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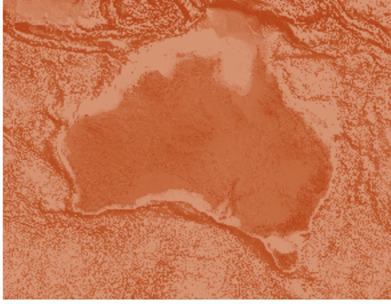

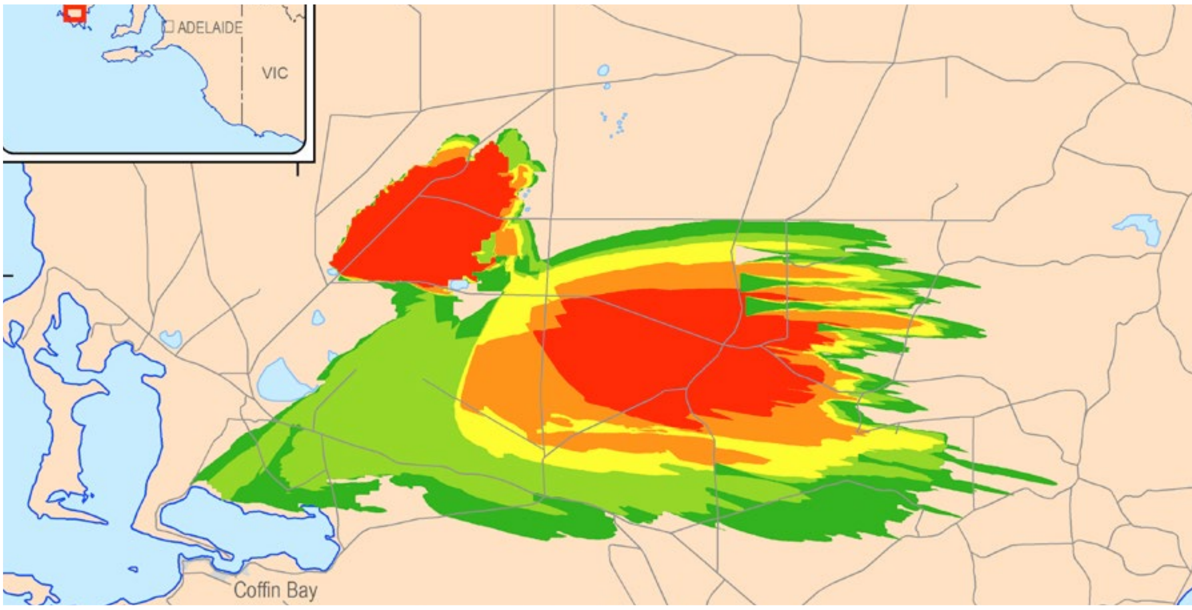

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Acknowledging and Understanding Variability in Simulating Bushfires

Part 2 - Evaluation of FireDST against the Wangary fire of 10 January 2005

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

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Contents

Audience

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 aims and scope 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.

Acknowledgements

The author would like to acknowledge the assistance of:

- The Bushfire CRC for funding and supporting the FireDST project team.
- 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.
- The end users on the F.I.R.E-D.S.T. Project Board for their in-depth knowledge of fire-fighting practices and for their support in looking to the future.

Abbreviations and 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	Unit in the 2006 Australian Bureau Statistics Census. Now called Statistical Area Level 1 (SA 1). Generally has a population of 200-800 people with an average of 400 people.
CSIRO	The Commonwealth Scientific and Industrial Research Organisation
Ensemble Footprint	The fire shape that encompasses the fire spread in 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	A set of fire spread simulation scenarios based on perturbations of certain input parameters.
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 level of damage to a building as a function of the hazard. The higher the hazard, the more likely the house will be destroyed.

1 Executive Summary

1.1 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:

1. 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 conditions; and
   - ignition timing and location.
2. Develop a methodology to assess the sensitivity of the estimated numbers of people and buildings exposed to a fire to these parameters;
3. Develop a methodology to assess the sensitivity of the buildings that are modelled to be destroyed by a fire to a range of parameters describing:
   - Surface weather;
   - fuel condition;
   - ignition location and time; and
   - Engineering vulnerability.

