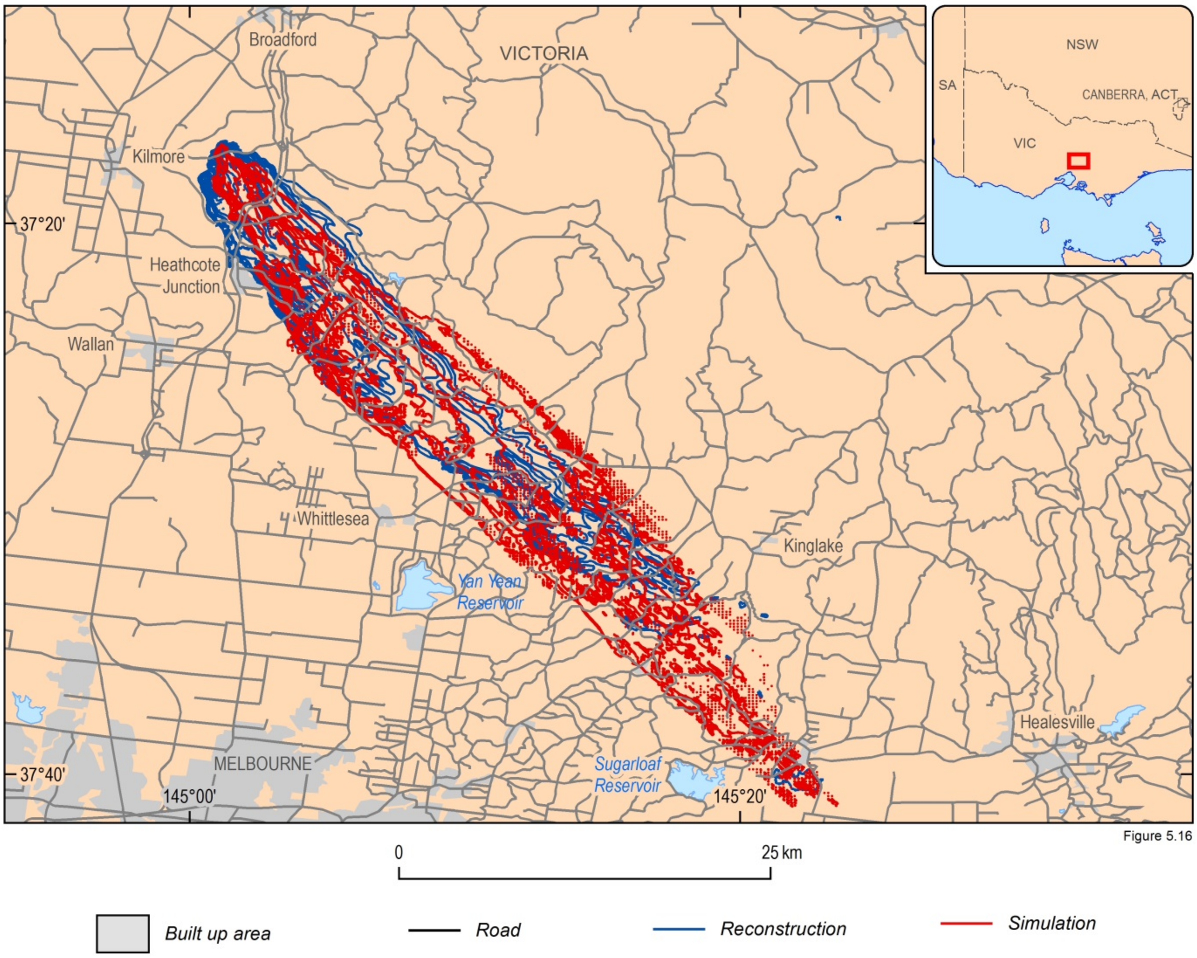


Figure 5.16 4000 m 5 minute bias corrected speed plus five m/s (red) with Kilmore fire reconstruction (blue) to 17:30.

5.3.5 Sensitivity to temperature

The fire spread for two temperature scenarios are shown in Figure 5.17 (temperature -2°C) and 5.18 (temperature +5°C). A decrease in temperature is reflected in a decrease in the width of the fire (thinner than the reconstruction). An increase in the temperature results in a wider and longer shape than the reconstruction.

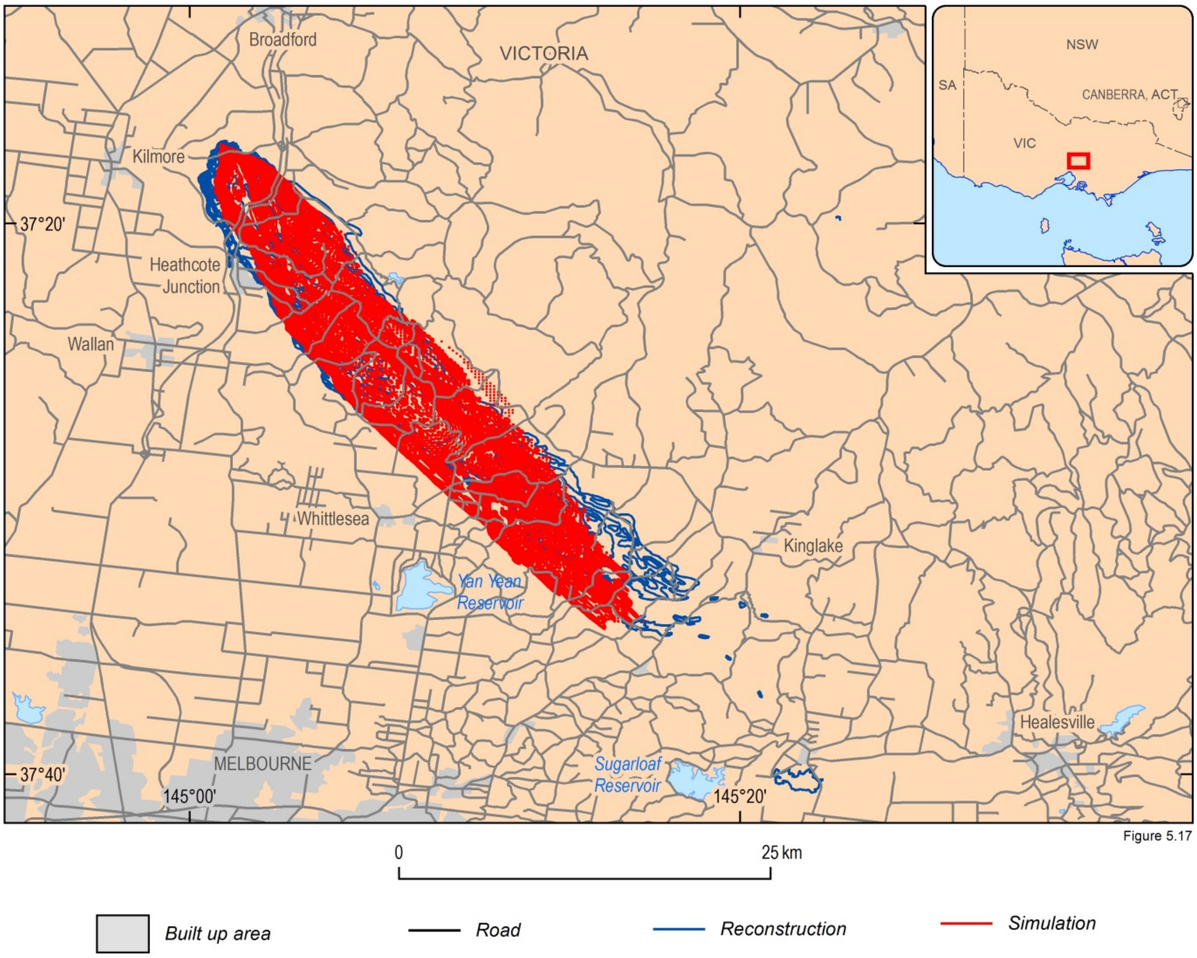


Figure 5.17 4000 m 5 minute bias corrected temperature minus two degrees C (red) with Kilmore fire reconstruction (blue) to 17:30.

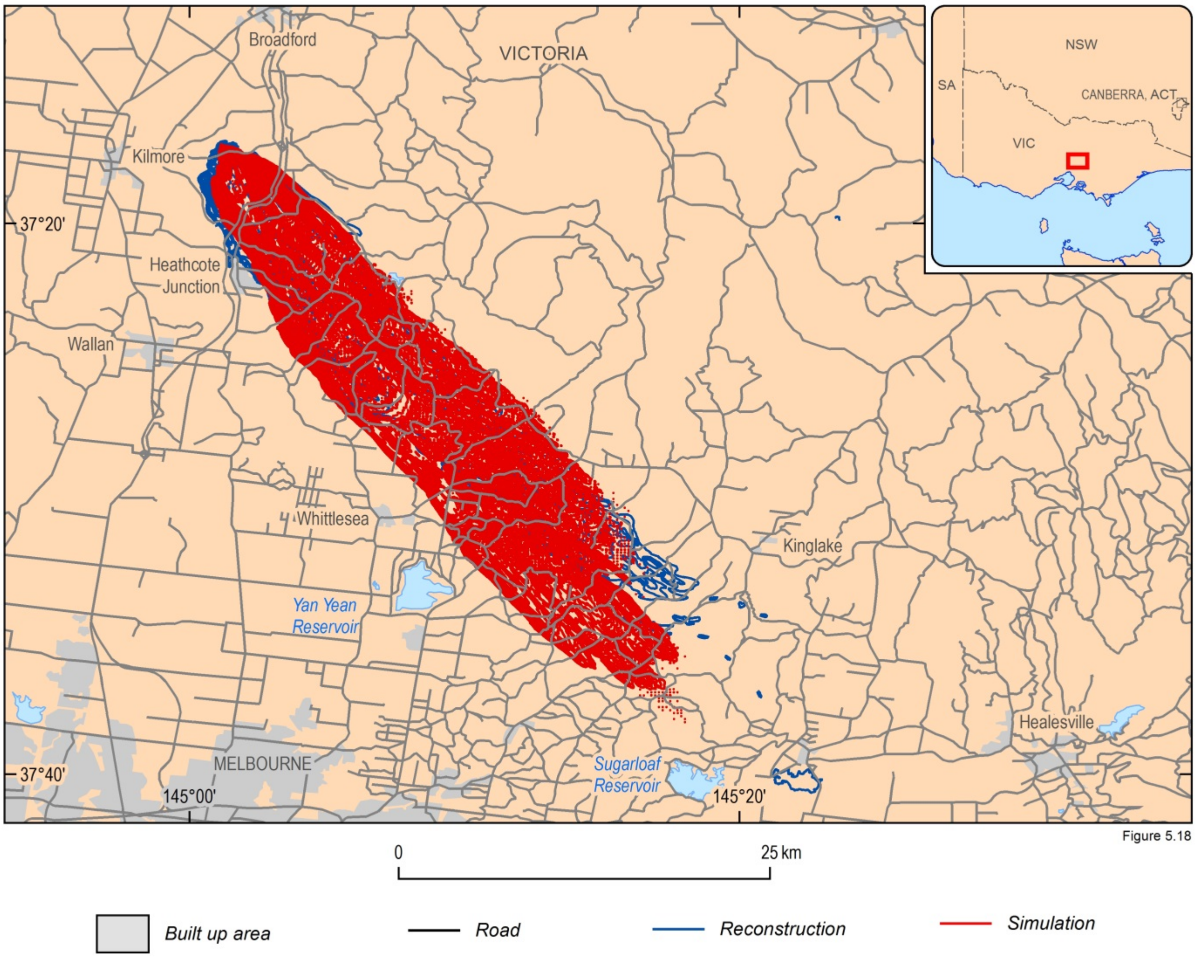


Figure 5.18 4000 m 5 minute bias corrected temperature plus five degrees C (red) with Kilmore fire reconstruction (blue) to 17:30.

5.3.6 Sensitivity to humidity

To demonstrate that the FireDST approach enables assessment of the modelled fire spread sensitivity to humidity, two humidity shifts are shown in Figure 5.19 (humidity minus two percent) and Figure 5.20 (humidity plus five percent). These two values were chosen because on the day of the Kilmore Fire there was low humidity and introducing large perturbations in the simulations would not reflect what could actually occur in the environment. As expected, a decreased humidity results in a larger fire shape in length and overall area (Figure 5.19). It is interesting to note that a global increase of humidity of 5 percent resulted in a fire shape that corresponded closely to the reconstructed shape of the historical fire (Figure 5.20). This indicates that if we only consider humidity variations, there could have been increased humidity present in the landscape that was affecting the fire spread.

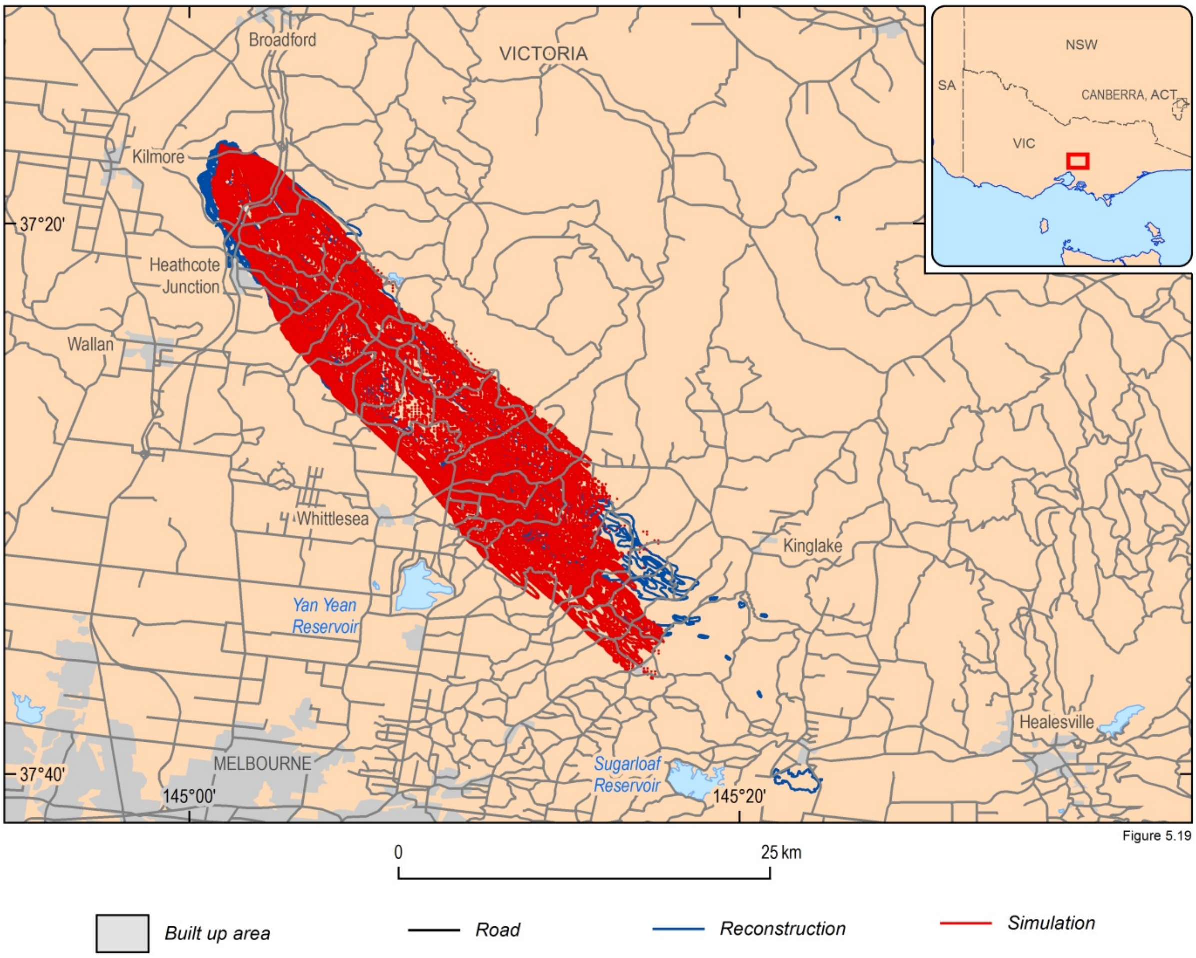


Figure 5.19 4000 m 5 minute bias corrected humidity minus two percent (red) with Kilmore fire reconstruction (blue) to 17:30.

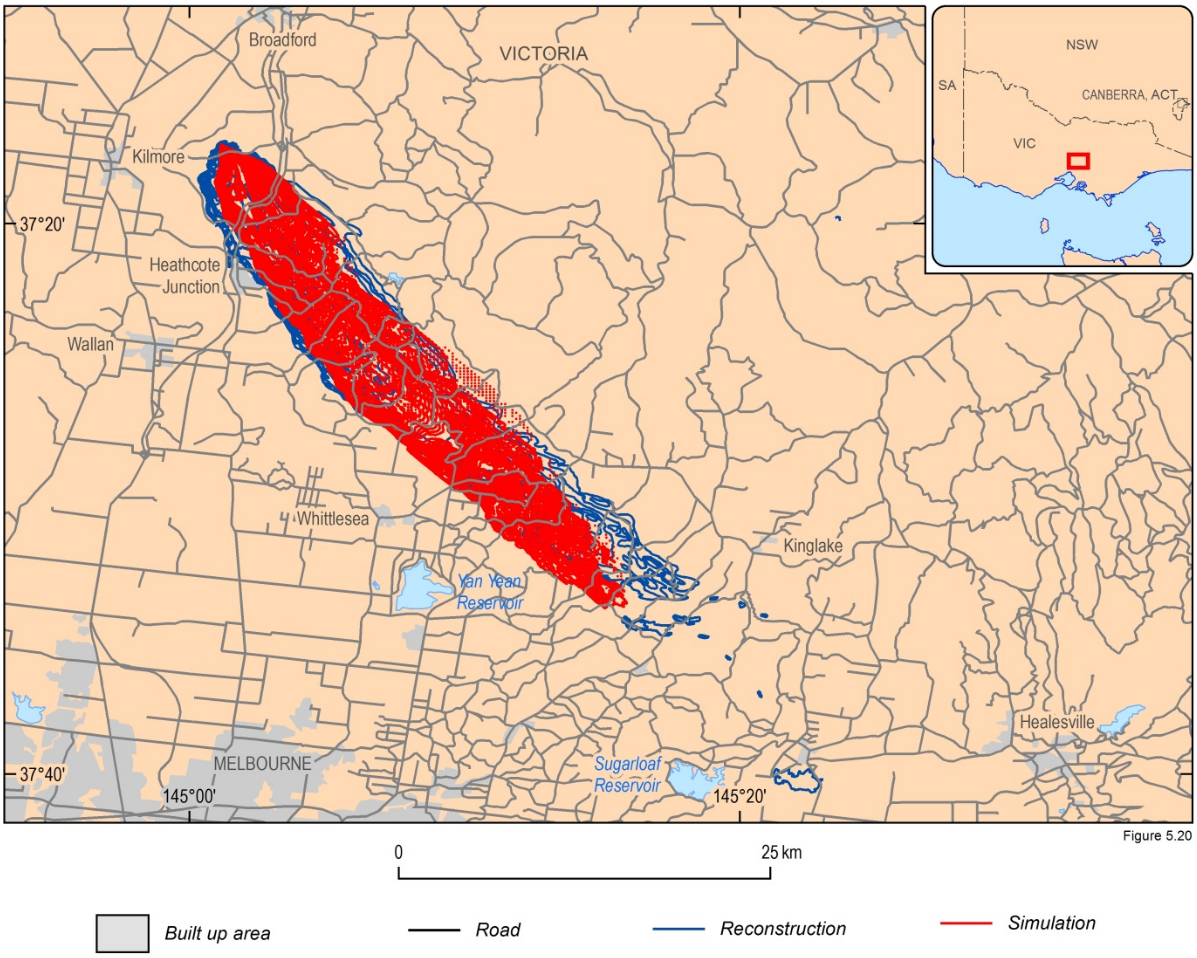


Figure 5.20 4000 m 5 minute bias corrected humidity plus five percent (red)) with Kilmore fire reconstruction (blue) to 17:30.

5.3.7 Sensitivity to multiple variations in the weather

The FireDST Weather Ensemble Generator enables any combination of the single weather files to be grouped into a weather scenario. Figure 5.21 shows a scenario where the following modifications were made to the conditions of the original Kilmore fire:

- Wind speed plus five m s^{-1}
- Wind direction plus ten degrees
- Temperature plus five degrees Celsius
- Relative humidity minus two percent

Multiple variations in weather meant the fire spread incorporated more complex interactions between weather variables. Comparing the results of this scenario with those shown in the previous sections of this chapter illustrates that. The resulting fire spread shown in Figure 5.21 does not closely reflect the influence of single individual parameter that defines the scenario. For example, the change in direction of the fire shape is less than that caused by the same perturbation to the wind direction in isolation (compare to Figure 5.13), and the size increase is larger than that caused by an increase in wind speed that generated Figure 5.16. This underlines that sensitivity of the modelled fire shape to key parameters cannot be judged in isolation when the modelled process is also sensitive to interactions between the parameters, caused by the physical processes that drive the fire.

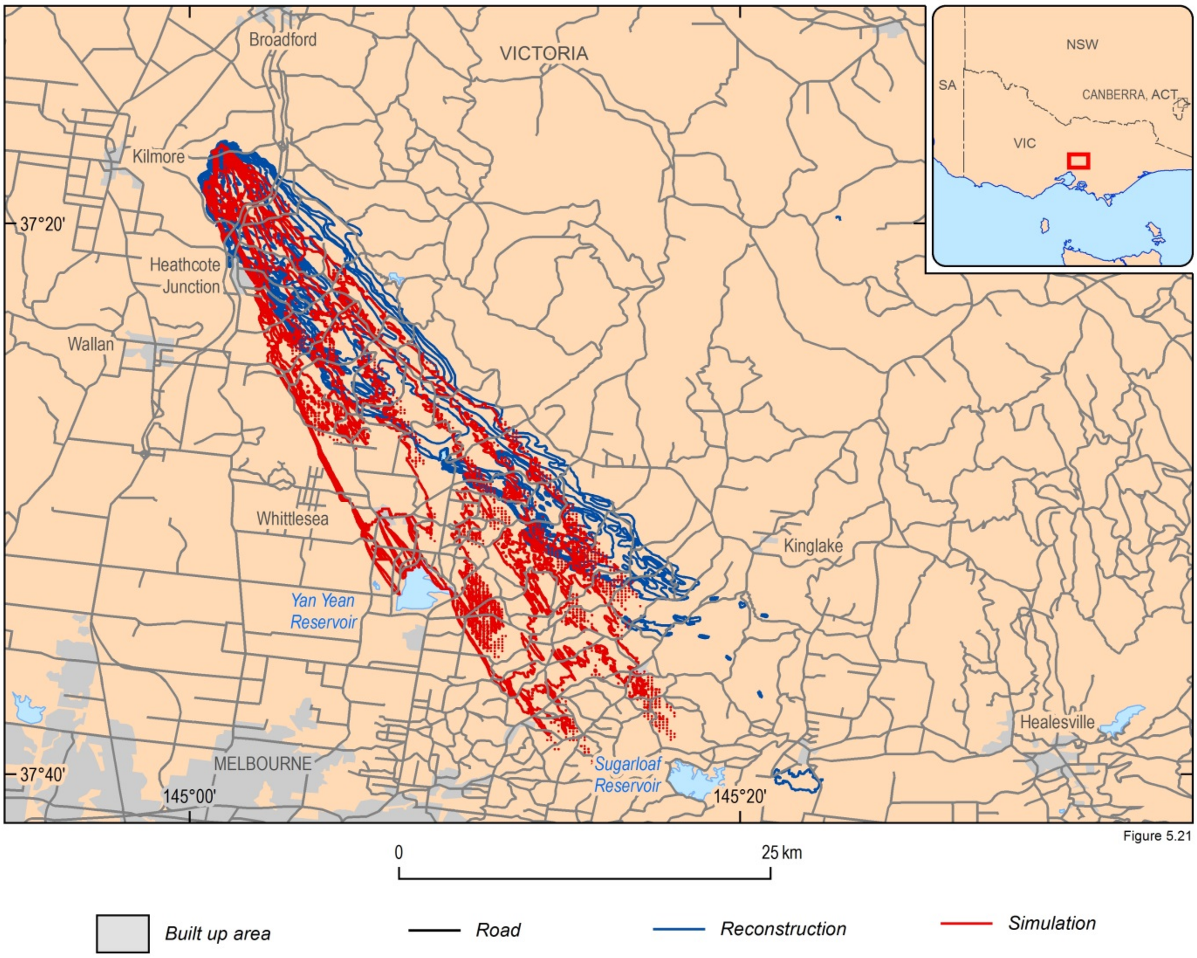


Figure 5.21 Kilmore simulation with ACCESS Weather at 4000 m 5 min interval, bias correction of wind speed, wind ninja, humidity minus two percent temperature plus 5 degrees, wind direction plus 10 degrees, wind speed plus five m/s to 17:30.

5.4 Conclusions and Future Work

The results in this chapter lead to the following conclusions on the variability of the fire spread to the surface weather conditions. The fire spread modelled by FireDST for the Kilmore fire underestimated the size of the historical event, based on the reconstruction of that event. Comparison with historical observations indicated that the modelled wind speeds were consistently under estimated by the ACCESS model. Bias correction of the ACCESS wind speeds slightly improved the accuracy of the fire spread for 4000 and 1200 m resolution but not the 440 m ACCESS results.

The introduction of local wind modifiers (from Wind Ninja) after bias correction improved the accuracy of the modelled fire spread. The benefit of the local modifiers was not evident for simulations based on the 440 m bias corrected weather data. The cause of this result is unknown and will need further investigation.

The FireDST Weather Ensemble Generator was shown to implement an effective approach to generate simultaneous modifications of temperature, humidity, wind speed and wind direction. Thus, FireDST provides a method for reflecting sensitivity to uncertainties in the surface weather inputs in the fire spread modelling.

The results also demonstrated that sensitivity of the modelled fire shape to perturbations in key parameters cannot be judged in isolation. The modelled process is also sensitive to interactions between the parameters, caused by the physical processes that drive the fire. When assessing robustness of a fire spread prediction or generating a probabilistic fire spread forecast, this interaction between the input parameters has to be explicitly built into the sampling design of ensembles.

5.4.1 Future Work

The scope of this research was limited to simple changes in the weather conditions. The choice of scenarios was not based on an understanding of the variations in the weather output. Furthermore, the changes implemented for each scenario were applied 'globally' across the landscape. Such global changes are not realistic, as local terrain and vegetation will affect the local conditions of the weather. For example bias in temperature or wind speed may vary between deep, vegetated river valleys and smooth exposed hill sides. Further work should identify the benefit of quantifying variations in local weather conditions at specific locations across the landscape.

6 Assessing sensitivity of the fire spread to the weather conditions in the upper atmosphere

6.1 Objective

Upper level wind speed and direction are key drivers of the spread of embers from the fire (Cruz *et al*., 2012). The objective of this research was to develop a methodology for integrating uncertainties in the wind direction and speed at different altitudes into the FireDST system. The main aims of this research were to:

Evaluate the vertical atmosphere weather conditions as a driver of the ember transport layer in the fire spread modelling. This was achieved by assessing different layers in the supplied 4000 m 15 minute 50 level (level 0 to level 49) ACCESS vertical atmosphere as part of the weather used to simulate the Kilmore fire and comparing the simulation with the reconstruction of the historical fire.

Evaluate the implication to fire spread models of perturbing atmospheric conditions.

6.2 Methodology

6.2.1 Background

Atmospheric wind speed and direction are critical in simulating the spread of embers and smoke from a fire. Atmospheric levels above the boundary layer (generally above 500m) provide a transport mechanism for the smoke to be transported long distances. The plume height for the Kilmore fire could have extended to 15 km above the ground surface (Cruz *et al*., 2012). This altitude is also consistent with other research on the plume height of catastrophic fires such as Canberra 2003 where the cloud tops of the plume extended to around 14 km above mean sea level (Webb *et al.,* 2004).

Two types of ember spread were apparent in the Kilmore fire: long and short range spotting. Around 4 pm long range spotting spot fires were detected 33 km ahead of the fire front and probably 40 km from the original fuel source for the embers (Cruz *et al.,* 2012).There were also short range ember storms apparent in the Kilmore fire. Cruz *et al.,* (2012) state that the strong winds at or just above ground level forced the burning embers through flat trajectories (rather than being lofted), delivering embers directly ahead of the fire to a distance of about 500 m.

To investigate the effect of both ground ember generation and lofted embers, the analysis described here examined the effect of all the simulation layers up to the top of the simulated atmosphere on the fire spread.

To enable this research, PHOENIX RapidFire was enhanced by the University of Melbourne to include an optional ember “transport layer” based on wind strength and direction inputs. This version was integrated into the FireDST system.

The Bureau of Meteorology generated a simulated atmospheric profile from 10 m to 60km for the Kilmore fire at 4000 m grid resolution at 15 minute time steps and 50 vertical heights (levels) for both wind speed and wind direction. Details of the 50 levels are shown in Table 6.1.

The PHOENIX RapidFire convection bubble model was modified by the University of Melbourne to include an extra “transport layer “ wind direction and wind speed. Each level was extracted from the ACCESS weather profile and used as the transport layer. The ACCESS 10 m (equivalent to the surface weather) 4000 m 15 minute files were used to provide the surface temperature, humidity, wind speed and direction

Table 6.1 Levels used in the vertical ACCESS wind speed and direction files.

Level	Altitude (m)
0	9.99777
1	50.0014
2	130.003
3	250.001
4	410.003
5	610.003
6	850
7	1130
8	1450
9	1810
10	2210
11	2650
12	3130
13	3650
14	4210
15	4810
16	5450
17	6130
18	6850
19	7610
20	8410
21	9250
22	10130
23	11050
24	12010
25	13010
26	14050
27	15130
28	16250
29	17410
30	18590
31	19770.3

Level	Altitude (m)
32	20951.7
33	22136.7
34	23329.7
35	24538
36	25772.5
37	27048.4
38	28385.6
39	29809.8
40	31353.3
41	33055.1
42	34962.2
43	37130.1
44	39623.5
45	42516.9
46	45895.4
47	49855.8
48	54506.4
49	59968.6

This section presents a brief analysis of the supplied ACCESS vertical atmospheric profile to provide an overview of the simulated atmospheric wind speed conditions. The analysis will review the wind speed conditions at or near the ignition point. The closest down-wind weather (ACCESS 4000 15 minute) grid point to the Kilmore ignition point (-37.285, 145.015) is in the pine forest adjacent to Saunders Rd (about 2.537 km to the ESE of the ignition point) at -37.296 145.040 (Figure 2.3).

An extract of the ACCESS modelled atmospheric profile wind speed over time at the closest down-wind point is displayed in Figure 6.1 to 6.4. Only the boundary layer wind speeds are shown in Figure 6.1(10 m, 50 m (level 1), to 850 m (level 6)). Figure 6.2 shows the layers just above the boundary layer (1130 m (level 7), to 3130 m (level 12)). Each wind speed at these altitudes is fairly uniform prior to around 19:12 when the simulated ACCESS cold front change has passed over this point. The large variations in wind speed after 19:12 are the results of the instabilities in the atmosphere after the passage of the cold front.

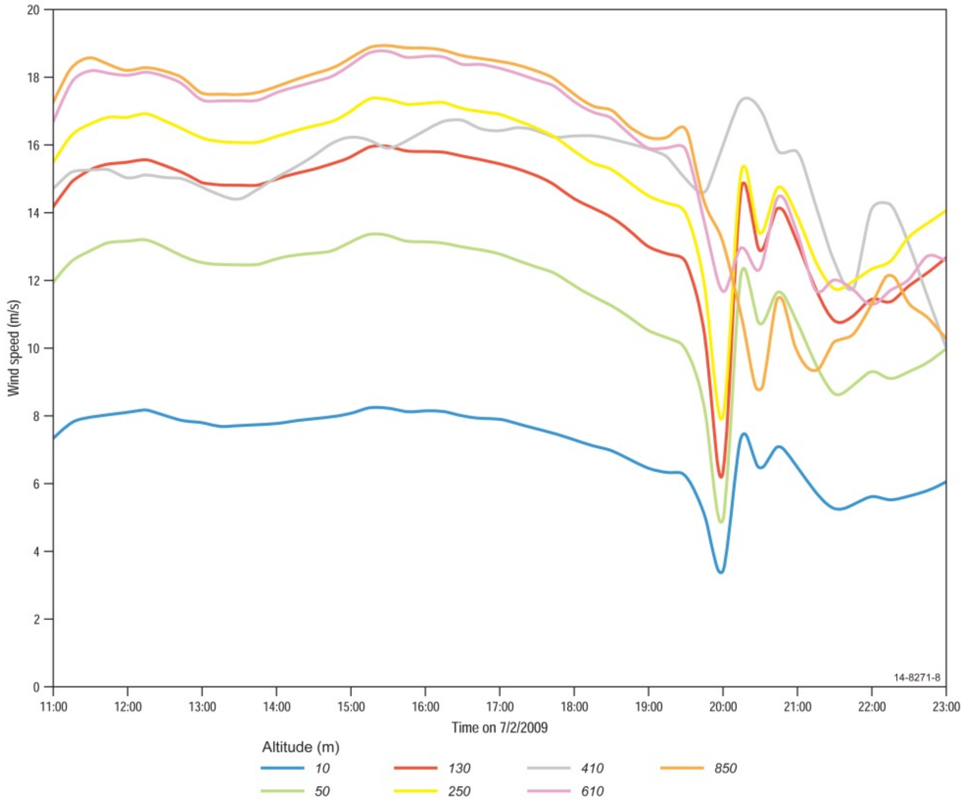


Figure 6.1 Wind speed at altitude (in boundary layer) by time for location -37.296, 145.040.

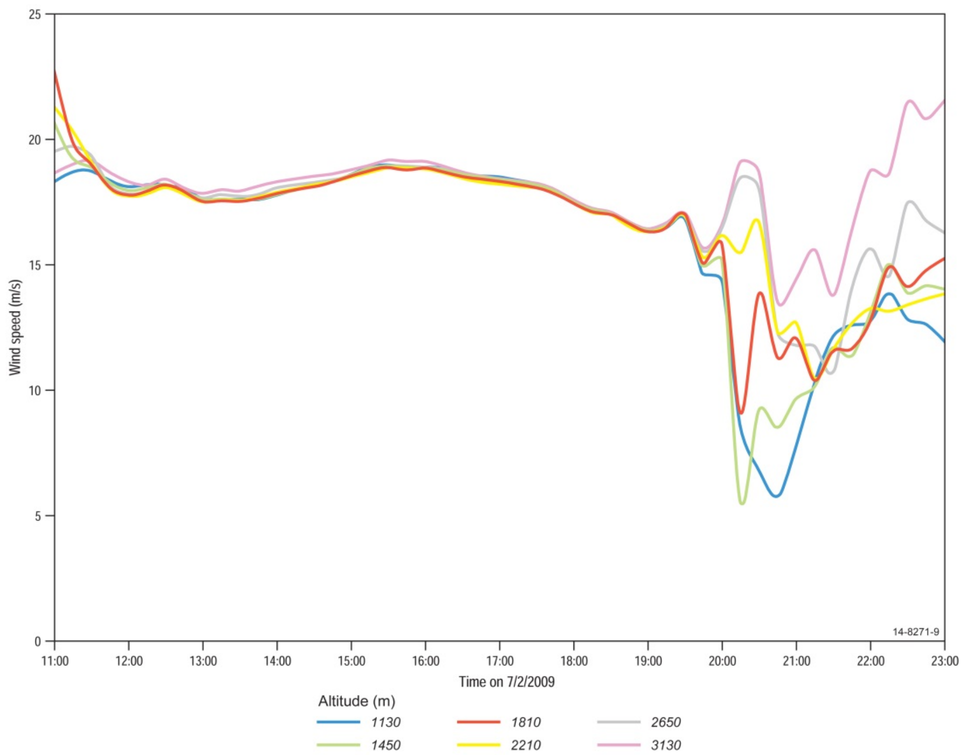


Figure 6.2 Wind speed at altitude (just above the boundary layer) by time for location -37.296, 145.040.

Figure 6.3 shows the upper atmosphere layers from 10 km (level 22) to 60 km (level 49)). As expected in the upper atmosphere Figure 6.3 shows much higher wind speeds than those in the lower regions of the atmosphere and the wind speeds show no influence from the passage of the cold front.

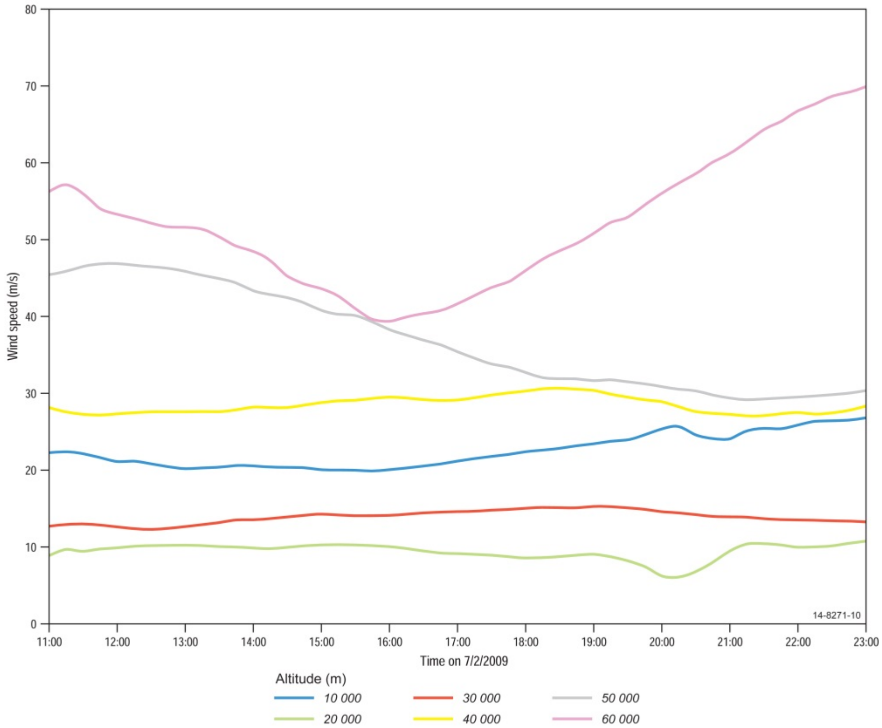


Figure 6.3 Wind speed at altitude by time for location -37.296, 145.04.

Figure 6.4 displays the atmospheric wind speed profile for the first 60 km altitude at this location (-37.296, 145.04) 15 minutes after the Kilmore fire ignition (25 hours or 1200 (noon) on 7 February 2009). The profile shown in Figure 6.4is very similar to standard atmospheric profiles generated by the release of weather balloons.

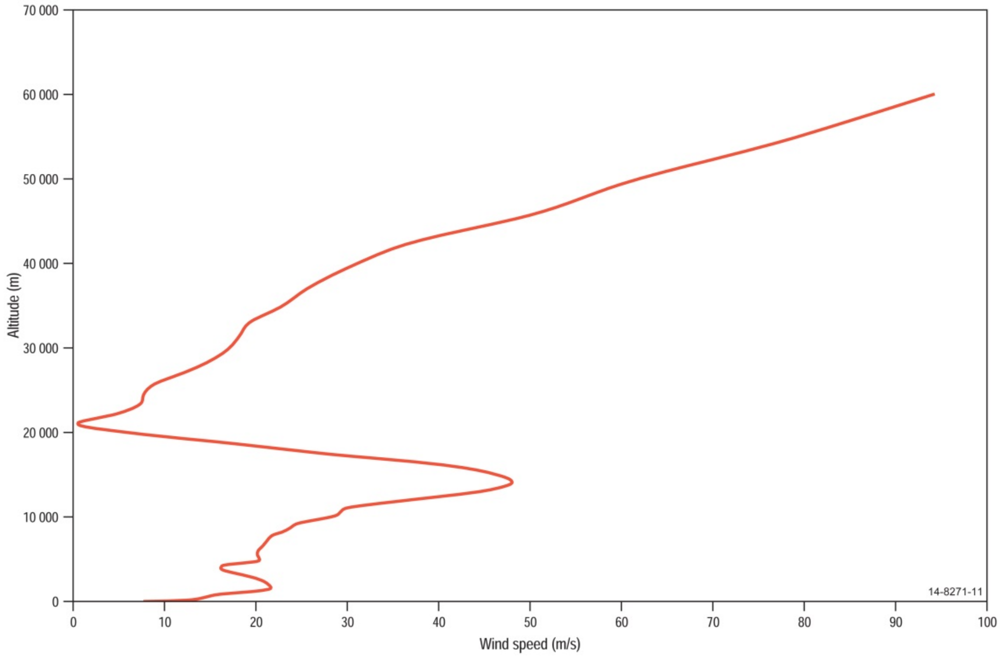


Figure 6.4 Altitude and wind speed for the first 60 km for location -37.296, 145.04.

6.2.2 Method

Simulations were conducted using a single set of surface weather conditions and standard physical conditions for all of the vertical simulations. The surface weather conditions were defined by the ACCESS 4000 m, 15 minute weather, which was both bias corrected and further adjusted using the Wind Ninja local wind modifiers (see Chapter 5). The upper level conditions were specified by each of the respective vertical layers in turn. This is the only section in this document where the 15 minute surface weather from ACCESS is used, as the upper level atmosphere was also modelled at a 15 minute resolution. Bias correction of the upper level wind speed, as described in Chapter 5 for surface winds, was not possible for winds in the vertical profile. This is because there was only one historical observation for the Kilmore case study area and time.

The fire simulation was halted at 1745 EDST on 7 February 2009. This ensured test simulations were run in the more stable atmospheric conditions prior to 17:45, which allows effective comparison of fire shapes produced by each level of the atmosphere. Had simulations been run after this time, the effect of the large variations in the weather caused by the passage of the cold front (see Figure 6.1) might have masked the sensitivity to different atmospheric levels.

The simulations in Section 6.3 examine the sensitivity of the supplied ACCESS vertical layer used to define ember transport.

6.3 Results and Discussion

6.3.1 Sensitivity to conditions up to atmospheric level 12

The simulation results for all levels up to level 12 (3130 m) showed two distinct sets of results.

The simulations based on upper level atmospheric conditions from levels 1 to 4 produced a good approximation of the fire reconstruction shape. The shapes produced more accurate simulations than using the 10m weather. Figure 6.5 shows the simulation shape for level 4 (410 m).

Simulations based on upper level atmospheric conditions specified in level 5 (610 m) to level 12 (3130 m) overestimated the fire shape. The area and forward rate of spread at these levels is almost double that in the actual fire reconstruction (see Figure 6.6).

Although the conditions in the ACCESS lower atmosphere (at and below level 4) reproduced the observed area and forward rate of spread of the Kilmore fire, the higher atmospheric levels must have been involved in the real ember transport to be able to send the embers up to 30 km (Cruz *et al.,* 2012). This suggests that either the new convection-driven ember transport mechanism in PHOENIX RapidFire does not accurately model fire spread using the upper level wind strength, or that the upper level winds were overestimated in ACCESS or that the ember transport mechanism in the Kilmore fire was only in the lower 400 m of the atmosphere (to 410m).

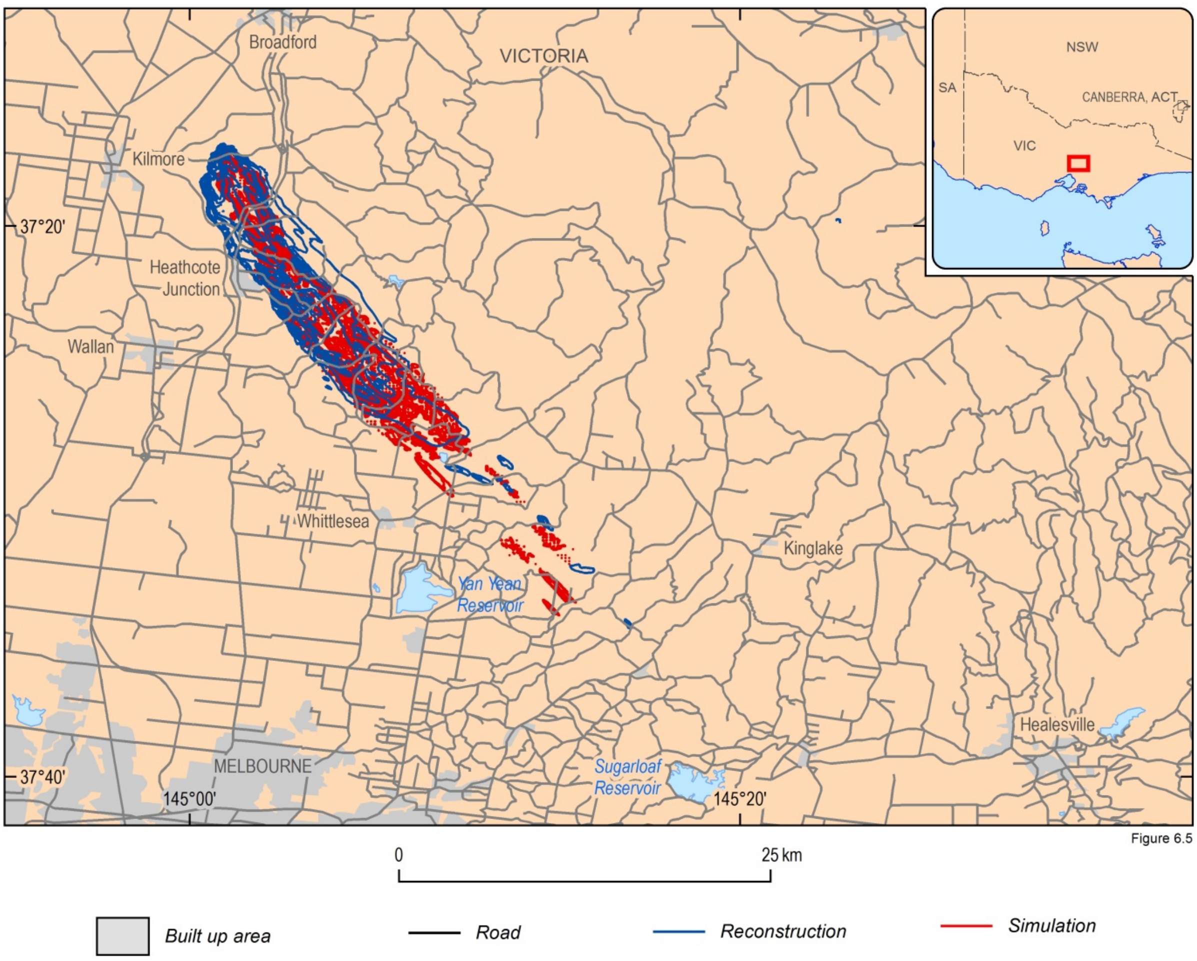


Figure 6.5 Level 4 as the transport layer (red) fire reconstruction (blue) to 16:30

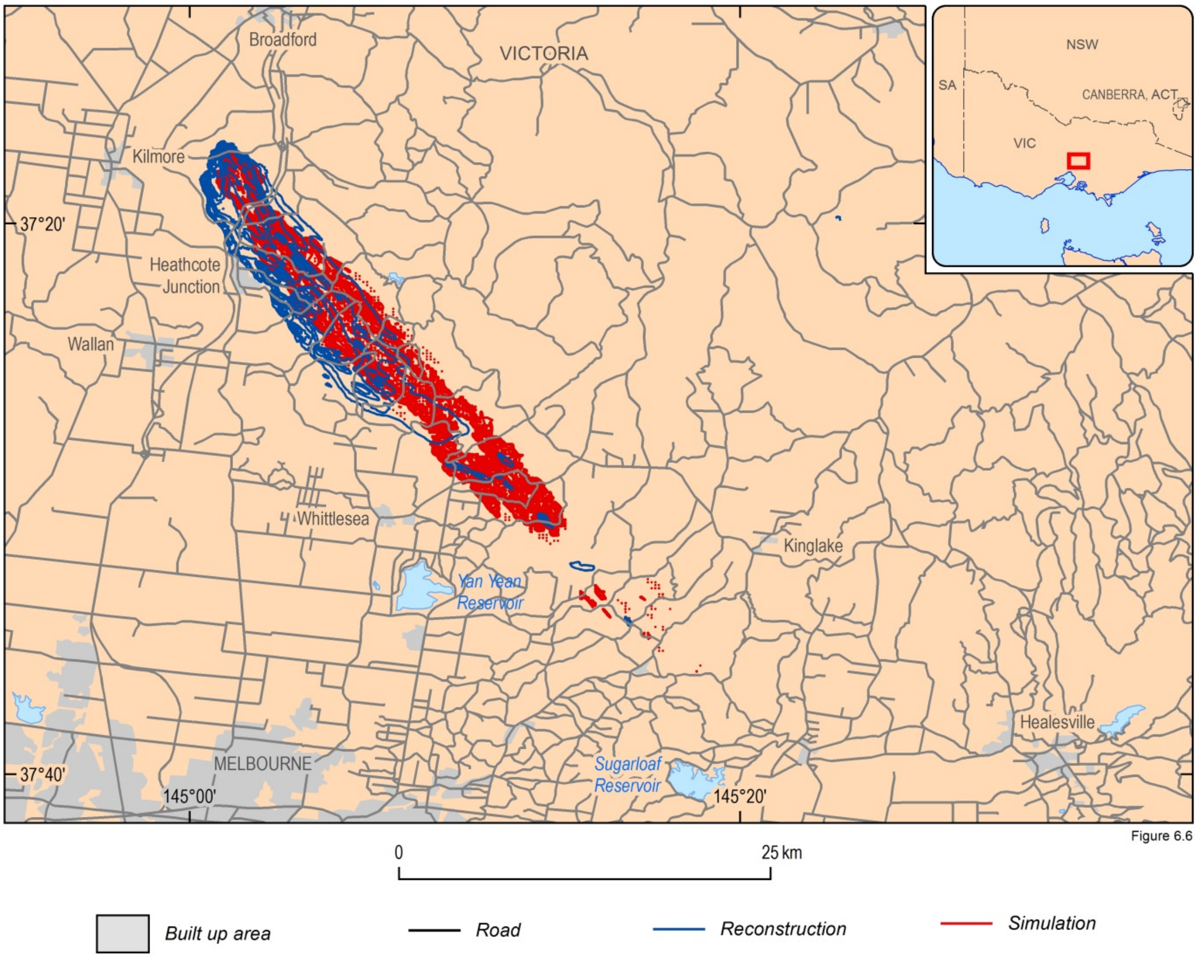


Figure 6.6 Level 12 as the transport layer (red) fire reconstruction (blue) to 16:30.

6.3.2 Sensitivity to conditions above atmospheric level 12

The analysis examined all levels from level 13 (3650 m) to level 49 (59968.6 m.) Throughout the vertical profile above level 13, the dominant wind direction was significantly different to the wind direction for the reconstruction of the Kilmore fire. Variations in wind direction and strength across these vertical levels resulted in large variability in the fire spread simulations, none of which approximated the reconstructed fire shape. For example the area and forward rate of spread in Figure 6.7 (for level 19 (7610 m) is almost triple the actual fire reconstruction area, with a directional spread towards the east. The upper level wind direction and strength at this altitude pushed the fire simulation through the heavily wooded National Park.