These research objectives focus on sensitivity of the modelled fire spread and impact. Sensitivity analysis is a key component for a better understanding of the robustness and error of model outputs. By addressing the objectives 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 that covers 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 a '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; and
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.

1.2 Project approach

Addressing the research 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:

1. New numerical weather prediction model (ACCESS) from the Bureau of Meteorology.
2. An updated version of the PHOENIX RapidFire bushfire simulator from the University of Melbourne.
3. Information on the built environment and population from the Australian exposure information system (NEXIS) from Geoscience Australia.
4. Census information from the Australian Bureau of Statistics.

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 within the fire spread, and models the potential destruction and damage to buildings as well as the number of people potentially displaced. 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 applied 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 report evaluates the results of sensitivity tests using FireDST in the case study of the Wangary fire of 10 January 2005.

Objective 1 – Assess and visualise variability in the fire spread

The range of fire spread within an ensemble was visualised by FireDST by overlaying the fire spread scenarios, and scoring the percentage of scenarios that overlap at any point. Ensembles provided key information on the sensitivity of fire spread simulation through the size of the resulting fire spread envelope.

FireDST currently considers all ensemble scenarios equally likely. 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. Defining this distribution was outside the scope of the project. However, even a 'pseudo-probabilistic' sensitivity ensemble gives information on the potential development of an event that cannot be provided by a single deterministic model run. FireDST proves it has the potential to do probabilistic fire spread modelling before, during or after 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 as defined by the wind direction, wind intensity, temperature, humidity and simultaneous permutations of those parameters. In addition, the sensitivity of the fire spread was assessed against the temporal and spatial resolution of the weather model input data.

The weather was simulated for the conditions during the Wangary 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 0.036º, 0.012º and 0.004º grid spacing (approximately 4000 m, 1200 m and 440 m grid resolution), in time steps of five minutes.

Based on the available weather reconstruction data, the fire spread modelled by FireDST for the Wangary fire underestimated the size of the historical event. This is likely to be due to underestimated wind speeds and wind direction at all resolutions. An approach to correct the bias in the ACCESS wind strength did not solve this issue completely. The relatively large difference between the FireDST modelled and historical fire spread, despite adjustments to the modelled weather conditions, suggests that the error in the weather data is not the dominant factor limiting the accuracy of the simulated fire spread.

A series of tests showed evidence of 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. Only a few of the results increased the accuracy of the simulations to the point where the simulations almost matched the reconstruction. This could either indicate inaccuracies in the modelled weather, but may also suggest that the impact of the perturbed input data compensates for other limitations in the fire spread modelling.

The results also demonstrated that sensitivity of the modelled fire shape to perturbations in key parameters cannot be assessed 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 the ensembles.

Finally, the results demonstrate the potential benefit of ensemble information. All initial simulations suggested that breakouts were likely; and indeed, the actual fire did break out on 11/1/2005. In the context of a fire, such information could prompt contingency planning, for example through considering measures to mitigate the effect of a breakout, should that occur in one or more of the more likely areas.

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

Upper level wind speed and direction are known to be key drivers of the spread of embers from a fire. FireDST includes a version of PHOENIX RapidFire with an improved parameterisation of ember transport, based on conditions in the upper atmosphere. Tests assessed the sensitivity of the modelled fire spread to the wind direction and speed in the upper atmosphere using this parameterisation scheme. The atmospheric conditions in the upper atmosphere were simulated by the Bureau of Meteorology ACCESS model, which modelled the vertical atmosphere at 50 heights (levels) each with 4 km horizontal resolution and time steps of 15 minutes.

The modelled fire spread showed limited sensitivity to the wind conditions from the vertical atmosphere up to level 39 (30 km). It is likely that the lack of sensitivity was due to FireDST only computing the limited impact of ember transport as a fire spread mechanism as the model assumed that only small amounts of embers were produced in the Wangary fire. Considering the predominant vegetation types were grassland and crops, the dominant fire spread mechanism in the Wangary modelling was radiation, which was much less sensitive to the wind conditions in the vertical atmosphere.

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

Fuel characterisation is known to be a major source of uncertainty for fire modelling. This project modelled the sensitivity of fire spread and impact projections to 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 confirmed that the simulated fire spread was sensitive to fuel load.