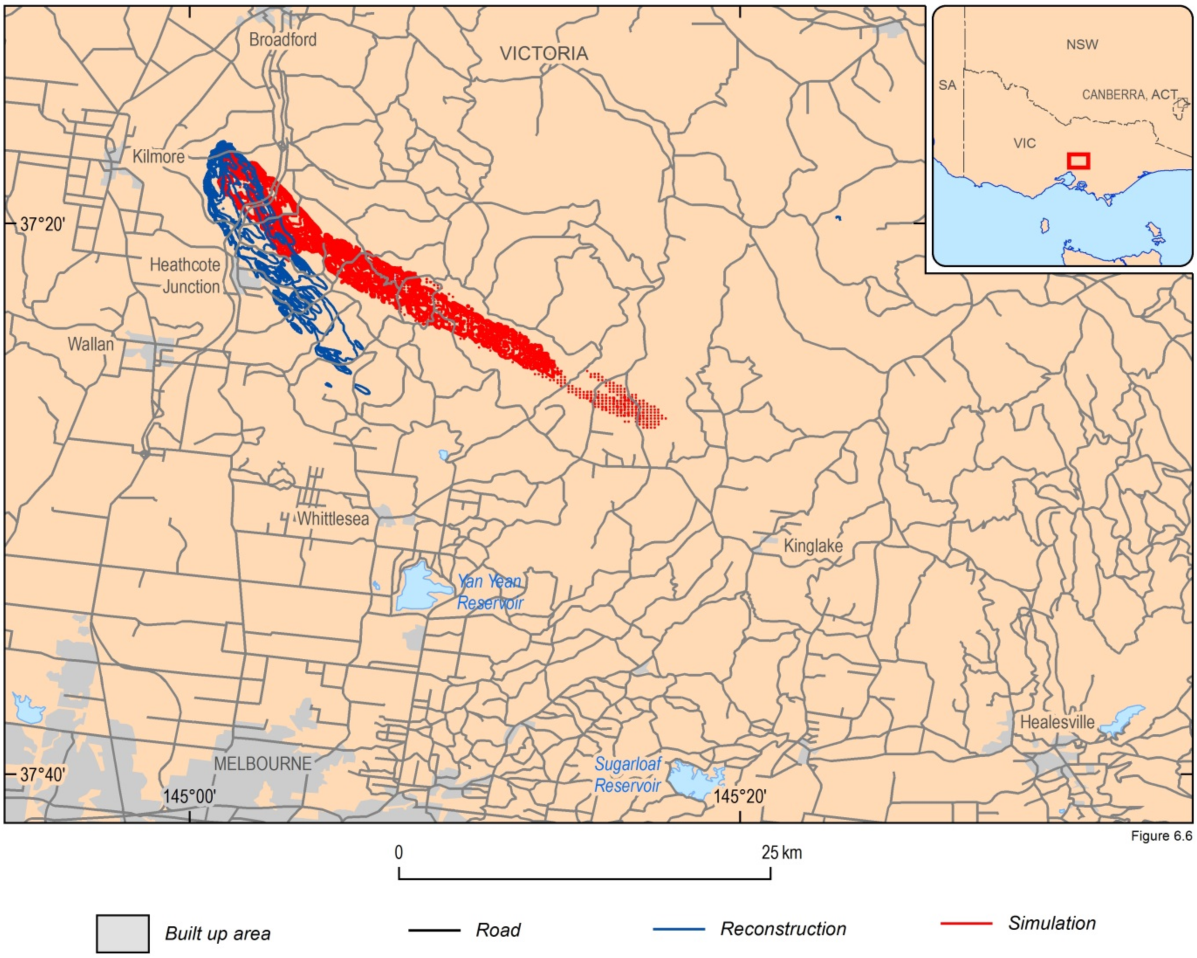


Figure 6.7 Level 19 as the transport layer (red) fire reconstruction (blue) to 1540.

The conclusion is that even though the smoke reached around 14km in the Kilmore fire that only the atmospheric winds in the levels to level 12 (3.1 km) could have been used in ember transport. If levels above level 12 had been used for ember transport then the actual Kilmore fire would have burnt in a completely different direction.

6.4 Conclusions and Future Work

The work described in this chapter has yielded further insights of the sensitivity of the Kilmore fire modelling to the upper level atmospheric conditions. Any bushfire simulation has to consider the upper level wind direction, as it drives the transport of fire embers. However, the work described here indicated not all vertical atmospheric levels produced results that matched the reconstruction of the Kilmore fire:

FireDST produced realistic results for the fire spread when using winds from lower levels in the boundary layer (level 0 to level 4, up to 410 m).

Simulations based on level 5 (610 m) up to level 12, (3130 m) overestimated the forward rate of spread, leading to a longer burnt area than the reconstructed Kilmore burnt scar. This indicates either that the modelled winds at those vertical levels were overestimated, or that the ember transport mechanism in PHOENIX RapidFire was too sensitive to wind, or that the ember transport mechanism in the Kilmore fire was only in the lower 400 m of the atmosphere (to 410m).

From level 13 (3.6 km) and up, the ACCESS wind direction differed significantly from the dominant wind direction of the actual Kilmore fire. This suggests that in the actual Kilmore event, winds at heights below level 13 played a role in ember transport and long distance spotting. Note that level 13 (at 3.6 km) is under a quarter of the observed plume height (at around 15 km) and this indicates that embers were not transported as high as the smoke.

6.4.1 Future Work

There is a range of further work required to validate and improve the parameterisation of convection and ember transport in PHOENIX RapidFire. University of Melbourne Team has identified several PHOENIX RapidFire improvements that could improve the representation of ember transport in the model. These improvements are chiefly aimed at refining the physical basis for the generation of the convection column and related issues, such as the coalescing of two fire fronts which affects the convective power of the fire.

Further work is needed to assess and validate what part of the vertical atmospheric profile is most effective to generate the correct convective strength in simulations of ember transport within the fire spread model.

The work here was initial research and only covered the use of the horizontal winds at each level. Further work should consider both the horizontal and vertical components in the ACCESS atmosphere to provide a more accurate model of the flow of embers between layers.

This research was based on ACCESS weather specified at 4000 m horizontal resolution and 15 minute time intervals. Future work could be conducted with 1200 m and 440 m resolution atmospheres that could then be directly matched with the supplied 10 m ACCESS weather (at 1200 and 440 m). Also, the 4000 m ACCESS atmosphere could be examined in conjunction with the 1200 and 440 m 10 m ACCESS weather files. Comparison of the simulation results would determine what spatial resolution would yield acceptable results for computational effort.

7 Assessing the sensitivity of the fire spread to the fuel load

7.1 Objective

This section examines the sensitivity of the fire spread modelling to the vegetation conditions, such as fuel load. The scope of the vegetation component of the research described here included varying two PHOENIX RapidFire parameters that vary the fuel load:

1. the fuel regeneration curves, and
2. the fire history.

In addition, the University of Melbourne conducted a sensitivity analysis of all the vegetation parameters used by PHOENIX RapidFire as part of the F.I.R.E.D.S.T. project. The results of this work are reported in the final FireDST Report (Cechet et al. 2014).

7.2 Methodology

7.2.1 Background

PHOENIX RapidFire relies on the parameterisation of vegetation information on a 180 m resolution grid. PHOENIX RapidFire also includes internal equations and factors to characterise the vegetation further. (Tolhurst *et al.,* 2010) This vegetation parameterisation can introduce error and uncertainty into the fire modelling process, notably in the vegetation type, fuel load and fuel curing prior to the simulated fire.

This analysis concentrates on two aspects of the fuel load: the fuel regeneration curves, which defines the amount of regrowth of fuel over time after a previous fire, and fire history information.

7.2.2 Method – fuel regeneration curves

In PHOENIX RapidFire, each vegetation type contains a parameterisation schema for the amount fuel in three layers: surface fuel, elevated fuel and bark. Each layer of fuel contains three variables which define the shape of the fuel regeneration curve (Tolhurst *et al.,* 2010). The variables used to calculate the fuel regeneration curves are:

r – Potential magnitude of increase in hazard
k – rate of reaccumulation of hazard and
c – practical minimum level of hazard

Modifying these variables changes the regrowth curves for the layer in the fuel. A sensitivity analysis of the fuel regeneration curves was conducted by the University of Melbourne (Cechet *et al.,* 2014).

The variability of the fuel load was evaluated by modifying the value of r (range 0 to 5) for all woodland and forest fuel types at the elevated and bark levels in the fuel. Increasing the value provided the simulated fire with more 'fuel' to drive the spotting mechanism. Hypothetically, the fire could then spread further. Decreasing the value decreased the amount of fuel available for ember transport, and so would produce a smaller fire shape.

7.2.2.1 Method – fire history

PHOENIX RapidFire can ingest a grid based ‘fire history’ file. Each cell contains either a blank value (indicating no previous fire) or a date (of the most recent fire that burnt that cell) (Tolhurst *et al.,* 2010). Based on the time since a cell was last burnt (either in a prescribed burn or an actual fire) and the cell vegetation type, PHOENIX RapidFire calculates the fuel load for that cell (see 7.2.2). If no previous burn is specified, the maximum fuel load is assumed.

The section below discusses the results from two tests:

Simulate the fire assuming the historical fuel load of 7 February 2009, based on the fire history prior to that date, and

Simulate the fire assuming a maximum fuel load, ignoring any fire history data.

7.3 Results and Discussion

7.3.1 Sensitivity to fuel regeneration curves

FireDST correctly models the variation in the fuel regeneration curves. Figure 7.1 shows the results for a simulation where the *r* values (elevated and bark) for the woodland and forest fuel types were elevated to 4.0 (from 2.5). The simulated fire shape was more extensive and had a larger forward rate of spread than the fire that assumed the standard fuel regeneration curves. This would be explained by the fact that the higher fuel load would generate more embers which spread the fire further and faster.

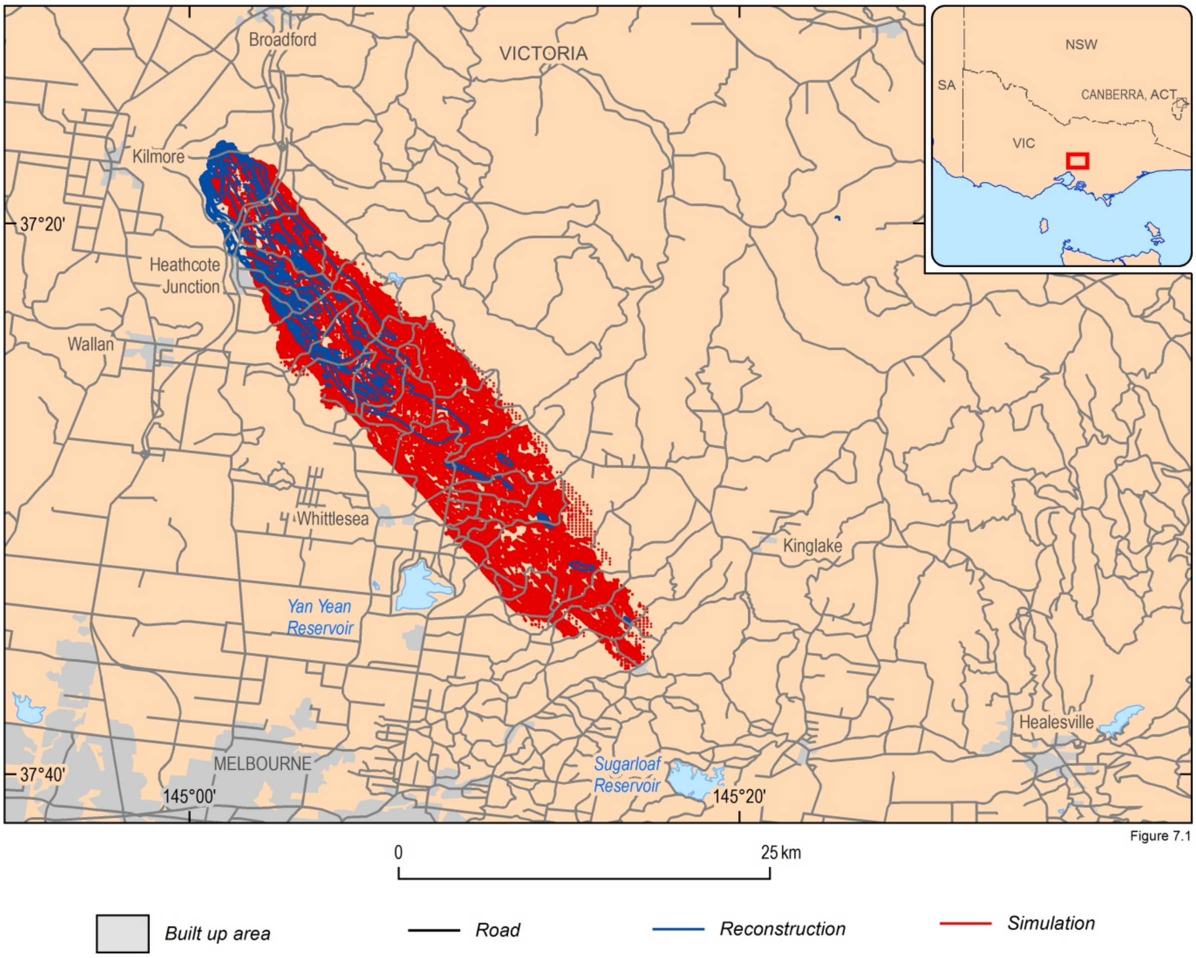


Figure 7.1 The effect of increasing the fuel regeneration curves for the Forest-fuel type to having bark_r =4 and elevated_r = 4.Simuation and reconstruction to 16:30.

Figure 7.2 shows the results for a simulation where the *r* values (elevated and bark) for all woodland and forest fuel types were lowered to 1.0 (from 2.5). The resultant fire shape was far smaller than the fire that assumed the standard fuel regeneration curve. Again, this was expected as there was less bark and elevated material to drive ember based fire spread.

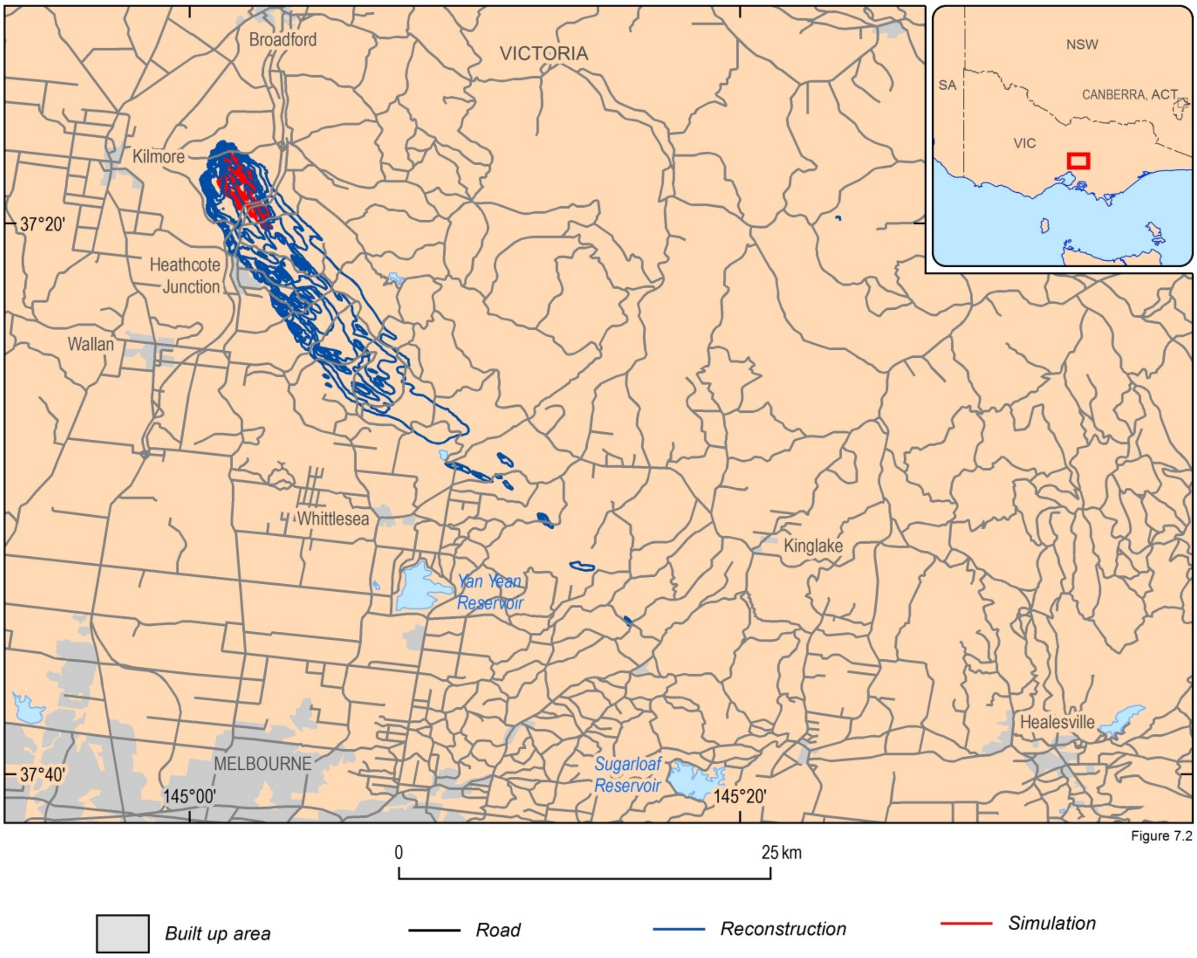


Figure 7.2 The effect of decreasing the fuel regeneration curves for the Forest-fuel type to having bark_r =1 and elevated_r = 1.Simulation and reconstruction to 16:30.

7.3.2 Sensitivity to Fire History

Figure 7.3 shows a simulation without the fuel history. When compared to a simulation using an actual fuel history, this simulation shows a larger burnt area as expected. The fire history acts to restrict the fuel load as the model accounts for regrowth since past fire events. By excluding the fire history, the fuel load is assumed to take a maximum value across the landscape. This translates into a larger fire spread, as shown in the result.

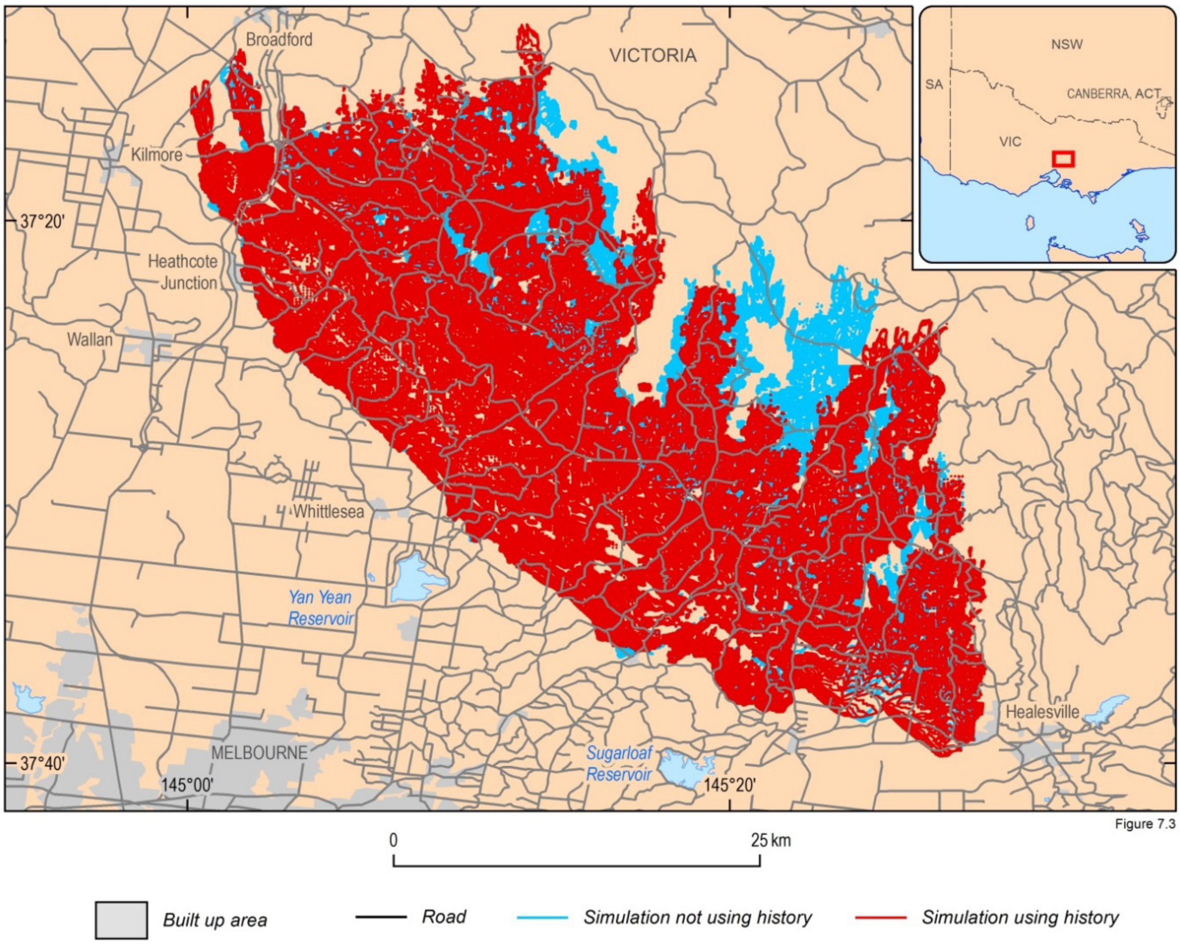


Figure 7.3 Sensitivity to fire history information up to 11:45 PM.

7.4 Conclusions and Future Work

This chapter discussed how FireDST enabled the assessment of the sensitivity of the fire spread simulation to the fuel load. Fuel load is determined by the time since a cell was last burnt, using fuel regeneration curves for each fuel type. Scenarios varying fuel loads were introduced by perturbing the fire history (time since last burnt) and the shape of the fuel regeneration curves. The results showed that the simulated fire spread was sensitive to the fuel load, in line with expectations.

7.4.1 Future Work

PHOENIX RapidFire includes a method for parameterisation of the regeneration of each fuel type following bushfires. These curves apply globally to the individual vegetation type across the landscape. Unfortunately the same vegetation type will regrow at different rates based on location characteristics (e.g. shrubs in a wet gully grow at different rates than shrubs growing on a dry plateau). It would be worth investigating the benefit of including location specific factors that take these conditions into account and modify the regrowth curves accordingly.

PHOENIX RapidFire includes fire history for when cells were last burnt and this is used by the fuel regeneration curves to predict the fuel load. However, when a fire burns it does not necessarily scorch every area to the same extent. For instance a crown fire may occur at one location but at another only the understory burns. Further work could investigate how this variability in post-fire fuel load can best be parameterised in the fire spread model.

8 Assessing the sensitivity of the fire spread to changes in ignition

8.1 Objective

This section examines the sensitivity of the fire spread modelling to changes in the ignition location and ignition time. There is always uncertainty in recording the actual ignition location and time because the first sighting of the fire is always subject to human interpretation. The scope of the research described here included:

1. Examining the sensitivity to ignition location.
2. Examining the sensitivity to variation in the ignition time of the fire

In this study, the input time is the best estimate of the ignition time and location of the Kilmore event. The ignition time for the historical Kilmore event was reasonably well constrained by the first call to emergency services (Gellie *et al.,* 2012). However the call was still around 10 minutes after ignition, and some uncertainty about the actual ignition time remains.

8.2 Methodology

8.2.1 Method –ignition location

The FireDST Ensemble Generator generated scenarios based on perturbations to an ignition point location. Ignition location was sampled by introducing offsets in distance along the cardinal axes (i.e. north, north east, east, south east etc.). The minimum offset from the input ignition location was set at 200 m to ensure that scenario ignitions were located different PHOENIX RapidFire grid cells (which are 180m).

8.2.2 Method –ignition time

The temporal variation was sampled as 5, 10, 15 and 20 minute deviations around the input ignition time.

8.3 Results and Discussion

8.3.1 Sensitivity to ignition location

Even with only a 200 m variation in ignition location, the four simulations presented variability in the fire spread. However, the differences were only minor and could be attributable to the slight differences in the vegetation that each fire consumed. Figure 8.1 shows the simulation shape for an ignition 200 m to the south of the Kilmore ignition which should be compared with Figure 5.7 which resulted in a slightly larger fire area (particularly in the south west of the simulation).

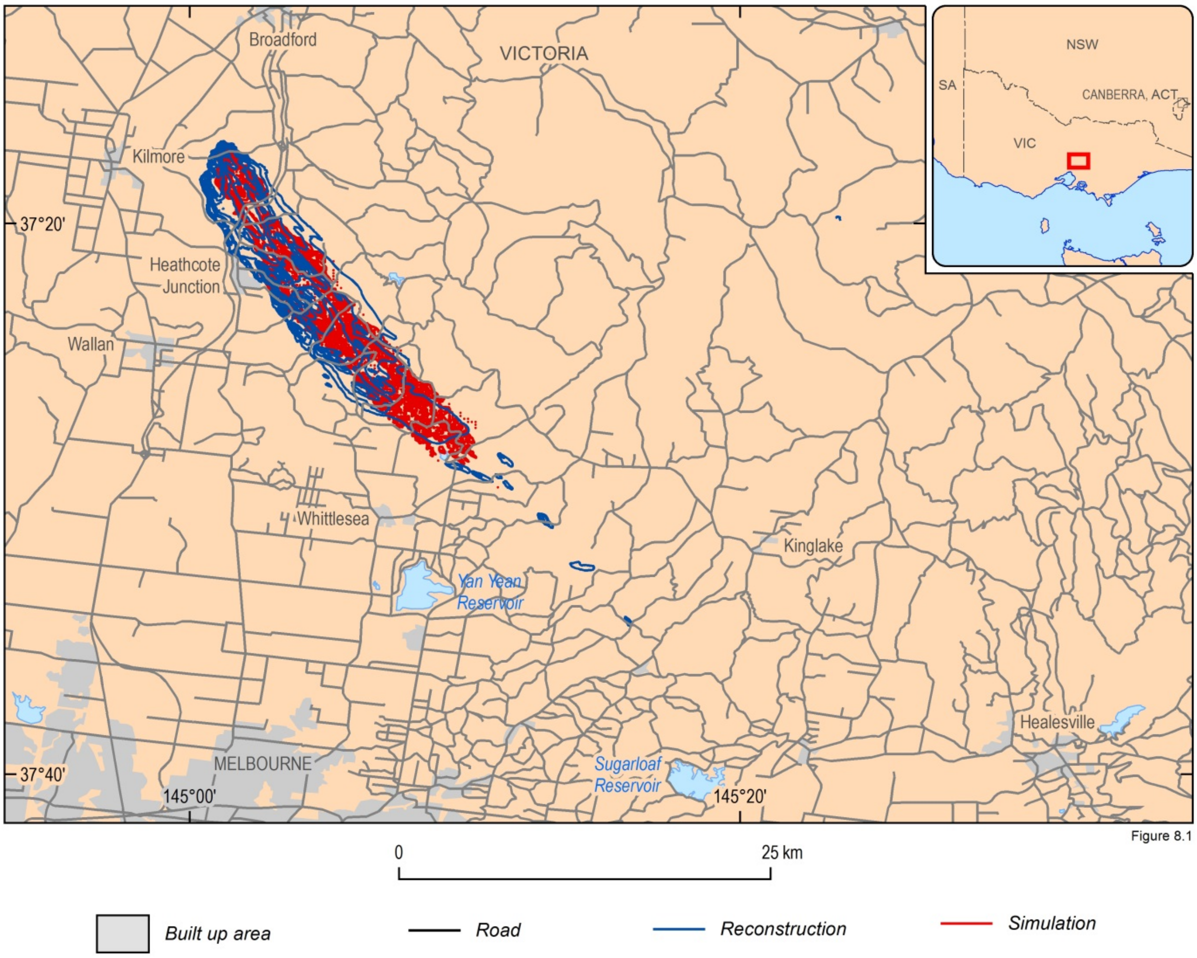


Figure 8.1 Ignition created 200 m to the north of the Kilmore ignition (using 4000 m 5 minute bias corrected Wind Ninja modified winds) to 16:30.

8.3.2 Sensitivity to ignition time

FireDST produced an ensemble consisting of eight scenarios with ignition times 20 min, 15 min, 10 min, 5 min prior and 5 min, 10 min, 15 min and 20 min after the (best estimate of the) historical Kilmore ignition time.

The simulations that had an earlier start time reached closer to Healesville as the fire had a longer time to spread to the south east before the change in wind direction occurred. Conversely, when the ignition time was delayed, the simulated fire shapes were shorter than the actual fire; probably because the fire had less time to spread before the change in wind direction.

8.4 Conclusions

This chapter discussed the results of an assessment of the sensitivity of the simulated fire spread to variations in the ignition conditions. FireDST was used to generate ensembles of scenarios with a perturbed ignition location and ignition time. This showed that the modelled fire spread is sensitive to variations in the ignition time and location. Sensitivity to ignition location appears to be mostly related to the change in the fuel conditions encountered by the fire. Sensitivity to the ignition time can be attributed to changes in weather conditions that influence the fire spread.

9 Estimating the number of buildings and people exposed to the fire spread

9.1 Objective

The work described in this chapter aimed to assess and visualise the number of buildings and people exposed to the fire as part of an integrated assessment of the fire spread and impact modelling.

9.2 Methodology

In risk assessment terminology, 'exposure' is commonly defined as the assets that are potentially at risk from bushfires. This could be buildings, people, roads and other infrastructure, or ecosystems. In this project, exposure was restricted to just residential buildings and people because this was the extent of the information available at the time.

The exposure information that underpinned the impact assessments in FireDST drew heavily on the National Exposure Information System database (NEXIS). NEXIS (Nadimpalli 2009; Canterford 2011) has been designed to provide exposure information for impact and risk assessments. It provides comprehensive and nationally consistent exposure information, derived primarily from reliable and publicly available datasets. The objective of NEXIS is to compile and maintain information at building level compatible with vulnerability assessment models for multi-hazards such as earthquakes, tsunami, tropical cyclones, floods, and bushfires.

The FireDST exposure information adopted the residential building information available in an older version of NEXIS for the case study, to reproduce as closely as possible the exposure that would have been around at the time of the Kilmore event. The 2011 version of NEXIS that was used contains information from the 2006 ABS Census.

Table 9.1 details the attributes (spatial, structural and economic) used in the FireDST exposure database based on the 2011 NEXIS residential exposure information. For each building, the database specifies the age of the building, the wall type and the roof type. All of these attributes are relevant in evaluating whether a building will be destroyed by fire (see Chapter 10). The database also contains an estimate of contents value and building replacement value.

Table 9.1 Spatial, structural and demographic/economic data fields for residential exposure derived from the 2011 version of NEXIS for FireDST.

Date type	Field Name
SPATIAL	Latitude Longitude Address Block size Floor area
STRUCTURAL	FCB type Roof type Wall type Age
DEMOGRAPHIC/ ECONOMIC	Income group No. residences No. people Structural value Tenure Contents value Motor Vehicle Access Age Group Need Assistance Volunteer Years at residence

The house location supplied by NEXIS was generally not accurate to the resolution required for fire modelling. In FireDST, the house location was adjusted to match the exact building location based on post-fire Kilmore survey data. Where survey information was not available, the house location was adjusted to the centre of the cadastral land parcel defined in the 250K resolution map.

The FireDST exposure also contains a variety of socio-economic information derived from the Australian Bureau of Statistics (ABS) 2006 Census. The NEXIS and ABS 2006 Census information was integrated so it could be stored as building-specific data. The 2006 Census information contains 14 vulnerability indicators (Metz and Canterford 2011) that have been included in the FireDST database. These indicators are listed in Appendix C Table C.1.

Unfortunately, the 2006 Census information was only published electronically at the Collection District level (this is at the resolution of a town or suburb between 200 and 800 people with an average of 400). For FireDST, the Collection District information from the 2006 Census was statistically averaged down to each house in the District.

Each house in a Collection District was allocated the same resident profile based on the Collection District information. An averaged profile is almost certainly inaccurate for most individual households, and may often not even be physically possible (e.g. 2.4 adults, or 0.5 people below 5 years of age). However, individual house statistics are aggregated back to larger areas (such as the mesh block – the smallest area available from the Australian Bureau of Statistics of about 50 houses) to serve as a reasonable approximation for the population profile exposed to the ensemble fire spread.

FireDST can display information on the local population exposed to the fire at the mesh block level (around 50 buildings). This information summarises the population either directly impacted by the ensemble spread or just outside the ensemble envelope, and includes some indicators of their potential vulnerability (Figure 9.2). To summarise the buildings and people exposed to the fire, the exposure is extracted for all locations within the ensemble fire spread. Statistics are produced for the buildings and people within each fire spread overlap interval.

The estimation of people exposed to the ensemble fire spread was based on the assumption that all residents were home. Clearly, this assumption is not valid where people have evacuated, are away at work, school or on holiday, or for empty holiday properties. This means that the exposure statistics are for the maximum residents that could be exposed to this fire ensemble.

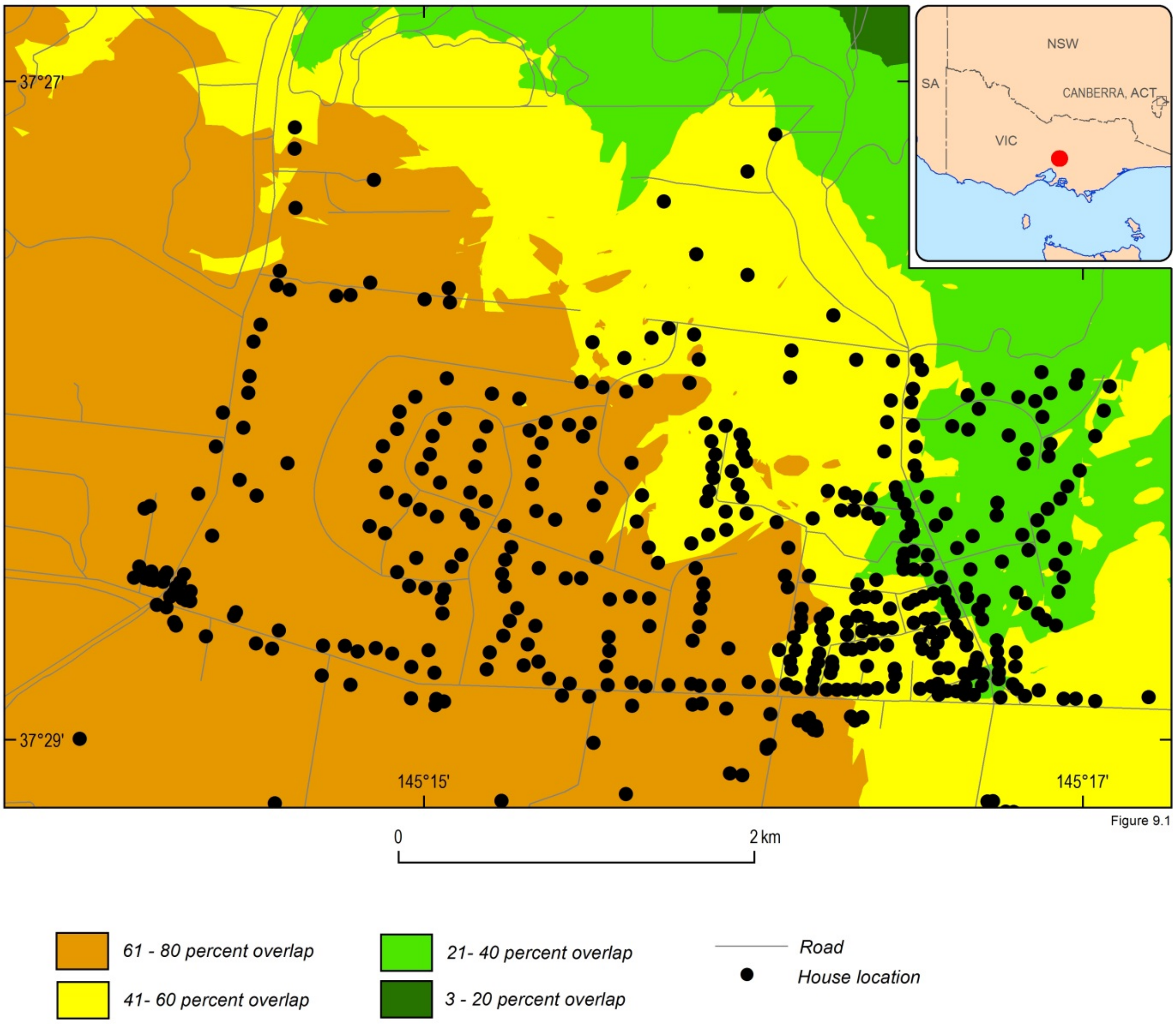


Figure 9.1 Part of the ensemble spread with building locations displayed.

9.3 Results and Discussion

9.3.1 Ensemble fire spread – viewing exposure statistics

Figure 9.1 shows the ensemble fire spread overlaid with building locations. Table 9.2 contains the statistics for the population exposed to the full ensemble fire spread. The table shows that six people live in the area that is burnt in over 80 percent of the ensemble scenarios. Table 9.3 shows that there are three houses in this area.

The statistics include the estimated value of the exposed property, and summaries of the age and mobility profile of the exposed population. The value estimates are not based on the relative severity of damage to the building, only on whether a building is exposed to the ensemble.

Table 9.2 FireDST People related exposure statistics for the ensemble simulation shown in Figure 9.1

Ensemble shape impact area likelihood	Number of People	Number of people over the age of 65	Number of people under the age of five	Number of people who need assistance
80-100	6	0	0	0
60-80	3	0	0	0
40-60	8	1	1	0
20-40	57	4	4	1
<20	1243	75	80	36

Table 9.3 FireDST Building related exposure statistics for the ensemble simulation shown in Figure 9.1

Ensemble shape impact area likelihood	Number of houses	Estimated house replacement cost $	Estimated house contents value $
80-100	3	894,736	379,048
60-80	1	429,811	182,086
40-60	3	1,280,978	542,676
20-40	24	9,165,252	3,824,227
<20	455	175,558,054	73,002,033

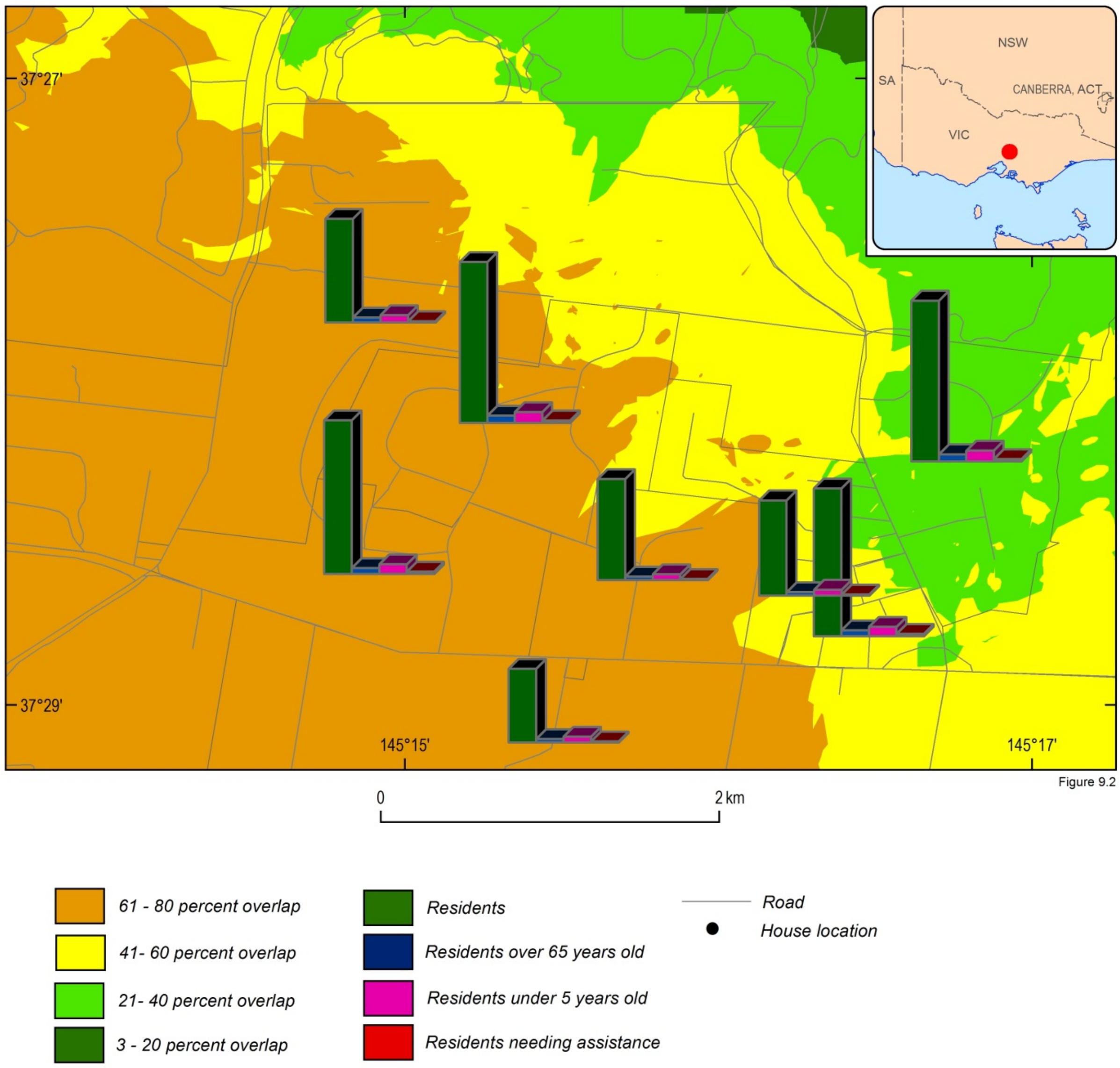


Figure 9.2 Ensemble spread with mesh block statistics displayed for the population in or just outside the ensemble fire spread envelope.

Figure 9.2 displays mesh block graphs (from left to right) showing four of the vulnerability indicators for population:

- The total population of the mesh block.
- The number of residents living in the mesh block area who are over 65 years old.
- The number of residents living in the mesh block area who are under the age of 5.
- The number of residents living in the mesh block area who have indicated in the Census that they are in need of assistance.

9.4 Conclusions and Future Work

The results in this chapter demonstrate a method for estimating the assets exposed with the ensemble fire spread. The ability to generate an inventory of the buildings and people that are exposed to a fire is a fundamental part of fire impact modelling. A comprehensive database of building and population statistics was developed based on existing information, mainly from Geoscience Australia and the Australian Bureau of Statistics. In combination with the fire spread information, FireDST system can quantify and visualise exposure information for either an ensemble or different levels of overlap within the fire spread ensemble.

Both the building and population profiles in this case study were statistically derived, that is: averaged, information. Although such numbers are likely to be correct over larger areas, they may contain significant uncertainty for individual locations. They are therefore not an appropriate basis for operational decisions, such as allocating resources to properties where assistance may be required in an evacuation situation.

9.4.1 Future work

Where actual population profiles are not available for individual households, Census population information is now available electronically at the Mesh Block resolution, which is approximately 50 houses. Further work could look at using this data in the impact analysis, to provide more accurate information on the population and their potential needs in fire events.

10 Estimating building loss using a fire spread ensemble

10.1 Objective

This research investigated how to assess the sensitivity of fire damage to buildings by developing an approach to quantify and view impact information for an ensemble fire spread.

10.2 Methodology

10.2.1 Background

Buildings can be destroyed by two main mechanisms; radiation and ember attack. As a fire front approaches, the building will experience an increasing level of radiation (heat) in front of the actual flames. This radiation will have a gradual effect on a building (for instance heating a window until it breaks) that could possibly lead to the building being destroyed. In this study direct flame contact is considered to be part of the radiation exposure received by the building. The second mechanism considered is exposure to embers. When a fire progresses through forested material much of the burning bark is lifted into the atmosphere and is dropped ahead of the main fire front in the form of burning embers. These embers can collect in gutters and crevices in buildings where they smoulder and eventually ignite.

FireDST developed an approach to integrate the hazard and impact model by computing the fire conditions at a building location for each fire simulation and then integrating these results into the ensemble. Chapter 9 describes the source and derivation of building location information used in FireDST.

In the 2009 Kilmore fire, 1178 residential buildings were destroyed (VBRC 2010). The post-fire survey information in FireDST indicates that there was a wide range of building age and type in the buildings destroyed.

10.2.2 Method

10.2.2.1 Individual Building Damage Estimation for each simulation

The fire spread module in FireDST, driven by PHOENIX RapidFire, models the fire's characteristics at the resolution of 180 m grid cells. The PHOENIX RapidFire simulates the hazard in terms of i) the maximum radiation intensity experienced in a grid cell (kW/m) , and ii) the total ember density received over the whole fire (Number/m^2).

The blue square in Figure 10.1 shows an example of a 180 m grid cell for which PHOENIX RapidFire provides the physical parameters characterising the fire hazard. Figure 10.1 shows the location of various buildings in the cell, as well as the surrounding vegetation and roads.

Ideally the radiation and embers experienced by each building in the cell will be different depending on the direction that the fire approached, the surrounding vegetation and buildings that can provide shielding or act as a local radiation source. Modelling this is a very complex physical problem that was divided into an incremental series of steps.

Figure 10.1 Example of buildings in a 180 m grid cell that also includes trees, hedges and open space. While FireDST assumes radiation is a function of distance of a building to the fire, it is in reality moderated by the proximity of vegetation or structures that may either have a shielding function, or act as an additional source of radiation.

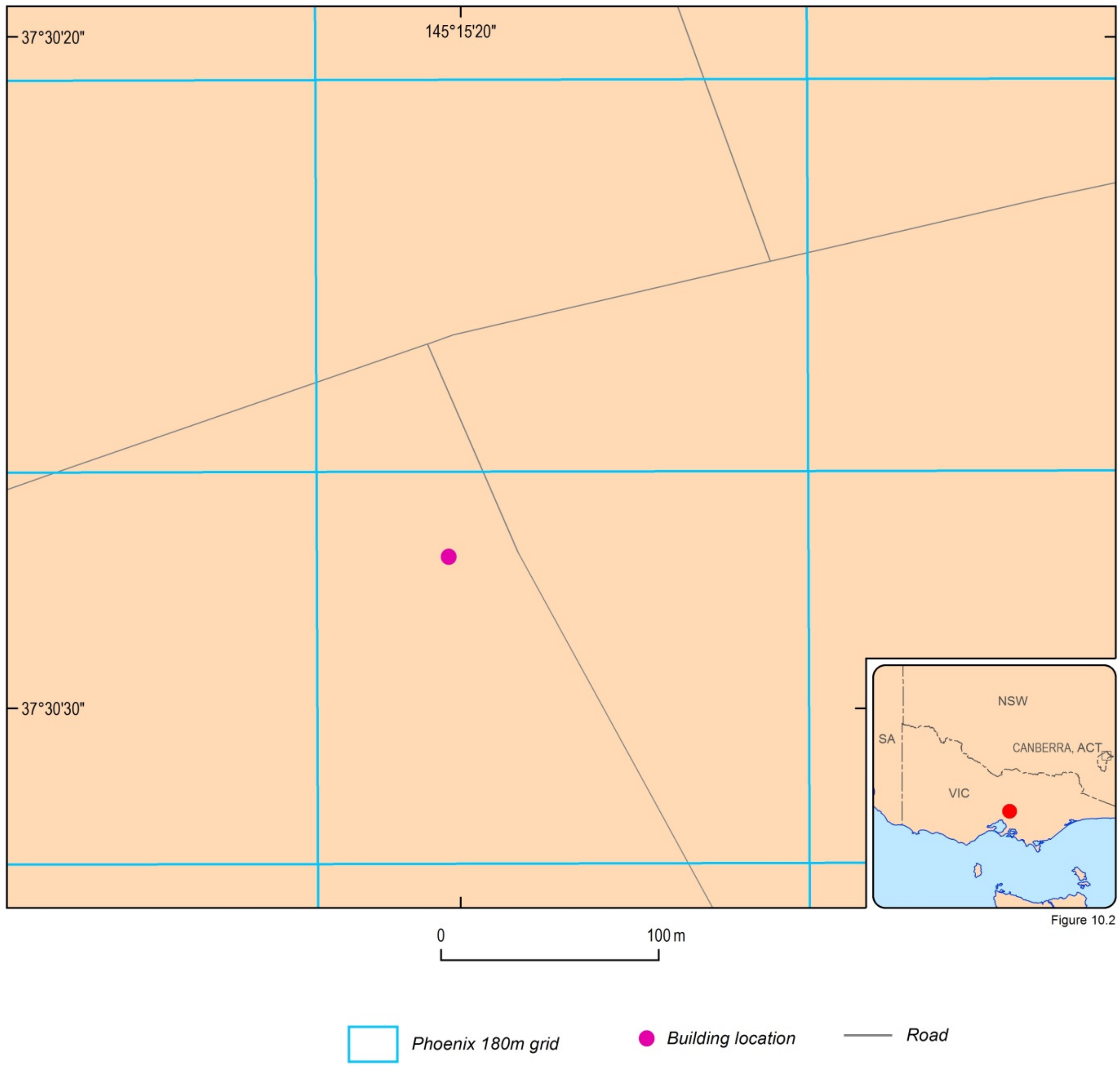


Figure 10.2 Contrast between the location (centroid) of a single building and the180 m grid cell. The characteristics of the fire hazard need to be scaled down from the larger grid cell to obtain the effect of the fire on the individual building.

10.2.2.2 Effect of radiation on the building

The 180 m grid cell fire characteristics are scaled down to the hazard experienced by the individual buildings in the cell. Each building is considered in isolation of its environment (Figure 10.2). Local information about vegetation surrounding the house is not considered, as this information was not available at the time of this research. Later chapters discuss the modelling of building to building ignition.

FireDST converts the maximum fire line intensity value in the 180 m cell (in kW per metre) to the radiation experienced at various distances away from the house (in kW per square metre). This conversion assumes the radiation experienced by the building is a function of distance from the fire line. As a default, FireDST assumes that the radiation is generated by the fire line intensity being 5 m away from the building.

In the context of this project, vulnerability curves are then used to specify the probable damage to a building as a function of the radiation and ember hazard experienced at the building. Damage is specified as a percentage loss. The higher the hazard intensity, the higher percentage damage, until the building is considered to be so damaged that it is classed as destroyed. The vulnerability of a building is a function of its physical characteristics, such as age, construction type and materials, maintenance status etc. Vulnerability functions for fire can even be direction specific, as the characteristics determining the building vulnerability may vary on with different angles of the fire's approach to the building. FireDST has been designed to have the ability to apply a large suite of specific vulnerability curves based on building characteristics or approach angle. However, at the time of this project, such specific curves were not available. This research developed an approach to integrating building damage as part of impact modelling through applying a single set of 'average' curves to all buildings.

CSIRO Environmental Sciences in collaboration with Geoscience Australia produced a set of four average vulnerability curves that were applied to each house. The four curves consisted of one for radiation hazard and three for ember attack hazard. The curve for radiation attack is shown in Figure 10.3

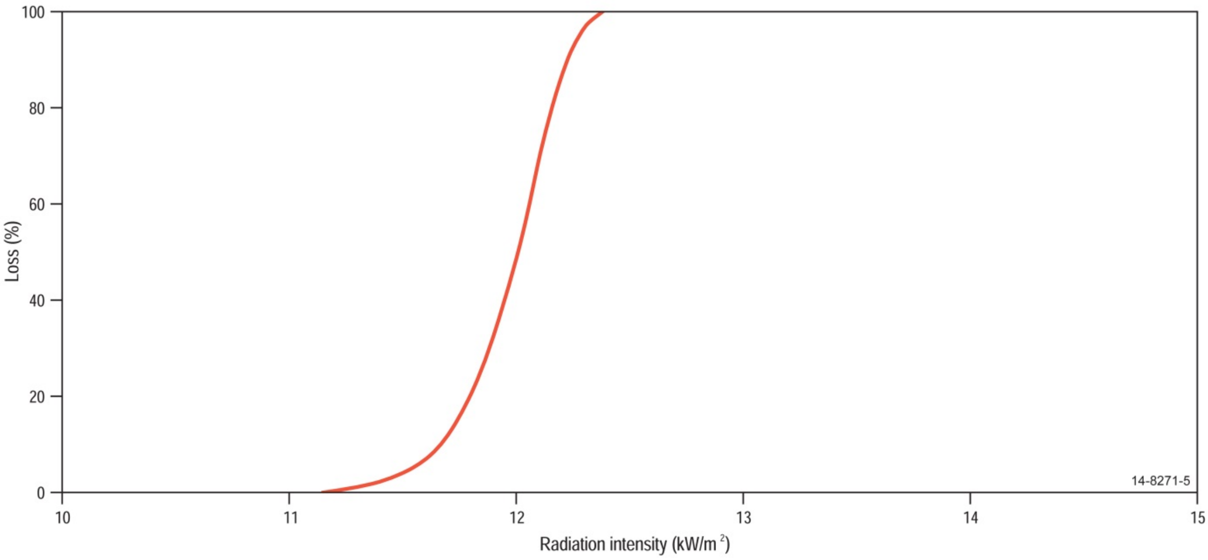


Figure 10.3 House loss as a function of radiation hazard, with total loss modelled at 12.5 kW per square metre of radiation.

The vulnerability curve for radiation hazard (Figure 10.3) assumes that 100% loss occurs when the radiation reaches 12.5 kW per square metre, which is the radiation level at which a standard pane of glass will break. Once windows are broken, radiation and burning embers can enter the building and cause catastrophic building fire (J. Leonard 2011 pers. comm.).