Increased fuel loads were found to generate fire spreads closer to the historical event than those based on the estimate of the actual fuel load, suggesting that fuel-related parameterisation could be a one of the sources of error for the Wangary event modelling. The Wangary fire occurred in a landscape with two dominant fuel types (grassland and crops). Moreover, the fuel load estimation did not account for seasonal effects, which are significant for crops and grasslands. As a result, parameterisation errors in fuel load estimation or fire spread for those fuels would significantly affect the range of model output.

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

The modelled Wangary fire showed limited sensitivity to the ignition location or timing. Factors causing this were related to the vegetation that the fire encountered in its development and due to the uniformity of the weather over the fire area in the day.

Objective 2 – Estimating exposure and impact by the 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. F.I.R.E-D.S.T. implemented a framework for the derivation of this exposure associated with modelling fire spread. A database of residential 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 a single fire scenario or from variations in a 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 fire characteristics through the application of a set of vulnerability curves. Building loss information can be directly related to the corresponding area of the ensemble fire spread. In order to apply these curves, the FireDST system down scales the PHOENIX RapidFire fire spread simulation results using a parameterisation of sub-grid scale fire conditions.

The sensitivity analysis of the building loss modelling in the Wangary fire showed two main results.

- Based on the simulated fire spread that best matched the historical fire, there was an accuracy of 100% in the predicted house loss. Given the known limitations of the modelling approach, this result suggests potential issues with overestimation of either the vulnerability, or the fire hazard in the Wangary fire.
- Ensemble results reflected the interaction between various fire and vulnerability parameters. The fire spread parameters used in the individual simulations create a range of hazard characteristics, from low intensity radiation fires to high intensity radiation fires. This range of intensity triggers sensitivity to the radiation threshold in the vulnerability model. Ultimately, the predicted house loss was limited by the accuracy of the fire spread modelling.

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 propagate a fire through the landscape over time. Such models typically assimilate information on the weather, terrain, and fuel load and type. Other models also 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 able to fully replicate historical fire spreads. 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 for 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 following organisations:

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 (NERAG 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 report describes the Geoscience Australia simulation system component, the 'proof-of-concept' FireDST system.