10.2.2.3 Effect of Embers on the building

FireDST computes the ember density hazard as the total number of embers per square metre in each of the 180 m grid cells within the fire spread. The current building database does not include floor area so the ember density hazard at the building location was assumed to be the same value as the total ember density experienced on the cell.

The vulnerability curves for ember density hazard (Figure 10.4) are developed based on the understanding that fuel moisture content drives the probability that exposed wood in a house is ignited by embers. CSIRO research has indicated that building wood will not be ignited by embers if the fuel moisture content is greater than ten percent (J. Leonard 2011 pers. comm.). Table 10.1 shows the relationship between fuel moisture and the respective vulnerability curves.

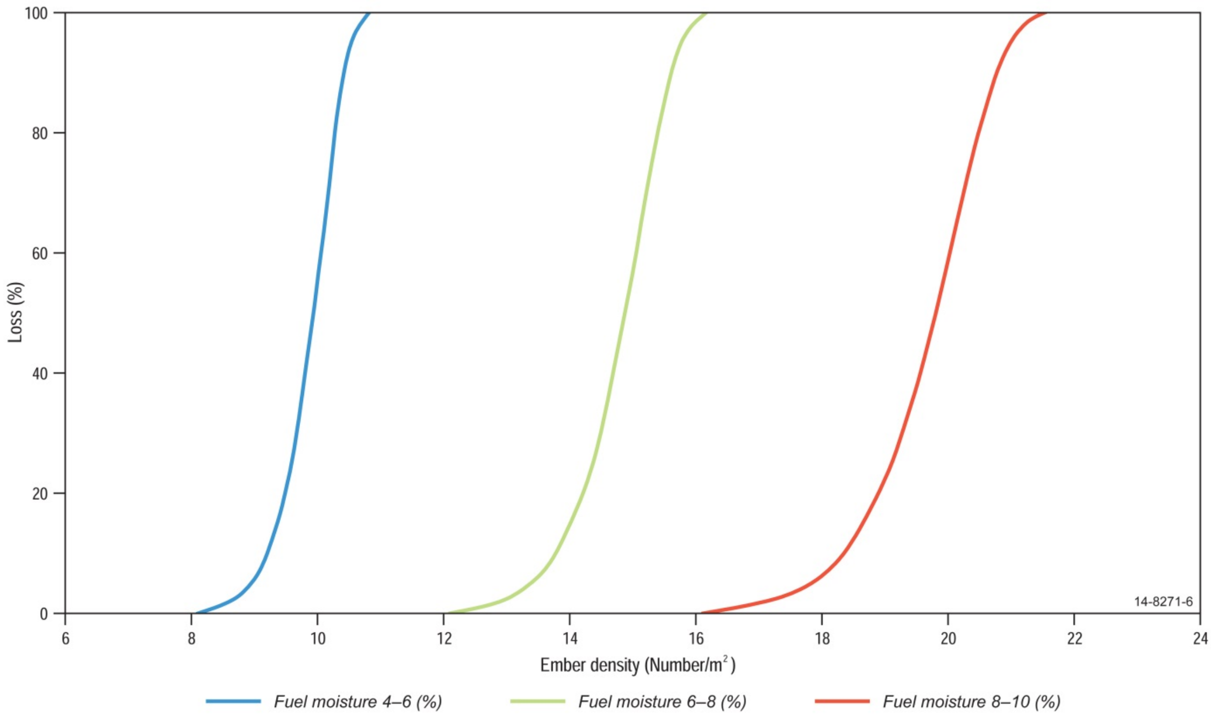


Figure 10.4 House loss as a function of ember density hazard (Number/sq.m.) for (a) 4 to 6% fuel moisture, (b) 6 to 8% fuel moisture and (c) 8 to 10% fuel moisture.

Table 10.1 Relationship between fuel moisture and the vulnerability curve.

Fuel Moisture	Vulnerability Curve
Zero to four percent	House will be destroyed by ember attack, no curve required.
Four to six percent	Four percent curve
Six to eight percent	Six percent curve
Eight to ten percent	Eight percent curve
Greater than ten percent	House is not vulnerable to ember attack, no curve required.

10.2.2.4 House loss modelling method

The vulnerability curves that were used in this study all had steep gradients as fire attack typically results in a quick transition between nearly undamaged (0 % loss) state of a building to total damage (100% loss).

It is also possible that some houses will come close to being destroyed but will just remain damaged. This research defined a “destroyed threshold” percentage where the building transitions from “damaged” to “destroyed” on the vulnerability curve.

As described above, the vulnerability of a building to radiation can be sensitive to the direction in which the fire approaches it. FireDST computes the angle of approach in 45 degree bins around each house to allow implementation of future angle-specific curves. However, in this study, the vulnerability was not actually modified with angle of approach.

The integrated approach of modelling fire spread and impact taken by FireDST was validated against the Kilmore fire by comparing actual building damage against the modelled damage. For this experiment, the vulnerability curves specified above were used assuming an ember destroyed threshold of 50%, radiation destroyed threshold at 50% and radiation distance as five metres. The vulnerability curve for radiation hazard assumed total loss (100%) at 12.5 kW per square metre.

In addition, the FireDST building information was augmented with additional data for buildings located within the Kilmore case study region, shown in Table 10.2. This data included building damage recorded in post-event surveys in the respective fires, as well as parameters specifying the vulnerability curve. The historical event damage record was not required for the actual modelling, but allowed assessment of the accuracy of the modelled damage.

Table 10.2 List of additional data parameters available within the FireDST exposure database utilised for the impact modelling.

Parameter name	Parameter description
Vulnerabilities	Consists of direction, ember_alpha and ember_beta, radiation_alpha and radiation_beta. These parameters define the vulnerability curve used for the direction of fire approach to each building
Damage	Results of the building survey after each fire. Contains DESTROYED, MINOR or NONE

10.2.2.5 Building destroyed estimation for the ensemble

The previous section has outlined how FireDST modelled whether a building in a fire spread simulation is damaged by the fire. When ensemble damage statistics are computed, building damage was summarised for each interval in the percentage overlap of the ensemble fire spread. A building is classified as destroyed if it has been destroyed in one or more of the simulations.

10.2.2.6 Sensitivity of house loss to vulnerability

The sensitivity of modelled house damage to various hazard and vulnerability parameters was assessed in a set of experiments. The sensitivity of house loss to the hazard was assessed through a 30-member ensemble sampling variability in weather and ignition information (Appendix C). Further tests examined the sensitivity of house loss to i) the vulnerability curve for radiation hazard, ii) the distance of the house to the fire front, and iii) the threshold where the building is assumed to be destroyed (Appendix E).

For the sensitivity of house loss to radiation vulnerability, a suite of curves was tested with total loss assumed at 12.5, 19, 29 and 40 kW per square metre, respectively. These particular radiation levels were selected in line with the radiation levels listed in the AS3959 Building Standard, Bushfire Attack Level. For the vulnerability tests, the fire characteristics were based on the fire spread scenario that best matched the historical footprints. In this case, that was the 4000 m resolution ACCESS run for the historical conditions, adjusted with bias correction and Wind Ninja multipliers, and the historical ignition.

The sensitivity assessment for the destroyed threshold was tested by sampling the destroyed threshold value from 5 percent damage to 95 percent damage in steps of five percent. As the value increases, more buildings would be classed as damaged, rather than destroyed.

10.3 Results and Discussion

Table 10.3 shows the impact statistics for the 30 member ensemble simulation in Figure 4.1. The exposure analysis indicates there are 455 houses exposed to the ensemble fire spread envelope (Table 9.2), of which 58 houses are modelled to be destroyed in at least one scenario (Table 10.3). This is a snapshot of the fire damage during the event, not the total house loss across the lifetime of the event. This demonstrates that ensemble information can illustrate the robustness of an impact estimate. Decision making might be adjusted considering either the significant range between the number of houses lost in the 'best' impact estimate and that modelled by one of the less frequent overlaps intervals.

Table 10.3 FireDST Building related impact statistics for the ensemble simulation shown in Figure 4.1

Ensemble shape impact area likelihood	Number of houses	Estimated house replacement cost $	Estimated house contents value $
80-100	3	894,736	379,048
60-80	1	429,811	182,086
40-60	3	1,280,978	542,676
20-40	24	9,165,252	3,824,227
<20	58	22,498,584	9,402,402

Based on the 'best fit' fire spread scenario and the default vulnerability curves, FireDST achieved an accuracy of 55% for the modelled house loss in the Kilmore event. While this demonstrates that vulnerability modelling still contains considerable errors, the sensitivity tests suggest priority areas for improvement. Modelled impacts showed sensitivity to changes in the radiation vulnerability curve. Table 10.4(a) shows that the highest accuracy was achieved by the curve assuming 100% loss at 12.5 kW/sq. m, which was used as the default curves in FireDST. The modelled house losses for the Kilmore case studies showed a linear decline in accuracy with an increasing radiation vulnerability threshold. This indicates that developing a better calibrated, validated, and particularly a more specific set of curves (based on house age or building type) is likely to improve the accuracy of loss modelling.

Table 10.4(b) presents the average accuracy across the ensemble that samples the error in the fire conditions, in terms of the surface weather, fuel and ignition. The average accuracy is lower than the figures reported in Table 10.4(a) because it is lowered by fire spread scenarios that did not reflect the historical event.

Table 10.4(b) shows fewer trends in the accuracy with an increasing radiation threshold than shown in Table 10.4(a). The modelled fire spread of the Kilmore event was sensitive to variability in environmental conditions such as the weather and fuel (see Chapters 5 and 7). These results show that the error in the fire spread overshadowed the sensitivity to the vulnerability assumptions. For cases such as this, the modelling results would be made more robust by focusing on improving the fire spread modelling.

Table 10.4 Accuracy of modelled house loss using different radiation vulnerability assumptions, (a) Accuracy of modelled house loss based on hazard from the scenario that best matched the historical footprint. (b) Accuracy averaged across an ensemble sampling variability in surface weather parameters, ignition timing and location, and fuel conditions.

Radiation value (kW/sq. m)	Modelled Accuracy 'Best' Footprint	(b) Average Modelled Accuracy Ensemble
12.5	55	24.2
19	55	33.8
29	54.6	28.2
40	52.1	24.4

Tests showed that house loss was sensitive to the distance assumed to be between the building and the fire line, with losses decreasing with distance. The sensitivity analyses suggested that assumption of 5 m distance produced results that matched the historical losses, and this value was chosen as a default in the modelling.

Results showed there was little or no sensitivity of house loss to the destroyed threshold on the vulnerability curve. This lack of sensitivity is likely to be caused by the steepness of the vulnerability curves used in this study.

10.4 Conclusions and Future Work

The FireDST system estimates the probability that a building is destroyed by fire, based on the building location and the bushfire characteristics. Building damage information can be directly related to the corresponding area of the ensemble fire spread. The project implemented a set of four vulnerability curves that estimated house loss as a function of radiation intensity and ember density. In order to apply these curves, the FireDST system integrates the large-scale fire spread modelling with a parameterisation of sub-grid scale fire conditions.

The accuracy of FireDST using the vulnerabilities to predict house loss for the individual houses in the Kilmore was 55%, demonstrating that vulnerability modelling is still in need of further development and validation. Estimated house loss was shown to be sensitive to the assumptions of the vulnerability function. Ideally, vulnerability functions should reflect differences in relevant building characteristics, such as construction type, age, building-code compliance and maintenance level. The vulnerability functions applied in this project did not vary with these characteristics, and could therefore only be expected to attain a limited level of accuracy for individual buildings.

Results also demonstrated that the performance of the vulnerability model is sensitive to the error in the fire spread modelling itself. Finally, it is likely that the performance of the impact model is also limited by its inability to reflect processes such as house-to-house ignition and human intervention. The following section develops an approach to parameterise the impact of these sub-grid scale processes on the house loss.

In summary, the results discussed in this chapter demonstrate that it is possible to estimate building damage information as part of a fire spread approach. Such an integrated approach could present a significant improvement in terms of potential information and efficiency over separate modelling processes. Furthermore, it is shown that the ensemble approach can be extended to include building damage and loss. The information that is generated by ensemble output can further help to understand the robustness and limitations of the impact modelling.

10.4.1 Future Work

Numerous key gaps remain to be filled to improve the ability of estimating house loss in (Australian) bushfires. The following points highlight some priority research opportunities:

There is a need for an improved set of validated vulnerability curves based on expanded research and validated by observations. Ideally, such curves should be tailored towards different building types and their characteristics. Even a very good ‘average’ curve can only result in inaccuracies, as it cannot capture the variability between building damage because, for example, a wood structure is more vulnerable than a brick building. This research needs to reflect the vulnerabilities of Australian buildings, as these are likely to differ from those in other countries were similar research is undertaken.

As an extension to the previous point, the vulnerability modelling approach should include a methodology to account for the influence of surrounding vegetation and buildings on house loss. Neighbouring “obstructions” can decrease the amount of radiation that a building will experience and therefore decrease the vulnerability. However, if the obscuring object itself ignites it may produce more radiation or embers, thus increasing the vulnerability. This research area has been partly covered in Chapter 10.

There is a need for a greater understanding, supported by observational evidence, of the sensitivity of building loss to the direction of the fire approach. This should validate the assumption that building vulnerability is determined by the dominant characteristics of the building that face the approaching fire. For example, for a brick structure, the effective vulnerability is assumed to be different if the fire approached a windowless wall as compared to a façade with glass doors and a wooden deck. While FireDST was designed to be able to modify the vulnerability based on direction of approach, there was as yet no evidence to support the implementation of this.

A confidence level could be calculated for the estimated damage to each building, based on the variability of the estimated damage across the ensemble.

11 Estimating the impact of human action on building damage in bushfires

11.1 Objective

The objective of this section of the research was to incorporate a methodology to estimate the impact of human activities aimed at defending a building against fire damage as part of the FireDST system. This methodology refines the FireDST approach to building loss estimation outlined in the previous chapter, by parameterising some of the processes that occur at the sub-grid scale.

11.2 Methodology

11.2.1 Background

Evidence suggests that if people are home when a bushfire comes through, their house is more likely to be saved (Blanchi et.al 2008). Various actions by occupants or fire-fighters can contribute to reducing the opportunities of house ignition.

Where fire spread simulation models include suppression activities, it is usually based on the deployment of emergency services to attack the fire. For example, the PHOENIX RapidFire system has a suppression module that models the effect of a pool of emergency services teams that are split to attack the flanks at the back of the fire in equal proportion on each flank. As described in Chapter 3, this suppression module was de-activated in FireDST for the work described in this report, so that the uncertainty introduced by using suppression across different simulations was removed.

This chapter describes how FireDST models fire suppression from the perspective of a building occupant, through a module called the Building Fire Impact Model (BFIM; Sanabria *et al.*, 2013). The BFIM computes the probability that house is destroyed by embers, as well as the probability of house to house ignition. The BFIM requires the location of buildings and the demographic profile of their occupants (see Chapters 3 and 8). Furthermore, the BFIM module accesses fire spread simulation information from the PHOENIX RapidFire module in FireDST.

The BFIM approach implements a probabilistic event tree (PET) system. A probabilistic event tree models various alternative outcomes in terms of their probability. The alternatives are termed 'branches'. There could be cascading outcomes, where branches themselves are split into further alternative sub-branches. The tree is resolved by combining the probabilities of all branches through the hierarchy. This gives a probability distribution of a final outcome.

11.2.2 Method

The BFIM model contains two components that are applied in two consecutive passes or sweeps across the event tree. The first pass examines if the total amount of embers deposited on a house would be reduced by human activity. Probabilities are assigned to branches in the probability tree for the effect of human action during or ahead of the fire, and the tree is resolved. For example, the BFIM specifies the probabilities that occupants are home, that they are prepared, that the house is prepared, that neighbours are available to help and that emergency service teams will be available. The combined probabilities enable the computation of a percentage ember reduction at the house. FireDST then uses this modified ember density value as hazard input into the ember vulnerability curve (see Chapter 10) to model the building damage by embers.

The second pass of the BFIM projects the probability that (unburnt) buildings will be ignited by nearby buildings that are burning. This pass also considers the impact of occupants, neighbours and emergency services that attempt to stop building-to-building ignition.

The PHOENIX RapidFire module in FireDST computes the resultant fire characteristics with the ember density (in number of embers per square meter) and maximum fire line intensity (kW/m) experienced in each 180 m grid cell. The first pass of the BFIM resolves various factors in the event tree to produce a percentage overall reduction in embers resulting from the human interaction (Table 11.1).

Table 11.1 Factors considered in the event tree by the BFIM.

Primary Indicator	Definition	Units	Comments
D	Wind Damage	Y/N	Can vary the amount of wind damage based on the Wind strength experienced (from PHOENIX RapidFire fire spread) and the House Age. Also calculated using two input threshold values: Threshold for wind damage(low) Threshold for wind damage(high)
LF	Local Forest Fuel	Y/N	Initially the BFIM will just select if the house is surrounded by forest vegetation (Y) or surrounded by grass (N), as this will make a difference with the local fire spread details in the model. In future this can be extended to include a classification of various types of fuel variations.
O	Number of occupants (normal)	Number	Number of people (including children) that are normally resident in the house
OH	Occupant at home	Y/N	Factor to examine the difference if the occupant is available.
N	Number of neighbours who assist	Number	Number of neighbours who are available to assist at the residents house
E	Number of Emergency Service Teams available	Number	Defines if an emergency vehicle can attend a house – based on distance from the fire station and time available.
EAT	Emergency Vehicle attendance time	Hours	Time that an emergency team can be present at the house to assist.
OA	Occupant age	<5yrs 5yrs to 64 years >65 years	Without knowledge of actual household emergency fire plans the model is assuming that all children will be evacuated and that one parent will leave with them. (in other words Remove 1 adult if there are children under 5 years old.) Also assuming that all elderly people will evacuate (Remove all people over 65 years old)
SP	Single Parent Family	People	If a single parent family resides at the house then they will not be available to fight the fire due to the OA rule where they have evacuated with their children.
P	Plan	PS,PG,PN	Remaining occupants have a fire plan which defines a definite decision to stay (PS) or to go (PG) or No Plan (PN)

Primary Indicator	Definition	Units	Comments
OP	Occupant prepared	H/M/L	Occupant is prepared and ready to fight the fire. Combination of factors included Training Equipment Level of education Can speak English Unemployed Is house main residence? Is house rented? Is the house a public rental? Level of income Occupant needs assistance Motor vehicle access Do they volunteer Are they new to the district <1 year Are they new to the district <5 years User supplies 3 values in the range 0.0 to 1.0 that represent the probability for the three branches of the PET related to High (H)/ Medium (M) and Low(L). All three values must add to 1.0
HP	House Prepared	Y/N	The house and grounds have been prepared to reduce impact of a fire.
FO	Fire Occurrence (time)	Time	Working/nonworking hours affects the number of people available
GF	Gust Factor	Number	Multiplier used to simulate the maximum random increase in wind speed due to wind gusts.
H1	Human factor 1	Percent	% occupants available on week days
H2	Human factor 2	Percent	% of occupants available on non-weekdays
NE	Neighbour Effectiveness	Percent	Neighbours who come to help are not necessarily familiar with the house of with the equipment. This factor reduces the effectiveness of the neighbour related to the effectiveness of the occupant
ME	Maximum efficiency in fighting dormant embers	Percent	Once the fire front has passed the main danger is from dormant embers. Because the people have spent time fighting embers and spot fires to this time they are now more exhausted and will have a lower efficiency in fighting the dormant embers
EDT	Ember Density Threshold	Percent	The percentage of the maximum ember density where human interaction is no longer possible.
RLO	Radiation limit for occupant	kW/m^{-2}	This is the radiation limit where a protected human has to retreat to safety as the radiation is too excessive. This is around 2 kW/m^{-2}
RLE	Radiation Limit for Emergency services	kW/m^{-2}	This is the radiation limit where a fully protected firefighter has to retreat to safety as the radiation is too excessive. This is around 4 kW/m^{-2}

The BFIM can modify the number of occupants, neighbours and emergency services that are assumed to be available during a fire, reflecting a range of scenarios or 'storylines'. Table 11.2 shows a few examples of such storylines. For instance, on a weekend (non-workday) the BFIM assumes the number of occupants is the value supplied from the 2006 Census (factor 1.0). In a catastrophic fire day scenario, the BFIM assumes that only half the occupants are available (factor 0.5). This may result in a fraction of a person being available at an individual residence; however, the BFIM aggregates to real numbers of people available across the whole region affected by the fire.

Table 11.2 Example storylines (scenario modifiers for population numbers) associated with the NEXIS database.

STORYLINES **Pre-defined and user-defined scenarios and the associated factors which modify the NEXIS population statistics**	**Occupant Factor**	**Neighbour factor**	**External factor**
DEFAULT (non-workday)	1.0	1.0	1.0
Fire Danger – VERY HIGH	1.0	1.0	1.0
Fire Danger - SEVERE-	0.9	0.8	1.0
Fire Danger - EXTREME	0.7	0.5	1.0
Fire Danger - CATASTROPIC	0.5	0.3	1.2
Event (carnival/show/concert etc.)	1.2	1.1	1.2
Major event (carnival/show/concert etc.)	1.4	1.2	1.4
User-defined	A	B	C

To validate both components of the BFIM in the Kilmore region, two study areas were selected. The first study area around Kinglake West (see Figure 11.1) was chosen to study the first pass of the BFIM because the area nearly matched the Australian Bureau of Statistics 2006 Census Collection District for that region. This allowed the real statistics about the population in the region to be used to estimate the impact of occupant action on the ember density.

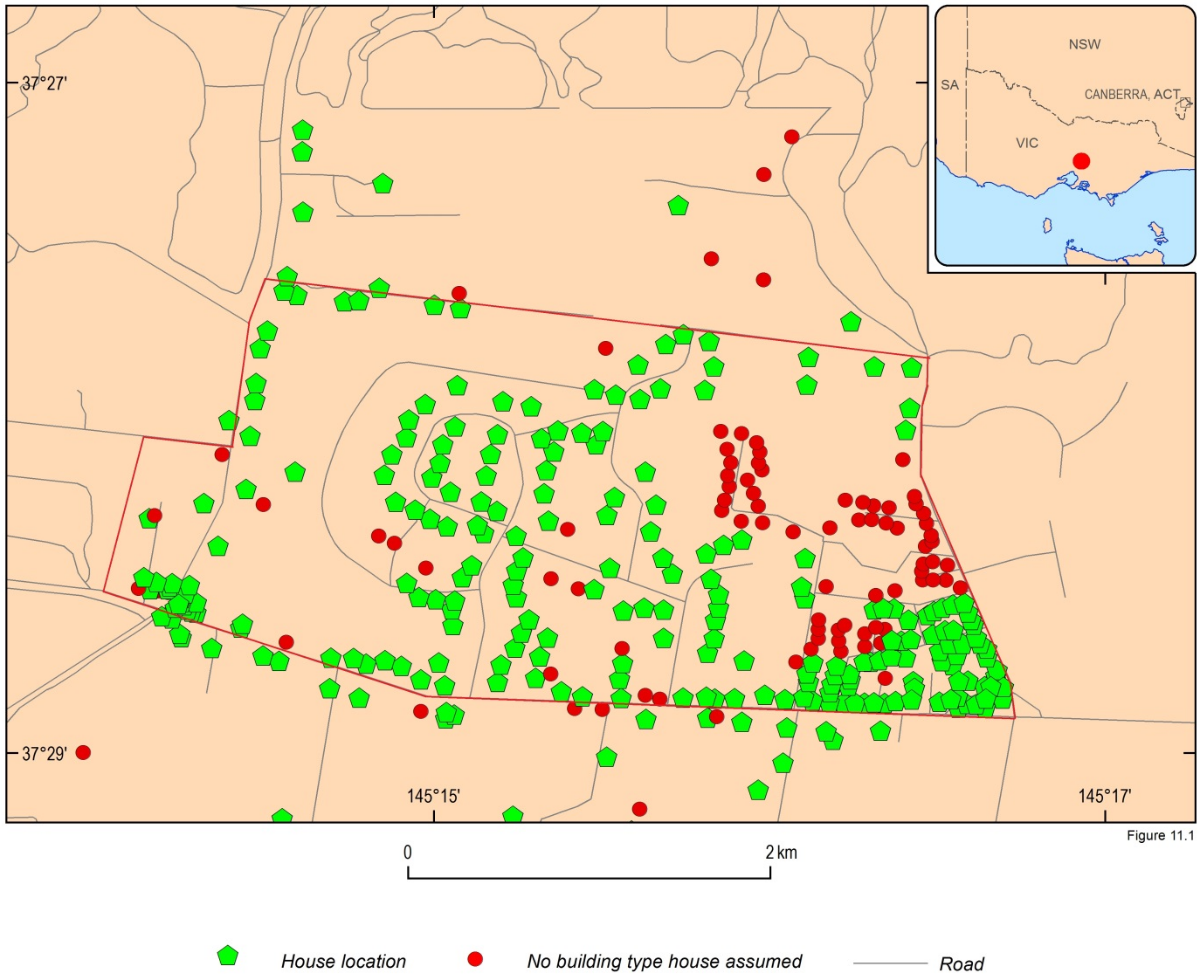


Figure 11.1 Human Interaction Study Area – Kinglake West region -all buildings inside the red polygon.

The second study area was around Pine Ridge Road in Kinglake West (see Figure 11.2), and was used to assess the effectiveness of the building-to-building ignition component of the BFIM. The second study area was chosen because information was available on non-residential structures such as garages and sheds not included in the NEXIS data. Non-residential buildings were expected to affect the potential loss of residential buildings, for example through shielding from radiation. This expectation was tested by assessing the sensitivity of the BFIM results between simulations with all buildings and only residential buildings. The additional information for garages and sheds was manually added to the FireDST buildings database.