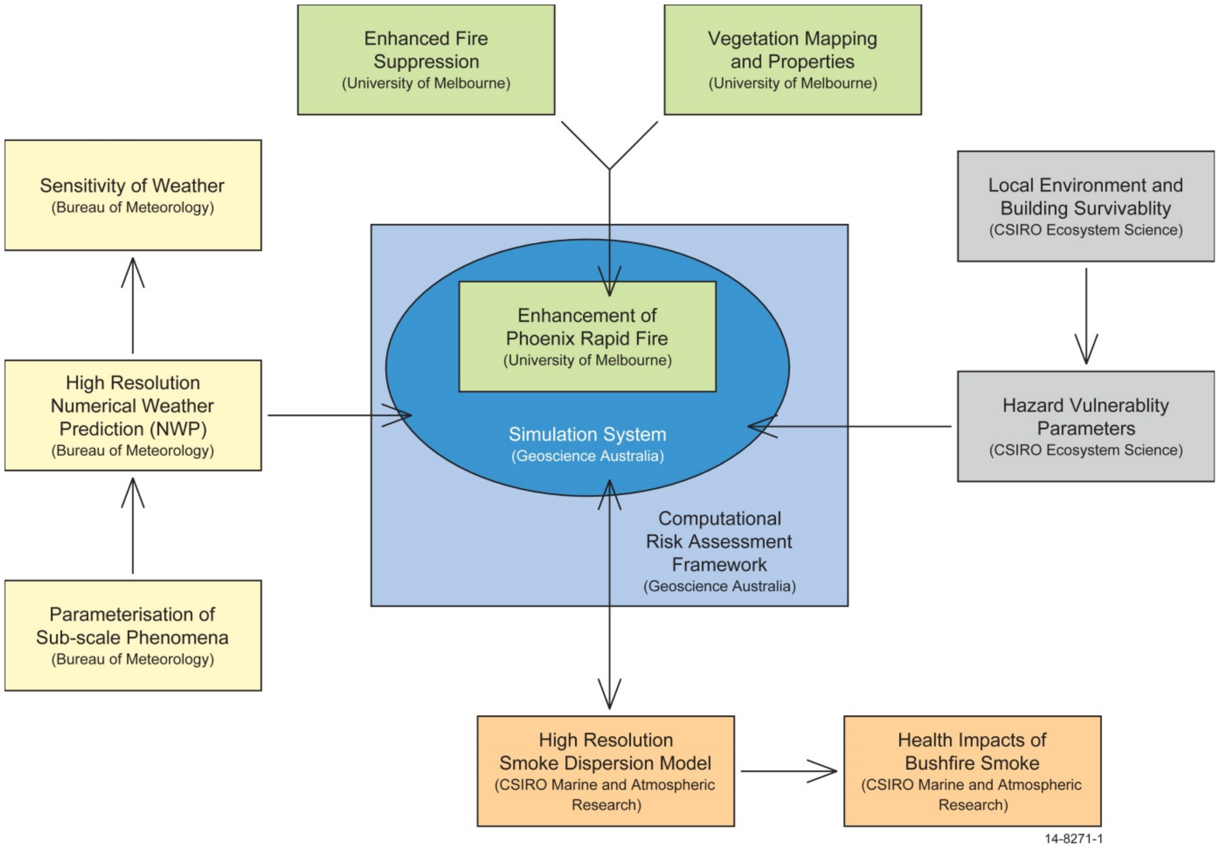

Figure 2.1 Relationship between the F.I.R.E.-D.S.T Project components.

FireDST is a computer system that integrates all of the components provided by the organisations involved in the F.I.R.E-D.S.T Project. FireDST was developed to enable research on issues related to hazard, exposure, vulnerability and impact of bushfires.

The 'proof-of-concept' FireDST system has been applied 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. The case studies were utilised to develop, test and validate the components of FireDST, as well as the FireDST simulation system outputs (spatial pattern of fire spread, house loss and people likely to be affected by smoke inhalation).

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 to address 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 conditions, and
- ignition.

Develop a methodology to assess the sensitivity of the estimated numbers of people and buildings exposed to a fire to these parameters.

Develop a methodology to assess the sensitivity of the buildings that are modelled to be destroyed by a fire to a range of parameters describing:

- Surface weather, fuel conditions and ignition, and
- Engineering vulnerability.

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:

- Development of an integrated fire spread and impact assessment methodology and tool.

- Incorporation of the ability to explore variability in key parameters as part of an integrated fire spread and impact modelling tool.
- 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.
- Improved understanding of the drivers of uncertainty in fire spread and impact modelling through sensitivity analysis of key input parameters.
- 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.
- 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.

2.3 Outline of this report

The F.I.R.E-D.S.T. project focused on three case studies to develop and validate the approaches needed to address the research objectives. This report describes the results of the case study of the Wangary Fire of 10 January 2005. Two other documents specify the results of the analyses of the case studies on the Kilmore East bushfire in Victoria on Black Saturday (February 2009) (French *et al*. 2014a) and the Mount Hall 2001 fire (French *et al*., 2014c). An overall summary of 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 outline some detail of the historical Wangary fire. Chapter 3 describes the FireDST system that was used to address the research objectives. Chapters 4 to 10 discuss the results of the Wangary Case Study. In particular,

- Chapter 4 discusses how FireDST assesses and visualises variability in the fire spread.
- Chapter 5 discusses how FireDST assesses the sensitivity of the fire spread to the surface weather.
- Chapter 6 discusses how FireDST assesses the sensitivity of the fire spread to the weather conditions in the upper atmosphere.
- Chapter 7 assesses the sensitivity of the fire spread to fuel parameters.
- Chapter 8 assesses 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.

2.4 The Wangary fire, 10 January 2005

This section provides an outline of the 10 January 2005 Wangary fire in SA, detailing the data sources and the information used in this case study.

The Wangary Fire is estimated to have started shortly after 15:00 on Monday 10 January 2005 in roadside vegetation on the eastern side of Lady Franklyn Rd approximately 45 km north west of Port Lincoln on the Lower Eyre Peninsula SA. The fire was deemed contained at 20:54 on 10 January. However weather conditions deteriorated on the morning of 11 January at around 09:30 and the fire broke through the containment lines. Six adults and three children died during the resulting fire (Schapel *et al.*, 2007). Around 78000 ha was burnt of which about 80% was productive agricultural land (Tolhurst *et al.* 2008a)

A reconstruction of the Wangary fire has been constructed by the University of Melbourne (Brett Cirulis and Dr Kevin Tolhurst) for the FireDST project. Shapefiles were provided as part of the reconstruction and were used in all simulation comparisons. Figure 2.2 to 2.11 show the reconstructed progression of the Wangary fire.