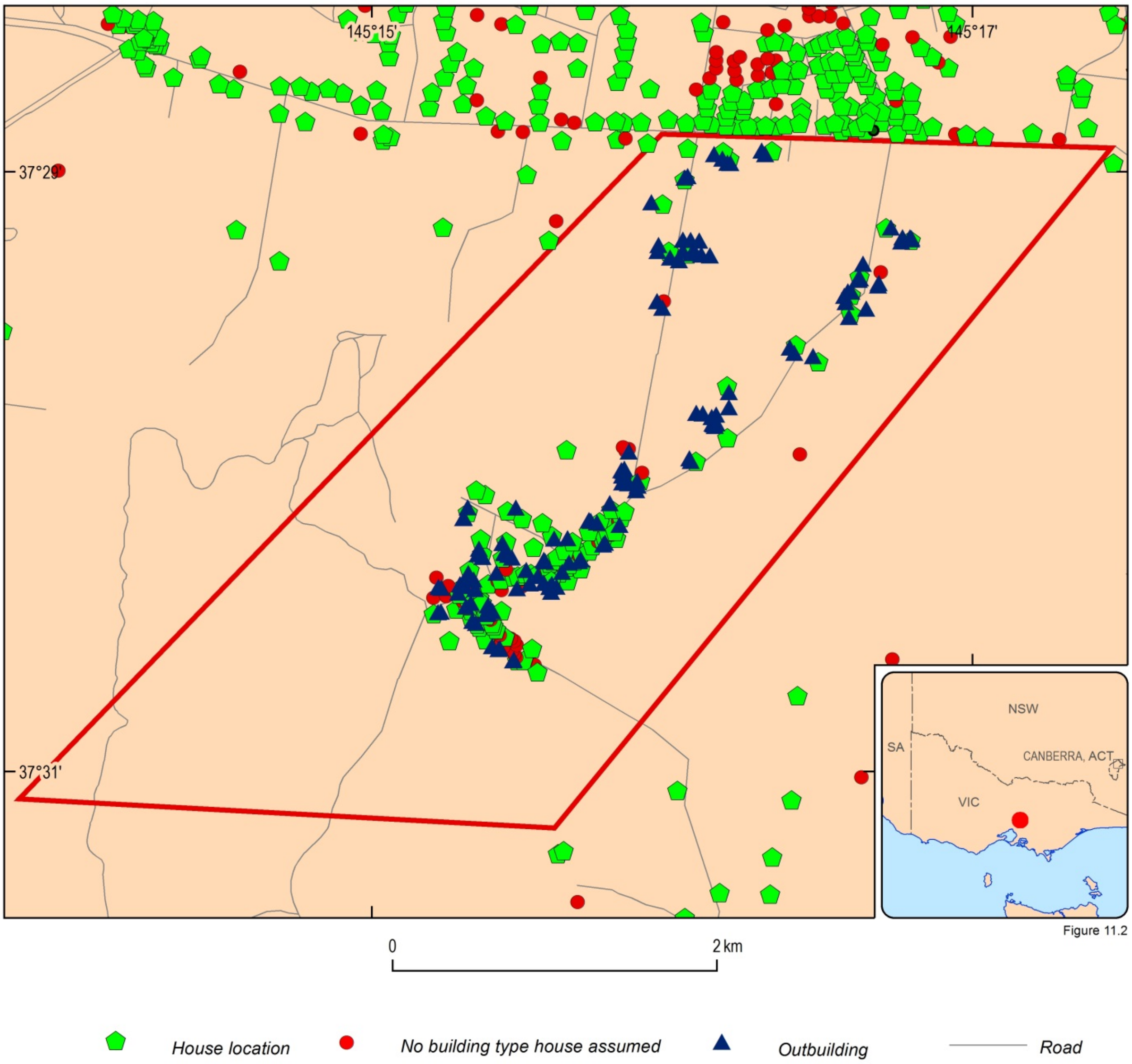


Figure 11.2 Building to Building Study Area – Pine Ridge Road region-all buildings inside the red polygon.

The BFIM was parameterised with values that allowed an initial assessment of whether the BFIM (Pass 2) is working correctly. Some of these values are not realistic; for example the maximum distance to neighbouring houses was set to 100 m to allow for more buildings to be considered in the interaction. In future it may be more realistic to apply a maximum distance that reflects the radiation generated by a burning building (which at the time of this research is unknown). In this example the BFIM input values are:

- Storyline – Extreme (see Table 10.2)
- Weekday – TRUE
- H1 (% occupants available on week days) – 10
- H2 (% of occupants available on non-weekdays) – 70
- Occupant preparation (L/M/H) – 0.1/0.5/0.4
- Max Distance to neighbouring houses – 100m
- Percent Neighbours effectiveness – 25 %

- Radiation limit for occupants – 1000 $kW/m^{2.}$ It should be noted that this should normally be around 2 kW/m^2. However, an excessively high value was required because the PHOENIX RapidFire module in FireDST only supplies the maximum fire line intensity rather than intensity over time. The maximum fire line intensity was several orders of magnitude greater than the 2 kW / $m^{2,}$ causing the BFIM to rule out human intervention. PHOENIX RapidFire needs to be modified to supply the calculated intensity over each time step which can then be evaluated against this radiation limit.
- Radiation limit for Fire Brigade – 1000 $kW/m^{2\ .}$ As above, it should be noted that this should normally be around 4 kW/m^2 however an excessively high value was required because PHOENIX RapidFire only supplies the maximum fire line intensity and not intensity over time.
- Ember density destroyed threshold (% of max) – 33%
- No of Emergency vehicles available – 4
- Emergency Vehicle attendance time – 0.5 hours
- Gust factor – 1.6
- Threshold for wind damage(low) – 28.0 m/s
- Threshold for wind damage(high) – 35.0 m/s
- Max human effort to fight dormant embers – 25%

11.3 Results and Discussion

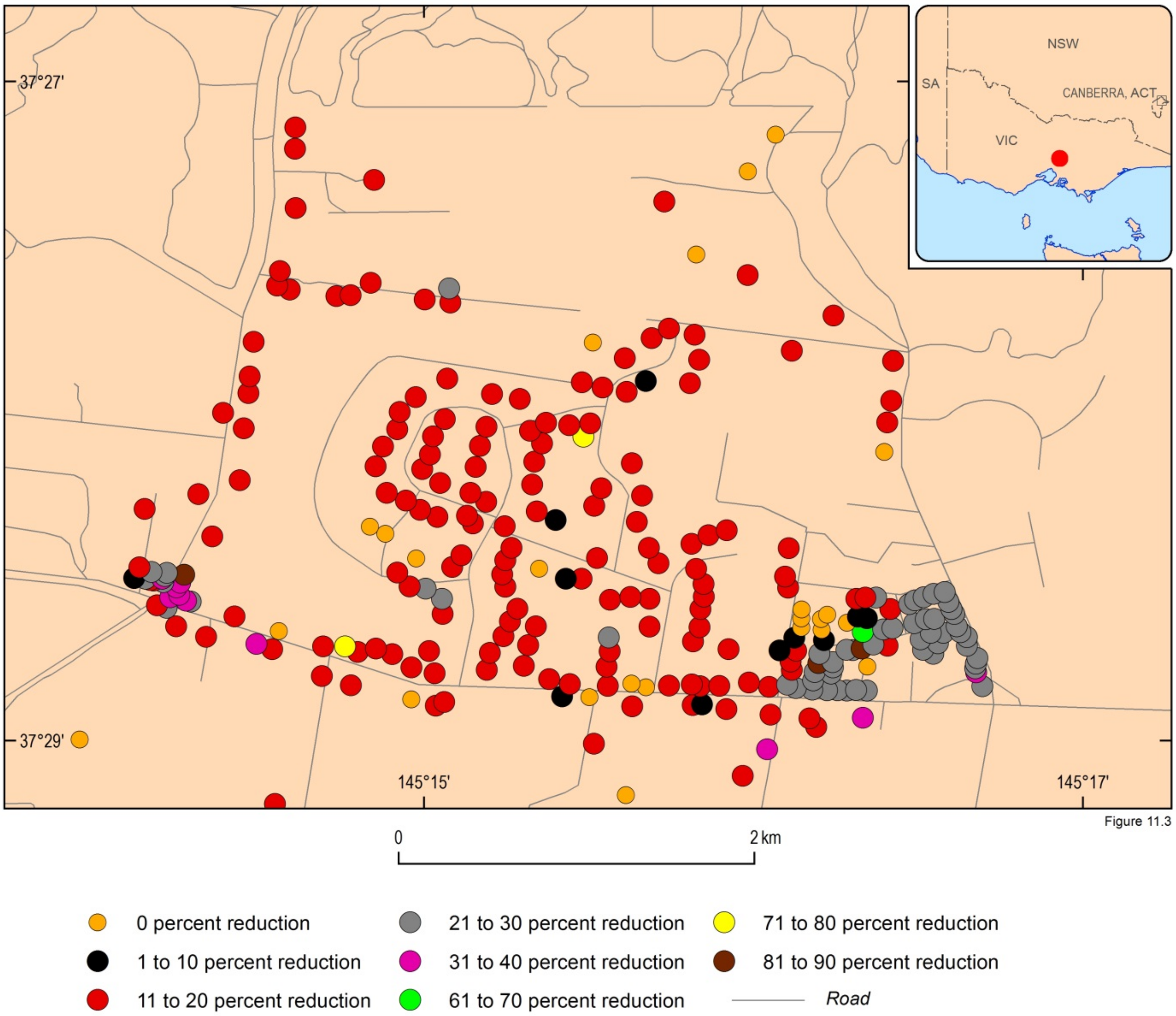


Figure 11.3 Reduction in ember density, as modelled by the BFIM for the first study area

11.3.1 Impact of human action on ember density

Figure 11.3 displays a result where all residences in the first study area experienced lower numbers of embers through human action. The reduction in embers varied between 13% and 35%.

Figure 11.4 shows the reduction in embers when action is taken into account for the second Study Area. Again the results show that all houses experience some reduction in embers (14 to 20%).

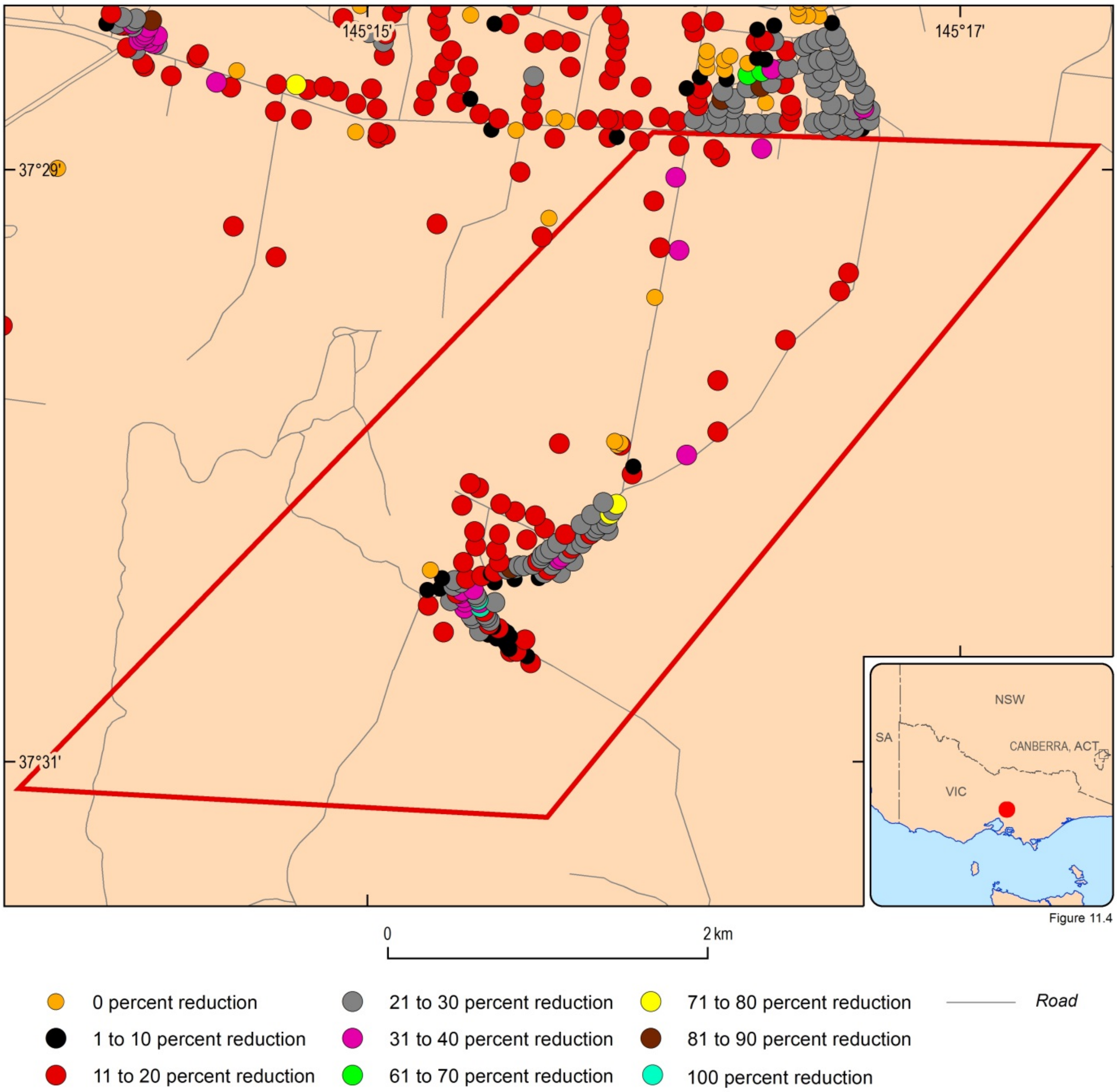


Figure 11.4 Reduction in ember density, as modelled by the BFIM for the second study area.

11.3.2 Sensitivity of building-to-building ignition

Figure 11.5contains the results for a BFIM simulation of the second study area that only considered residential buildings (excluding garages and sheds). When all buildings were included in the BFIM (including garages and sheds), two additional residences were found to have a high probability of being destroyed by building-to-building ignition (Figure 11.6). This validates the assumption that all structures and buildings must be included in the BFIM.

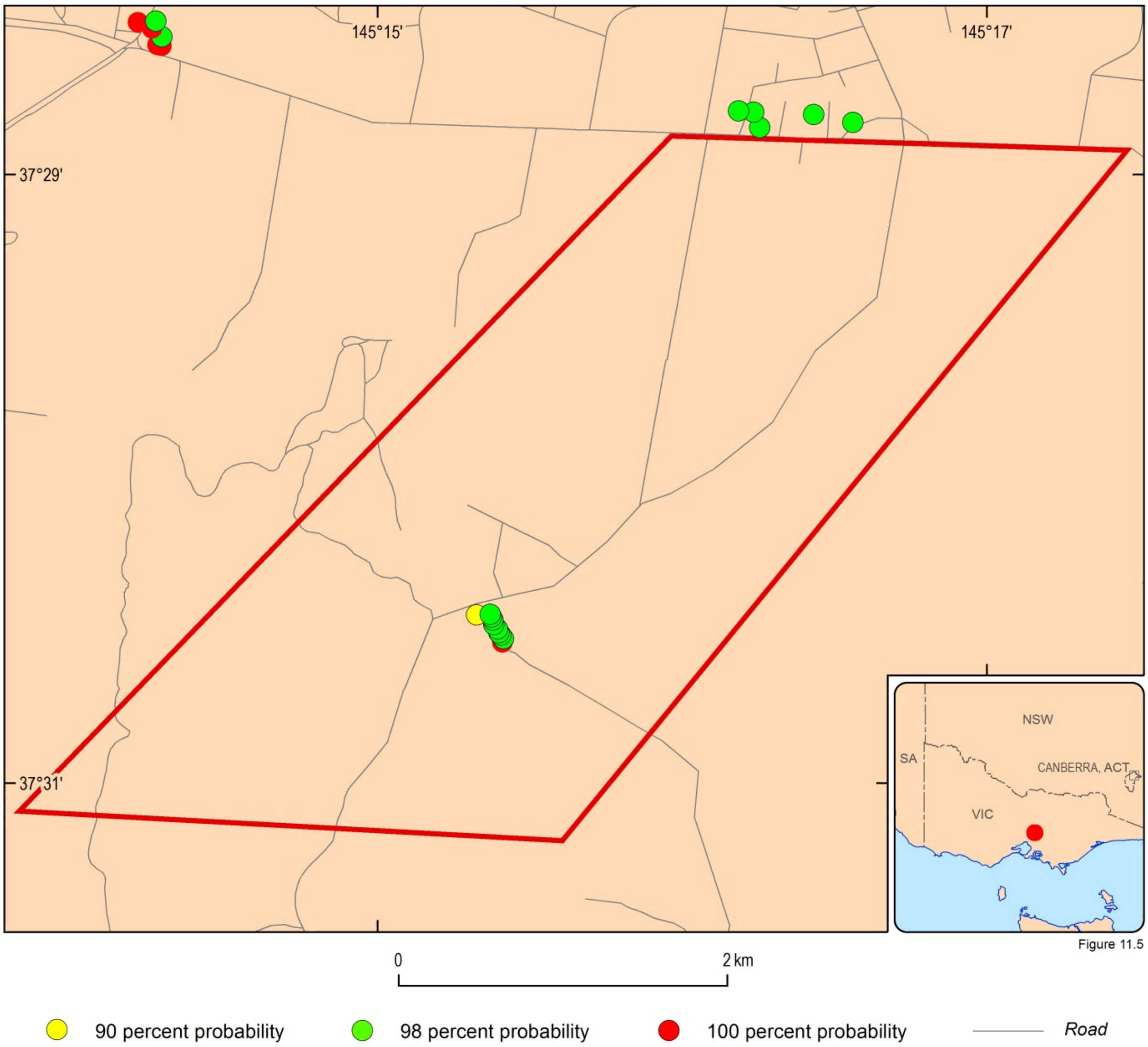


Figure 11.5 House loss from building-to-building ignition based on a BFIM run for residential buildings only.

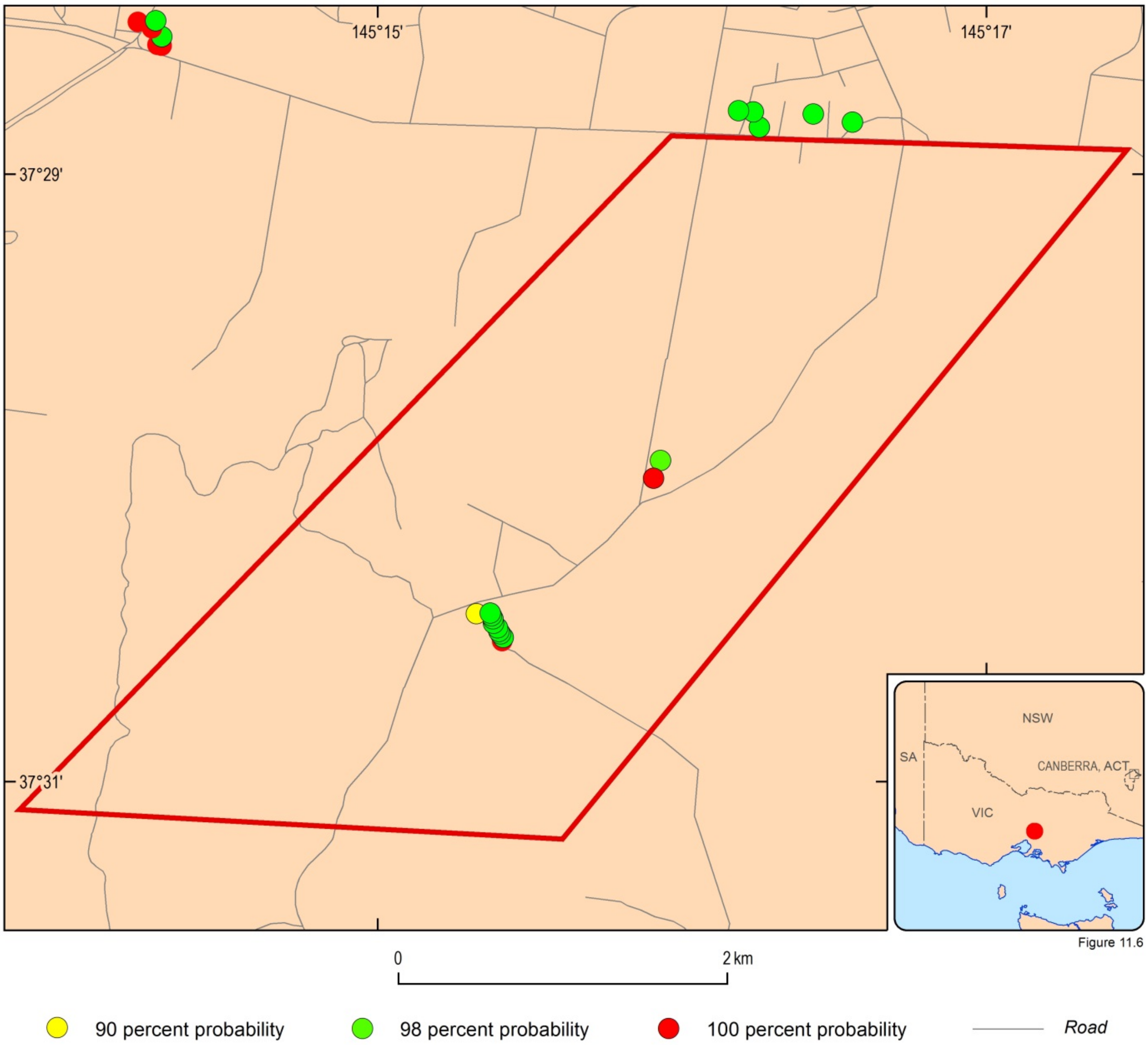


Figure 11.6 House loss from building-to-building ignition based on a BFIM run with all buildings included.

11.4 Conclusions and Future Work

FireDST provides an integrated approach to estimation of building damage and loss. To do this, the model needs to down-scale from PHOENIX RapidFire 180 m grid cell fire spread modelling to calculate the fire impact at the individual house. FireDST estimates building damage based on these local fire conditions considering not only the buildings themselves, but also the complex impacts of human action ahead of and during the fire. This chapter focused on the module in FireDST that looks at this last component, the Building Fire Impact Model (BFIM).

The results of this work demonstrate that FireDST can estimate to what extent human action limits ignition from embers or building-to-building ignition. As such estimates are sensitive to an accurate representation of sources of ignition, it is important that the BFIM component of FireDST can draw on a complete database of buildings.

The initial results developed with the BFIM for the Kilmore case study showed that the approach was flexible and could be developed to refine the ‘standard’ engineering vulnerability modelling approach such as that in the previous section. At this time, however, the BFIM makes many assumptions that are difficult to validate without extensive observations, and further work is essential to develop a robust version of the model that can be incorporated effectively in a system such as FireDST.

11.4.1 Future Work

The BFIM as a model of the effect of human action to combat house ignition during a bushfire is in an early stage of development. A more detailed analysis of the effectiveness of each variable in the BFIM is required.

There would be a significant advantage from using a fire spread model that would output the ember density throughout the lifetime of the simulated fire, for example in discrete time intervals. Currently, PHOENIX RapidFire accumulates the total ember density, but does not store the variability of the value in time. However, there will be points during the lifetime of the fire where the ember density will exceed safe or viable levels for human exposure. At those times, human suppression activities should be discounted, but at other times, human action can make a significant difference in the potential fire damage to a building.

Along the same line as the previous point, there would be an improved accuracy from using a fire spread model that would output the radiation received in each cell over time. Currently the PHOENIX RapidFire module in FireDST just provides the maximum fire line intensity encountered in each cell during the lifetime of the fire. However, the radiation levels over time are pertinent, as humans can continue to fight a fire as long as radiation conditions do not exceed a threshold.

A significant advance would be offered by a methodology that is able to consider buildings in terms of fuel to better capture the fire spread in the urban interface. Different building types will have different combustion rates, with analogous differences in the energy that is released when they are ignited.

12 Assessing sensitivity of smoke movement to the fire spread

12.1 Objective

The aim of the work described in this chapter is to examine the sensitivity of smoke and gas combustion products to fire spread. This is done by assessing scenarios from an ensemble spread model of the smoke associated with a bushfire.

Only four scenarios were considered in this part of the work, due to the computation time required to produce a set of smoke concentrations from one fire.

12.2 Methodology

12.2.1 Background

CSIRO Marine and Atmospheric Research (CMAR) has developed a model that simulates the spread of bushfire smoke and gas combustion products over the landscape using time based fire isochrones produced by the PHOENIX RapidFire model. The CMAR smoke dispersion model accounts for smoke and combustion products at (in atmospheric terms) ground height (10 m). The combustion products are Carbon Monoxide (CO), Nitrogen Monoxide (NO), Ozone (O3) and smoke particles less than 2.5 microns in size (PM2.5). The model output is given on a 1 km grid with hourly time steps. Cechet *et al.*, (2014) contains a full description of the model, as well as a summary of the results for each smoke product for the Kilmore case study.

12.2.2 Method

The ensemble used to assess sensitivity of the smoke consisted of four scenarios of the Kilmore fire. The scenarios were based on the best estimate of the historical ignition time, but assumed ignition locations 500 m to the north, south, east and west of the actual Kilmore ignition. The perturbation of the ignition location was chosen as half a grid cell in terms of the resolution of the CMAR smoke dispersion model. All simulations used 4000 m 5 minute ACCESS meteorology with bias correction and Wind Ninja local modifiers applied (see Chapter 4). Each of the scenarios was run through the smoke/combustion product model to compute the concentration isochrones for the combustion products.

There is a difference between the computation and visualisation of the ensemble fire spread results, and the equivalent outputs for the smoke and combustion products. To be meaningful, the ensemble spread of the combustion products needs to be visualised not only as isochrones, but also as a map of the ensemble concentrations of those products. The concentration is given by the maximum concentration across all of the scenarios that affect a grid cell. As with the ensemble fire spread, the information can be visualised across the lifetime of the fire, or at discrete points in time.

12.3 Results and Discussion

12.3.1 Sensitivity of smoke – Carbon Monoxide (CO)

Figure 12.1 to 12.4 show the isochrones for Carbon Monoxide (CO) at four time steps: 15:00, 17:00, 19:00 and 21:00 hours. Figure 12.2 provides a good example of how the ensemble smoke spread and the concentration relate to each other. This figure shows that, at 17:00 hours, Healesville was experiencing CO concentrations in the 81-100% section of the ensemble, which corresponds to all four scenarios in this (small) ensemble. The maximum smoke level experienced was 8401 to 12100 parts per billion. Figure 12.2 indicates that some areas may be affected by high levels of CO in some, but not all scenarios. This demonstrates that smoke and combustion products are sensitive to differences in the fire spread, in this case driven by a relatively minor variation in ignition point.

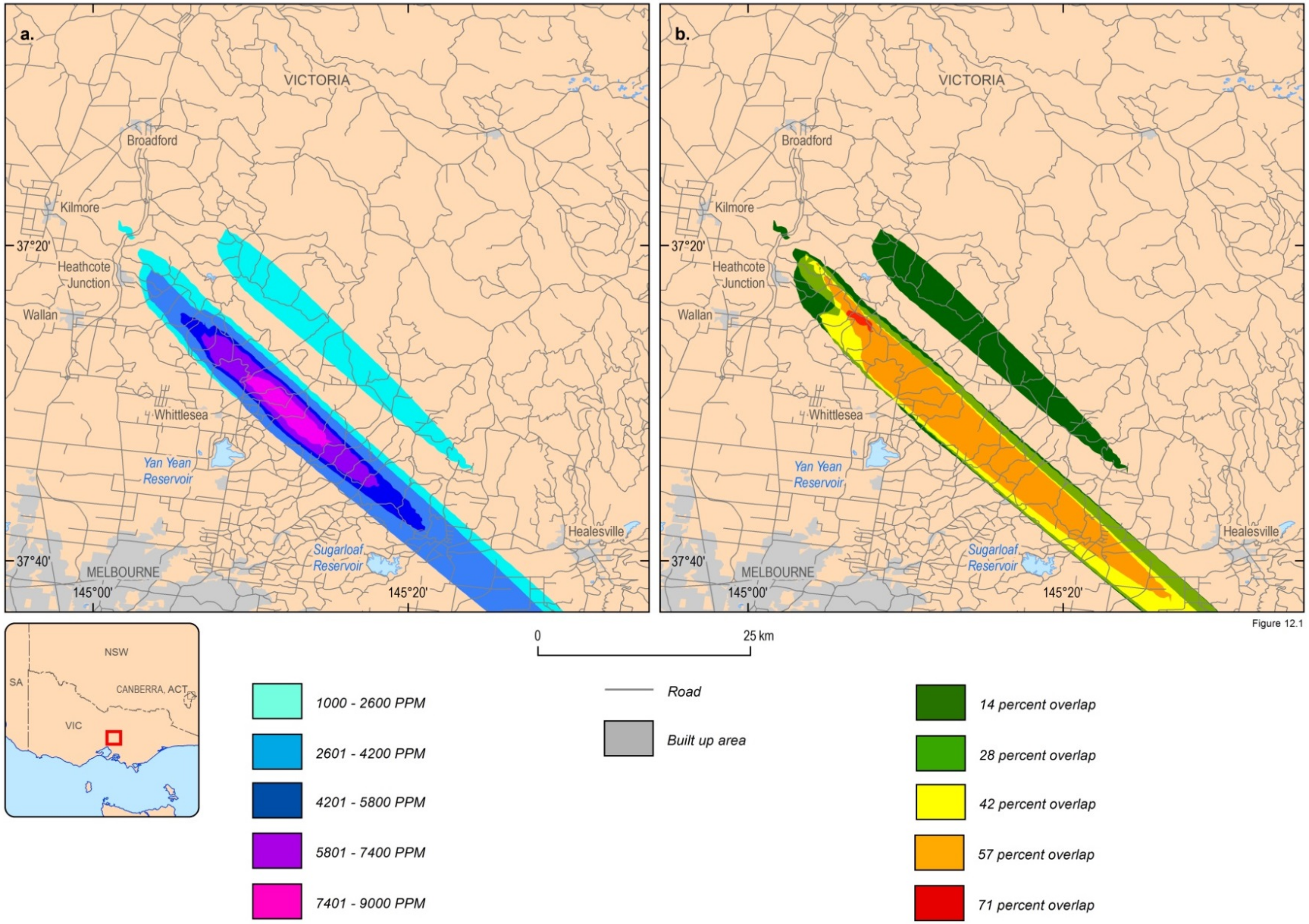


Figure 12.1(a) Ensemble concentration of CO at 15:00 hours. *(b) Percentage overlap for CO at 15:00 hours.*

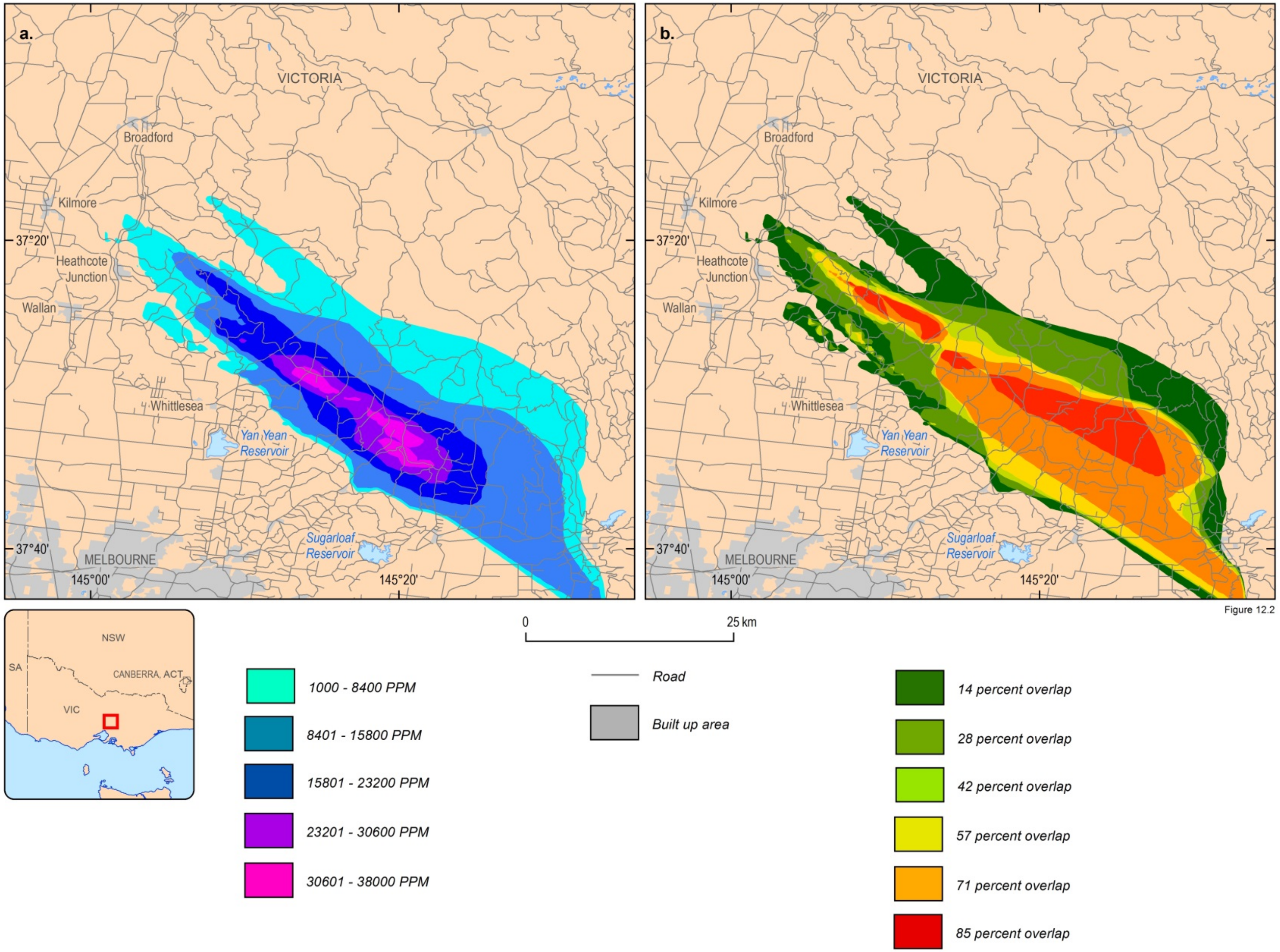


Figure 12.2 (a) Ensemble concentration of CO at 17:00 hours. (b) Percentage overlap for CO at 17:00 hours.

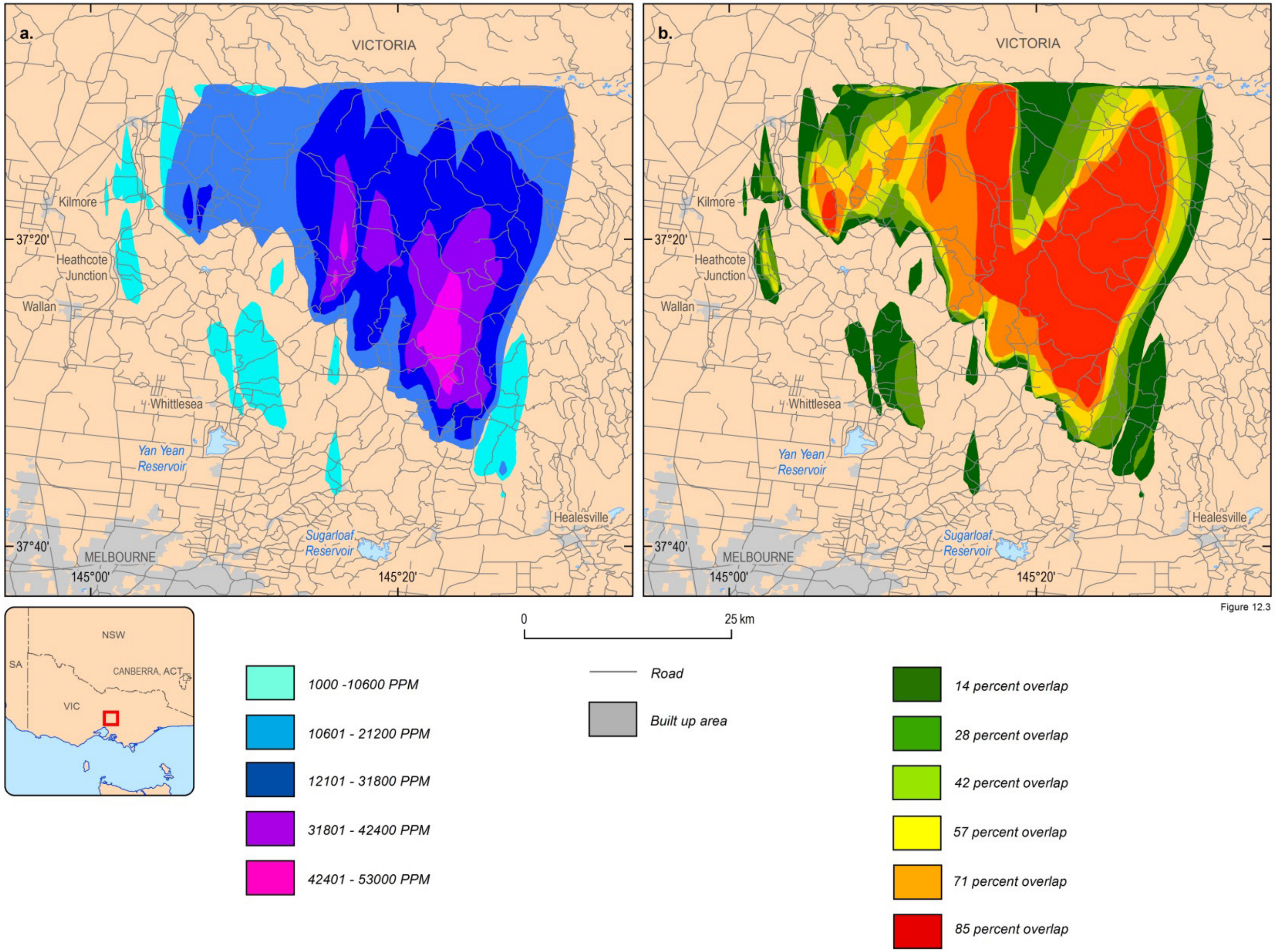


Figure 12.3 (a) Ensemble concentration of CO at 19:00 hours. *(b) Percentage overlap for CO at 19:00 hours.*

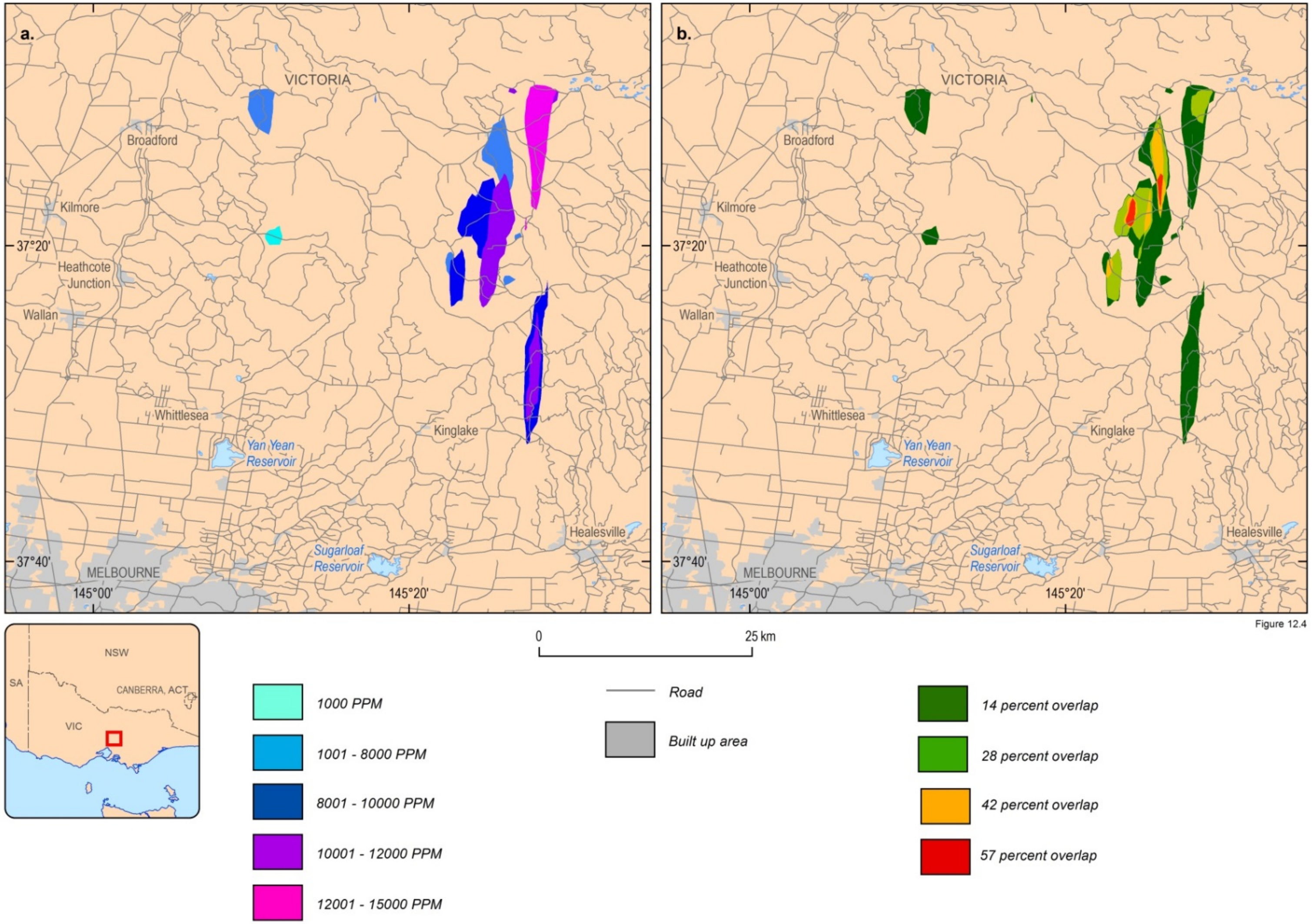


Figure 12.4 (a) Ensemble concentration of CO at 21:00 hours (b) Percentage overlap for CO at 21:00 hours.

12.3.2 Sensitivity of smoke –Nitrogen Dioxide (NO_2)

This section discusses the sensitivity of Nitrogen Dioxide (NO_2) generated for the Kilmore fire modelling. Figure 12.5(a) displays the maximum NO_2 concentration in parts per billion that occurred at 17:00 hours in the four member ensemble. Figure 12.5(b) displays the percentage overlap of the NO_2 simulations at that time. Figure 12.5 shows that at 17:00 hours the highest concentration of NO_2 was south west of Healesville, where 56 to 70 parts per billion of NO_2 was experienced; the area was affected by smoke in all of the ensemble scenarios.

12.3.3 Sensitivity of smoke – Ozone (O_3)

Figure 12.6displays the maximum concentration and the percentage overlap of the Ozone ($O_{3)}$ modelling across all scenarios at 17:00 hours. This figure shows that, at 17:00, Healesville was experiencing 10 parts per billion of ozone at a maximum; the area was affected by smoke in 14-20% of the ensemble, i.e. in one of the four ensemble members.

12.3.4 Sensitivity of smoke – Particles ($PM_{2.5}$)

Figure 12.7(a) displays the maximum concentration of $PM_{2.5}$ particles that occurred across the ensemble at 17:00 hours, and Figure 12.7(b) displays the percentage overlap of all the $PM_{2.5}$ scenarios at that time. This figure shows that, at 17:00 hours, Healesville was experiencing up to 600 micro grams per cubic metre of $PM_{2.5}$ particles; the area was affected by smoke in 81-100% of the ensemble, i.e. all of its scenarios.

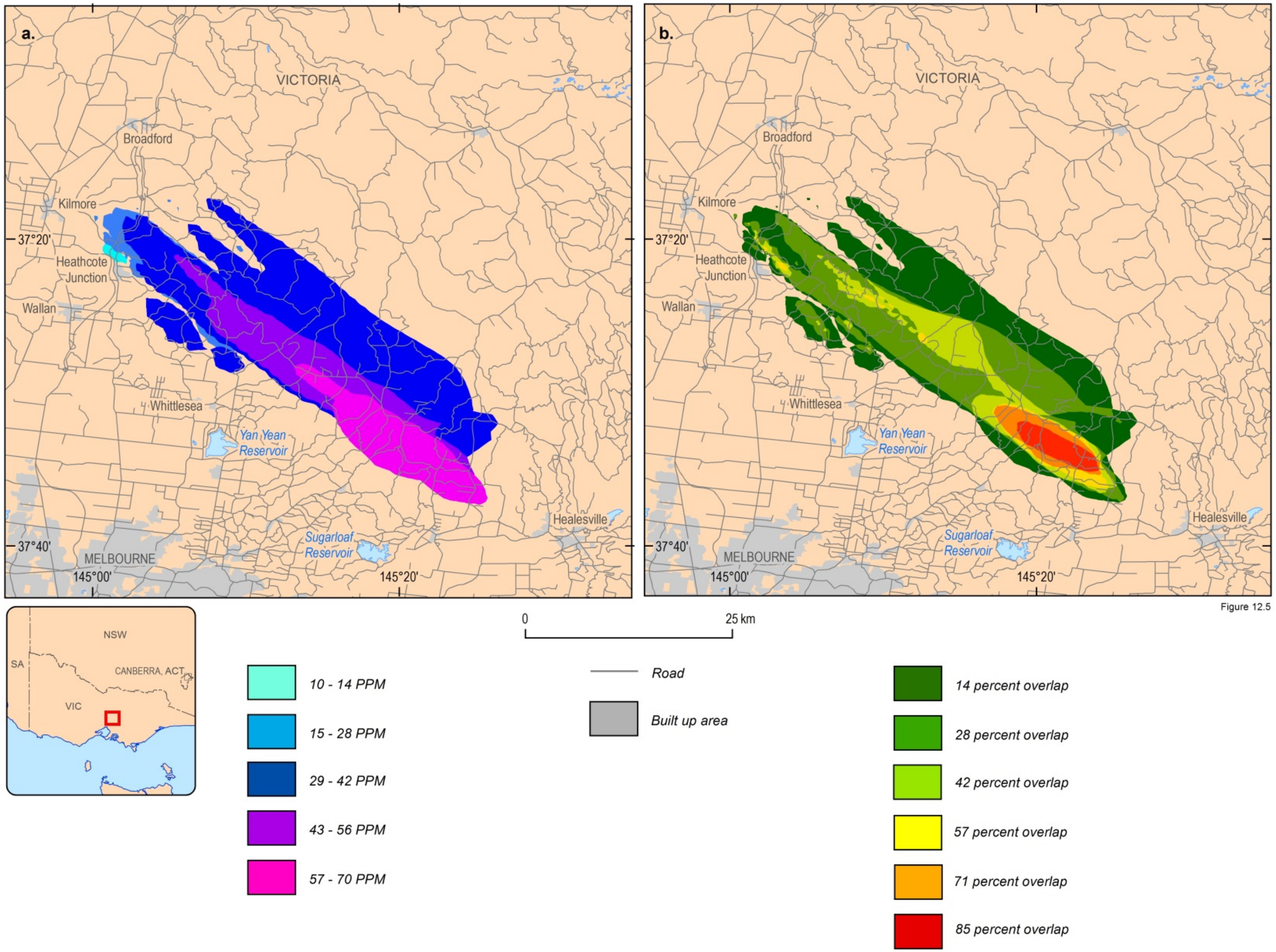


Figure 12.5 (a) Ensemble concentration of NO_2 at 17:00 hours. *(b) Percentage overlap for NO_2 at 17:00 hours.*

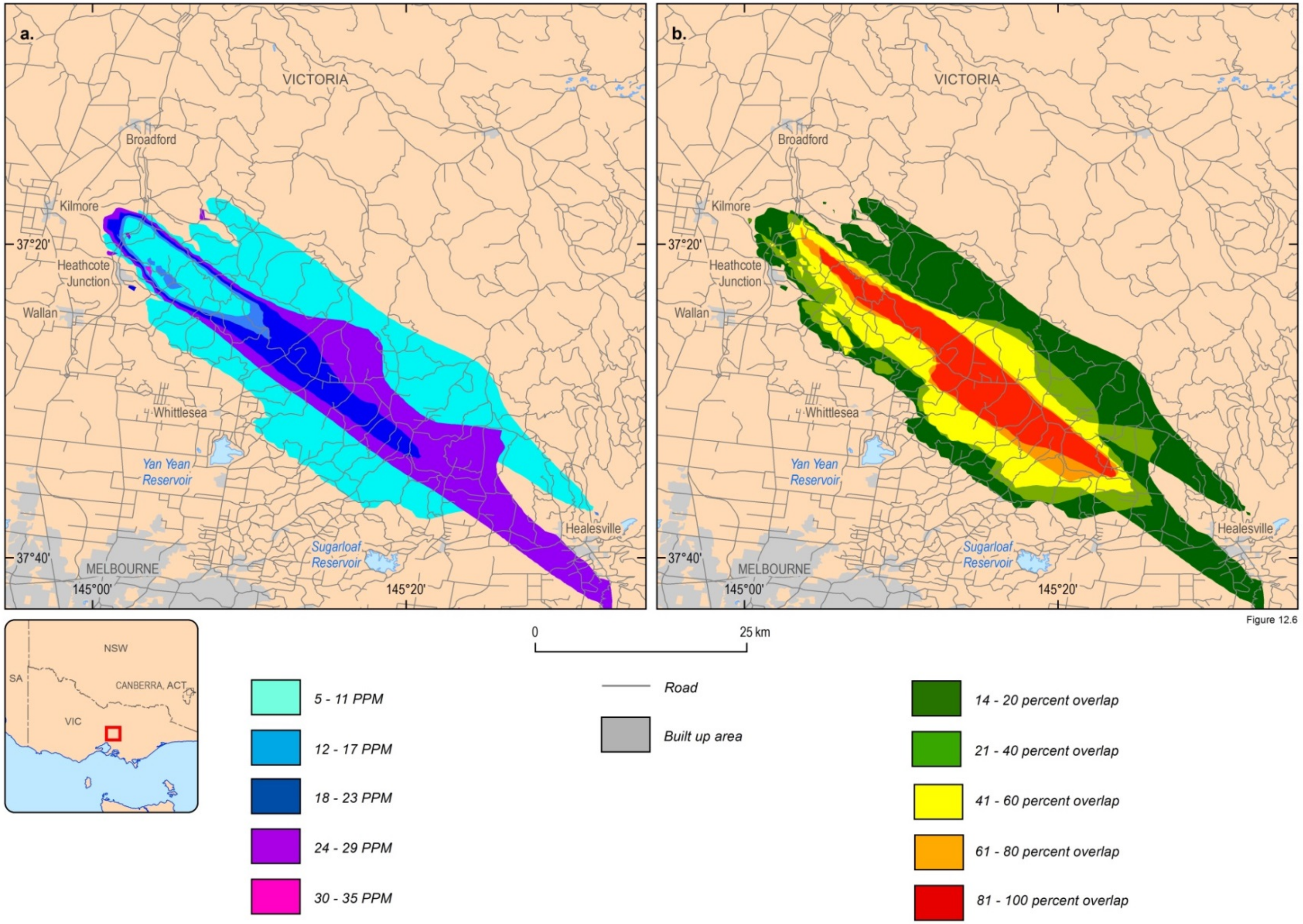


Figure 12.6 (a) Ensemble concentration of O_3 at 17:00 hours. *(b) Percentage overlap for O_3 at 17:00 hours.*

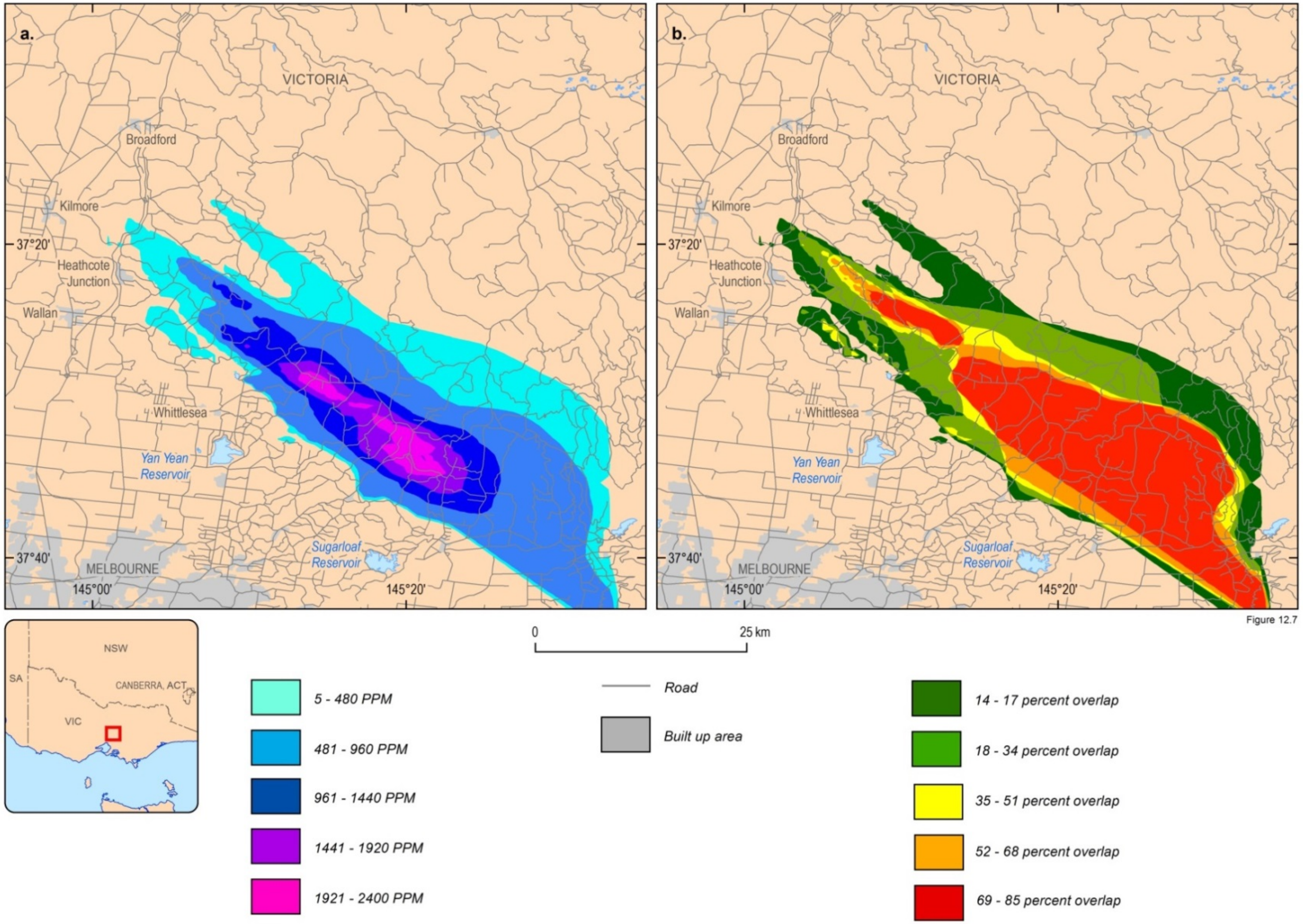


Figure 12.7(a) Ensemble concentration of $PM_{2.5}$ at 17:00 hours. (b) Percentage overlap for $PM_{2.5}$ at 17:00 hours.

12.4 Conclusions and Future Work

The results in this chapter demonstrate the ensemble approach applied to fire spread modelling can be extended to the modelling of smoke and combustion products. The integrated ensemble approach generates scenarios of smoke related products, which can be interpreted in terms of the sensitivity of the spread and concentration of those products to uncertainty or error in the modelling parameters.

The methodology for displaying the results from ensemble smoke and combustion was developed in a slightly different manner than that for fire spread. The visualisation includes mapping the intensity, in terms of the maximum concentration, as well as the overlapping spread of the gases.

It has to be noted that the combination of the maximum concentration of smoke products and smoke spread has to be interpreted with some caution. The maximum concentration of smoke products is the maximum intensity experienced across all ensemble members. While the grid cell may be affected by smoke in all scenarios, the displayed intensity may not reach the displayed maximum in all scenarios. The maximum intensity is a conservative estimate in that it shows a ‘worst case’ scenario, which can be interpreted in terms of a range of consequences, including population health and agriculture or viticulture. Alternative measures of the smoke and combustion product intensity would be average intensity, or the intensity range in each cell.

Finally, the results in this chapter show that the spread of smoke and combustion product modelling results are sensitive to relatively minor variations in the conditions in which the fire occurs. While this in itself may not be surprising, the exploration of the sensitivities and uncertainties of the modelling process will contribute to a more robust interpretation of the output of an integrated fire and smoke model. The FireDST system enables expanding this understanding through providing an environment in which to explore those sensitivities.

12.4.1 Future Work

At this stage in its development, the CMAR smoke and combustion model is extremely computationally intensive. A model run takes more time than the time taken by the actual fire spread. Further development and optimisation should improve the computation time. This process would be supported by analysis of the model’s spatial and temporal resolutions that balance run time against accuracy of the output. Both defining both acceptable run times and accuracy levels will require clear specification of the intended use of the model outputs.

FireDST has a discrepancy in the resolution of the fire spread simulation (180 m grid) to that of the smoke simulation (1 km grid cell size). Further investigation needs to validate the optimum resolution of the fire spread modelling that yields an acceptable smoke simulation. This may suggest further opportunities to optimise efficiency of the code.

The present study only assessed sensitivity of a very limited ensemble. To get a better understanding of the sensitivities of smoke and combustion product modelling, the methodology would have to be applied to the full range of parameters used in both the fire spread and the smoke modelling. This includes for example the resolution (see previous point).

The CMAR smoke and gas model results are recorded at ground level, i.e. 10 m. This is useful for health warnings and impact modelling. However, it would be useful to explore the potential value in the modelling results at higher levels in the atmosphere. Such information could potentially support Emergency Services agencies in interpreting sightings of smoke plumes.

13 Conclusions from the Kilmore Case Study

The results discussed in this report demonstrate the potential of the FireDST approach for assessing aspects of the sensitivity of modelled fire spread and impact for the Kilmore 2009 event. In line with the research objectives laid out in Chapter 2, FireDST provides an integrated fire spread and impact model. Furthermore, it implements an approach to assess and visualise sensitivity of modelled fire spread and impact to input parameters and assumptions. The FireDST system is applied to assess the sensitivity of the fire spread and impact to surface weather, fuel load, ignition, and vulnerability assumptions. The methodology was extended to enable assessment of the sensitivity of smoke to a range of parameters.

The Kilmore case study results demonstrate some fundamental benefits from ensemble information that are not easily achieved in 'best estimate' single scenario model outputs. The range of the ensemble fire spread or impact is a direct measure of the model sensitivity to the parameters sampled to generate the ensemble. Therefore, such information supports better understanding of the robustness of model outputs.

A few key findings of this work include:

The modelled fire spread for the Kilmore event based on the ACCESS simulations of the surface weather, ignition and fuel at the time did not match the historical fire spread very well. This was likely due to complex terrain conditions, and their impact on local weather driving the fire, particularly the wind speed. Various approaches to adjusting the winds (bias correction and wind multipliers) resulted in a better match between observed and modelled fire spread.

The FireDST ensemble approach did generate scenarios that were a close match to the historical fire. This demonstrates that an ensemble fire spread can highlight potential scenarios that are realistic, but are not the 'best estimate'. Identifying those scenarios may result in different decision processes around a fire event.

This report does not attempt to rank the sensitivity of the fire spread and impact to different parameters. This would only have been possible if the perturbation range of parameters was set on a consistent basis to be comparable, i.e. based on the probability distribution of the uncertainty.

The sensitivity of fire spread modelling is not static, but changes between different events, and even within the lifetime of an event.

Testing sensitivity of fire spread modelling to individual parameters in isolation ignores the interactions between the parameters and their impact on the fire. In other words, a scenario generated by a combination of perturbed parameters may not reflect the variation caused by the individual parameters. To ensure a realistic sensitivity assessment, ensembles should include combinations of parameters.

As noted above, the scenarios in FireDST are not currently weighted by probability. With that information, the methodology used by the FireDST system would generate probabilistic fire spread and impact estimates.

The accuracy of the impact modelling is fundamentally linked to and limited by the fire spread modelling.

Although a single study is a limited basis on which to judge the performance of the FireDST house loss approach, sensitivity tests have indicated various opportunities for improvement of the model accuracy. The vulnerability model used to estimate house loss in FireDST is generic, and needs to be developed and validated for different house types. Furthermore, the Building Fire Impact Model that is used to estimate the impact of sub-grid scale processes such as human action and house-to-house ignition is still largely theoretical, and needs to be supported by further data. However, this has to be seen in context of the previous point, that the impact modelling is primarily sensitive to the quality of the fire spread input.

The final report of the F.I.R.E-D.S.T. project (Cechet *et al.*, 2014) discusses the Kilmore case study in context of the other case studies and the objectives of the entire project.

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Appendix A Automated Weather Stations used in bias correction of the weather

Table A.1 2006 Automated Weather Stations used in the Kilmore weather bias correction calculation

Station name	Latitude	Longitude	Not all directions
Aireys Inlet	-38.458	144.088	Y
Albury Airport AWS	-36.069	146.951	
Avalon Airport	-38.029	144.478	
Ballarat Aerodrome	-37.513	143.791	
Bendigo Airport	-36.739	144.327	
Cape Otway Lighthouse	-38.856	143.513	
Charlton	-36.285	143.334	
Colac (Mt. Gellibrand)	-38.233	143.792	
Coldstream	-37.724	145.409	
Deniliquin Airport AWS	-35.557	144.946	
Eildon Fire Tower	-37.209	145.842	
Essendon Airport	-37.728	144.907	
Frankston AWS	-38.148	145.116	Y
Kyabram	-36.335	145.064	
Laverton Airport	-37.856	144.757	
Mangalore Airport	-36.889	145.186	
Melbourne Airport	-37.666	144.832	
Melbourne Regional Office	-37.807	144.970	
Moorabbin Airport	-37.980	145.096	
Mt. Baw Baw	-37.838	146.275	Y
Mt. Buller	-37.145	146.439	Y
Mt. Hotham	-36.977	147.134	Y
Pound Creek	-38.630	145.811	
Pyrenees (Ben Nevis)	-37.228	143.201	
Redesdale	-37.019	144.520	
Rutherglen Research	-36.105	146.509	
Swan Hill Aerodrome	-35.377	143.542	
Scoresby Research	-37.871	145.256	
Sheoks	-37.908	144.130	
Viewbank	-37.741	145.097	
Wallan (Kilmore Gap)	-37.381	144.965	Y
Wangaratta Airport	-36.421	146.306	

Station name	Latitude	Longitude	Not all directions
Yarram Airport	-38.565	146.748	
Yarrawonga	-36.029	146.031	

Appendix B Ensemble – Scenario Labelling

Each scenario described in this report is defined by a combination of parameter settings. The following list defines the codes with the parameter settings. The scenario names, specified in Appendices C and E, are a combination of these codes that specify the scenario's parameter settings.

KI – Kilmore

VN – No vertical atmosphere included in the modelling

W400 – 440 m resolution weather, i.e. ACCESS model grid resolution 440 m

W1200 – 1200 m resolution weather, i.e. ACCESS model grid resolution 1200 m

W3600 – 4000 m resolution weather, i.e. ACCESS model grid resolution 4000 m

T05 – 5 minute time steps

T15 – 15 minute time steps

T30 – 30 minute time steps

T60 – 60 minute time steps

S0 – no Suppression; the suppression component was deactivated in the PHOENIX RapidFire module

B0 – No bias correction of wind speed

BC – Bias correction of wind speed

M0 – No local wind modification was applied to the wind speed

MN – Wind Ninja local wind modification was applied to the wind speed

GP – Grid plus 2 degrees Latitude

GM – Grid minus 5 degrees Latitude and Longitude

TEP – Temperature plus

TEM – Temperature minus

RHM – Relative humidity minus

RHP – Relative humidity plus

WDP – Wind direction plus

WDM – Wind direction minus

WSP – Wind speed plus

WSM – Wind speed minus

Appendix C Ensemble – Scenarios Applied in F.I.R.E-D.S.T. for Kilmore

These individual PHOENIX RapidFire simulations make up the ensemble shown in Figure 4.1. The meaning of the scenario labels is given in Appendix B

KI_VN_W400_T05_S0_MN_BC

KI_VN_W1200_T15_S0_MN_BC

KI_VN_W3600_T30_S0_MN_BC

KI_VN_W3600_T60_S0_MN_BC

Kilmore20090207_VN_W3600_T15_BC_S0_MN_IK200E

Kilmore20090207_VN_W3600_T15_BC_S0_MN_IK200N

Kilmore20090207_VN_W3600_T15_BC_S0_MN_IK200S

Kilmore20090207_VN_W3600_T15_BC_S0_MN_IK200W

Kilmore20090207_VN_W3600_T15_S0_MN_BC_RHM2

Kilmore20090207_VN_W3600_T15_S0_MN_BC_RHM2_TEM2

Kilmore20090207_VN_W3600_T15_S0_MN_BC_RHM2_TEP5

Kilmore20090207_VN_W3600_T15_S0_MN_BC_RHM2_TEP5_WDM10

Kilmore20090207_VN_W3600_T15_S0_MN_BC_RHM2_TEP5_WDP10

Kilmore20090207_VN_W3600_T15_S0_MN_BC_RHP5

Kilmore20090207_VN_W3600_T15_S0_MN_BC_RHP5_TEM2

Kilmore20090207_VN_W3600_T15_S0_MN_BC_RHP5_TEM2_WSM5

Kilmore20090207_VN_W3600_T15_S0_MN_BC_RHP5_TEM2_WSP5

Kilmore20090207_VN_W3600_T15_S0_MN_BC_TEP5

Kilmore20090207_VN_W3600_T15_S0_MN_BC_TEP5_WDM10

Kilmore20090207_VN_W3600_T15_S0_MN_BC_TEP5_WDP10

Kilmore20090207_VN_W3600_T15_S0_MN_BC_TEM2

Kilmore20090207_VN_W3600_T15_S0_MN_BC_TEP5

Kilmore20090207_VN_W3600_T15_S0_MN_BC_TM30

Kilmore20090207_VN_W3600_T15_S0_MN_BC_TM60

Kilmore20090207_VN_W3600_T15_S0_MN_BC_TP30

Kilmore20090207_VN_W3600_T15_S0_MN_BC_TP60

Kilmore20090207_VN_W3600_T15_S0_MN_BC_WDM10

Kilmore20090207_VN_W3600_T15_S0_MN_BC_WDP10

Kilmore20090207_VN_W3600_T15_S0_MN_BC_WSM5

Kilmore20090207_VN_W3600_T15_S0_MN_BC_WSP5

Appendix D 2006 Census Human Vulnerability Indicators

Vulnerability Indicator	Description
Young at risk	Anyone under the age of five
Aged at risk	Anyone aged 65 or older
Insufficient English	Any person who identified in the Census as able to speak English not at all or not well.
Not completed Year 12	Any person who has indicated in the Census that they have not completed schooling to Year 12 (approximately 18 years of age)
Need for Assistance	Any person who has identified in the Census that they need assistance with self care activities such as feeding, dressing and washing, or need assistance with communication
Volunteering rate	This Census indicator measures the number of people who spend time in volunteer activities.
Low Income Households	Households who have indicated in the Census that they have an income of less than $500
No Motor vehicle access	Measures the number of households that do not have access to a motor vehicle.
New One Year	Occupant lived in the property less than a year. This is based on the stated address of the person one year ago.
New Five Year	Occupant lived in the property less than five years. This is based on the stated address of the person five years ago.
Single Parent Families	All families that have children under 15 years old and that have only one parent living at that location.
Indigenous	All persons who identify as being Aboriginal or a Torres Strait Islander.
Public Housing	All persons who rent their house from a state or territory housing authority.
Unoccupied homes	When the Census is collected the collector notes if a form is not completed and if the house appears to be unoccupied at the time of their visit

Appendix E Vulnerability Sensitivity Analysis Simulation Set

Table E.1 lists the PHOENIX RapidFire scenarios that were used in assessing the sensitivity of the house loss to the vulnerability functions, described in Chapter 9. See Appendix B for the meaning of the scenario labels.

Table E.1 FIRE-DST scenarios used in each vulnerability sensitivity run.

Number	Indicator
1	KI_VN_W400_T05_S0_M0_BC
2	KI_VN_W400_T15_S0_M0_BC
3	KI_VN_W400_T30_S0_M0_BC
4	KI_VN_W400_T60_S0_M0_BC
5	KI_VN_W1200_T05_S0_M0_BC
6	KI_VN_W1200_T15_S0_M0_BC
7	KI_VN_W1200_T30_S0_M0_BC
8	KI_VN_W1200_T60_S0_M0_BC
9	KI_VN_W3600_T05_S0_M0_BC
10	KI_VN_W3600_T15_S0_M0_BC
11	KI_VN_W3600_T30_S0_M0_BC
12	KI_VN_W3600_T60_S0_M0_BC
13	KI_VN_W400_T05_S0_MN_BC
14	KI_VN_W400_T15_S0_MN_BC
15	KI_VN_W400_T30_S0_MN_BC
16	KI_VN_W400_T60_S0_MN_BC
17	KI_VN_W1200_T05_S0_MN_BC
18	KI_VN_W1200_T15_S0_MN_BC
19	KI_VN_W1200_T30_S0_MN_BC
20	KI_VN_W3600_T05_S0_MN_BC
21	KI_VN_W3600_T15_S0_MN_BC
22	KI_VN_W3600_T30_S0_MN_BC
23	KI_VN_W3600_T60_S0_MN_BC
24	Kilmore20090207_VN_W400_T05_S0_M0_BC
25	Kilmore20090207_VN_W400_T05_S0_MN_BC
26	Kilmore20090207_VN_W1200_T05_S0_M0_BC
27	Kilmore20090207_VN_W1200_T05_S0_MN_BC
28	Kilmore20090207_VN_W3600_T05_S0_M0_BC

Number	Indicator
29	Kilmore20090207_VN_W3600_T05_S0_MN_BC
30	Kilmore20090207_VN_W3600_T15_S0_M0_BC_GP2L
31	Kilmore20090207_VN_W3600_T15_S0_M0_BC_RHM2
32	Kilmore20090207_VN_W3600_T15_S0_M0_BC_RHP5
33	Kilmore20090207_VN_W3600_T15_S0_M0_BC_TEM2
34	Kilmore20090207_VN_W3600_T15_S0_M0_BC_TEP5
35	Kilmore20090207_VN_W3600_T15_S0_M0_BC_TM30
36	Kilmore20090207_VN_W3600_T15_S0_M0_BC_TM60
37	Kilmore20090207_VN_W3600_T15_S0_M0_BC_TP30
38	Kilmore20090207_VN_W3600_T15_S0_M0_BC_TP60
39	Kilmore20090207_VN_W3600_T15_S0_M0_BC_WDM10
40	Kilmore20090207_VN_W3600_T15_S0_M0_BC_WDP10
41	Kilmore20090207_VN_W3600_T15_S0_M0_BC_WSM5
42	Kilmore20090207_VN_W3600_T15_S0_M0_BC_WSP5
43	Kilmore20090207_VN_W3600_T15_S0_MN_BC_GP2L
44	Kilmore20090207_VN_W3600_T15_S0_MN_BC_RHM2
45	Kilmore20090207_VN_W3600_T15_S0_MN_BC_RHP5
46	Kilmore20090207_VN_W3600_T15_S0_MN_BC_TEM2
47	Kilmore20090207_VN_W3600_T15_S0_MN_BC_TEP5
48	Kilmore20090207_VN_W3600_T15_S0_MN_BC_TM30
49	Kilmore20090207_VN_W3600_T15_S0_MN_BC_TM60
50	Kilmore20090207_VN_W3600_T15_S0_MN_BC_TP30
51	Kilmore20090207_VN_W3600_T15_S0_MN_BC_TP60
52	Kilmore20090207_VN_W3600_T15_S0_MN_BC_WDM10
53	Kilmore20090207_VN_W3600_T15_S0_MN_BC_WDP10
54	Kilmore20090207_VN_W3600_T15_S0_MN_BC_WSM5
55	Kilmore20090207_VN_W3600_T15_S0_MN_BC_WSP5
56	Kilmore20090207_VN_W3600_T15_S0_M0_BC_GM2LL
57	Kilmore20090207_VN_W3600_T15_S0_M0_BC_GM05LL
58	Kilmore20090207_VN_W3600_T15_S0_M0_BC_GP05LL
59	Kilmore20090207_VN_W3600_T15_S0_M0_BC_RHM2_TEM2
60	Kilmore20090207_VN_W3600_T15_S0_M0_BC_RHM2_TEP5
61	Kilmore20090207_VN_W3600_T15_S0_M0_BC_RHM2_TEP5_WDM10
62	Kilmore20090207_VN_W3600_T15_S0_M0_BC_RHM2_TEP5_WDP10
63	Kilmore20090207_VN_W3600_T15_S0_M0_BC_RHP5_TEM2
64	Kilmore20090207_VN_W3600_T15_S0_M0_BC_RHP5_TEM2_WSM5
65	Kilmore20090207_VN_W3600_T15_S0_M0_BC_RHP5_TEM2_WSP5
66	Kilmore20090207_VN_W3600_T15_S0_M0_BC_RHP5_TEP5

Number	Indicator
67	Kilmore20090207_VN_W3600_T15_S0_M0_BC_RHP5_TEP5_WDM10
68	Kilmore20090207_VN_W3600_T15_S0_M0_BC_RHP5_TEP5_WDP10
69	K_VN_W3600_T15_S0_MN_BC_RHM2_TEP5_WDM10_WSP5_GM02LL
70	K_VN_W3600_T15_S0_MN_BC_RHM2_TEP5_WDM10_WSP5_GP02LL
71	Kilmore20090207_VN_W3600_T15_S0_MN_BC_GM2LL
72	Kilmore20090207_VN_W3600_T15_S0_MN_BC_GM05LL
73	Kilmore20090207_VN_W3600_T15_S0_MN_BC_GP2L
74	Kilmore20090207_VN_W3600_T15_S0_MN_BC_GP05LL
75	Kilmore20090207_VN_W3600_T15_S0_MN_BC_RHM2_TEM2
76	Kilmore20090207_VN_W3600_T15_S0_MN_BC_RHM2_TEP5
77	Kilmore20090207_VN_W3600_T15_S0_MN_BC_RHM2_TEP5_WDM10
78	Kilmore20090207_VN_W3600_T15_S0_MN_BC_RHM2_TEP5_WDP10
79	Kilmore20090207_VN_W3600_T15_S0_MN_BC_RHP5_TEM2
80	Kilmore20090207_VN_W3600_T15_S0_MN_BC_RHP5_TEM2_WSM5
81	Kilmore20090207_VN_W3600_T15_S0_MN_BC_RHP5_TEM2_WSP5
82	Kilmore20090207_VN_W3600_T15_S0_MN_BC_RHP5_TEP5
83	Kilmore20090207_VN_W3600_T15_S0_MN_BC_RHP5_TEP5_WDM10
84	Kilmore20090207_VN_W3600_T15_S0_MN_BC_RHP5_TEP5_WDP10
85	Kilmore20090207_VN_W400_T05_BC_S0_MN_IK200E
86	Kilmore20090207_VN_W400_T05_BC_S0_MN_IK200W
87	Kilmore20090207_VN_W400_T05_BC_S0_MN_IK200N
88	Kilmore20090207_VN_W400_T05_BC_S0_MN_IK200S
89	Kilmore20090207_VN_W3600_T15_BC_S0_MN_IK200E
90	Kilmore20090207_VN_W3600_T15_BC_S0_MN_IK200W
91	Kilmore20090207_VN_W3600_T15_BC_S0_MN_IK200N
92	Kilmore20090207_VN_W3600_T15_BC_S0_MN_IK200S
93	Kilmore20090207_VN_W400_T05_BC_S0_M0_IK200W
94	Kilmore20090207_VN_W400_T05_BC_S0_M0_IK200N
95	Kilmore20090207_VN_W400_T05_BC_S0_M0_IK200S
96	Kilmore20090207_VN_W3600_T15_BC_S0_M0_IK200E
97	Kilmore20090207_VN_W3600_T15_BC_S0_M0_IK200W
98	Kilmore20090207_VN_W3600_T15_BC_S0_M0_IK200N
99	Kilmore20090207_VN_W3600_T15_BC_S0_M0_IK200S

Tables E.2 to E.4 list the vulnerability functions that were tested as part of the sensitivity analysis.

Table E.2 Vulnerability sets used (VGR Generic set – applied to all houses).

Definition	Comments
Generic Radiation curve (centred on 12.5 kW)	Uses 12.5 kW per square metre (mainly houses that are built to older building standards). BAL-12.5
Generic Ember Vulnerability for 4- 6 % Humidity	In using the Generic Vulnerabilities, FIRE-DST uses the 4-6% ember curves to use at the house based on the PHOENIX RapidFire cell Humidity.
Generic Ember Vulnerability for 6 to 8 % Humidity	In using the Generic Vulnerabilities, FIRE-DST uses the 6-8% ember curves to use at the house based on the PHOENIX RapidFire cell Humidity.
Generic Ember Vulnerability for 8 to10 % Humidity	In using the Generic Vulnerabilities, FIRE-DST uses the 8-10% ember curves to use at the house based on the PHOENIX RapidFire cell Humidity.

Table E.3 Vulnerability sets used (Radiation Extension Sets – all use Generic Ember Curves for all houses).

Primary Indicator	Definition	Comments
VR19	Radiation Resistant (centred on 19 kW)	Radiation curve shifted to the right to make houses more resistant to radiation – centred on 19 kW.(matches BAL-19 in AS3959)
VR29	Radiation Resistant (centred on 29 kW)	Radiation curve shifted to the right to make houses more resistant to radiation – centred on 29 kW (matches BAL-29 in AS3959).
VR40	Radiation Resistant (centred on 40 kW)	Radiation curve shifted to the right to make houses more resistant to radiation – centred on 40 kW. (matches BAL-40 in AS3959)

Table E.4 Variables used in testing each vulnerability set.

Primary Indicator	Definition	Test values	Units	Test Environment	Comments
RAD	Radiation	5 to 95 percent in steps of 5	Percent	Ember Destroyed Threshold = 50% Distance = 5 m	The Table D.2 radiation sets are tested for sensitivity to variation in the radiation destroyed threshold on the supplied radiation curve in the Table D.2 set.
EMB	Ember	5 to 95 percent in steps of 5	Percent	Radiation Destroyed Threshold = 50% Distance = 5 m	The Table D.2 ember sets are tested for sensitivity to variation in the ember destroyed threshold on the supplied ember curve in the Table D.2 set selected from the actual humidity.
DIST	Distance	100,95,90,85,80,75,70, 65,60,55,50,45,40,35,30, 25,20,15,10, ,5, 1	metres	Ember Destroyed Threshold = 50% Radiation Destroyed Threshold = 50% (centre of curve)	The Table D.2 sets are tested for sensitivity to variation in the distance. Maximum distance will depend on whether the change in distance is having any affect.