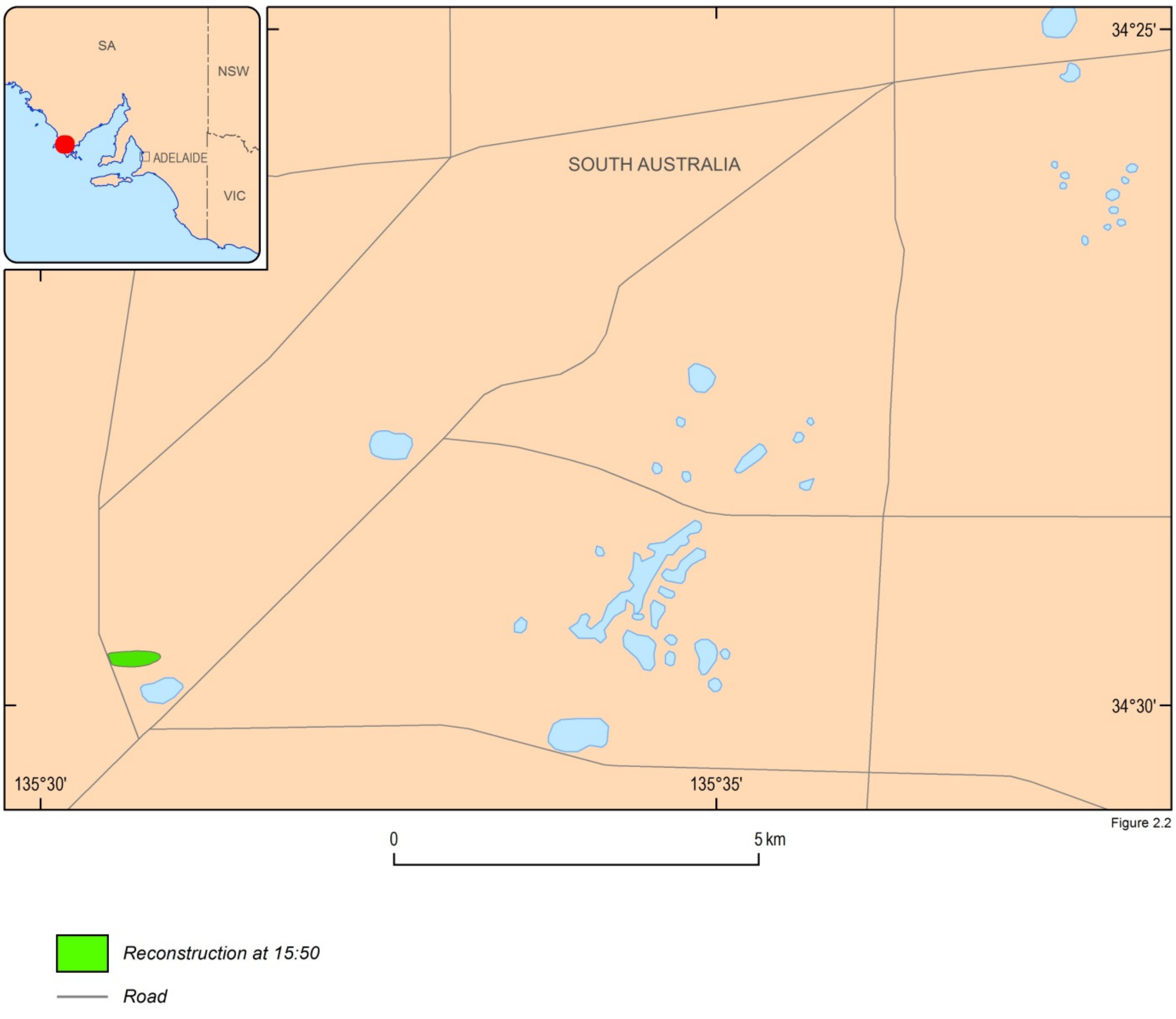

Figure 2.2 Wangary fire ignition location and reconstructed fire size at 15:30 on 10/1/2005

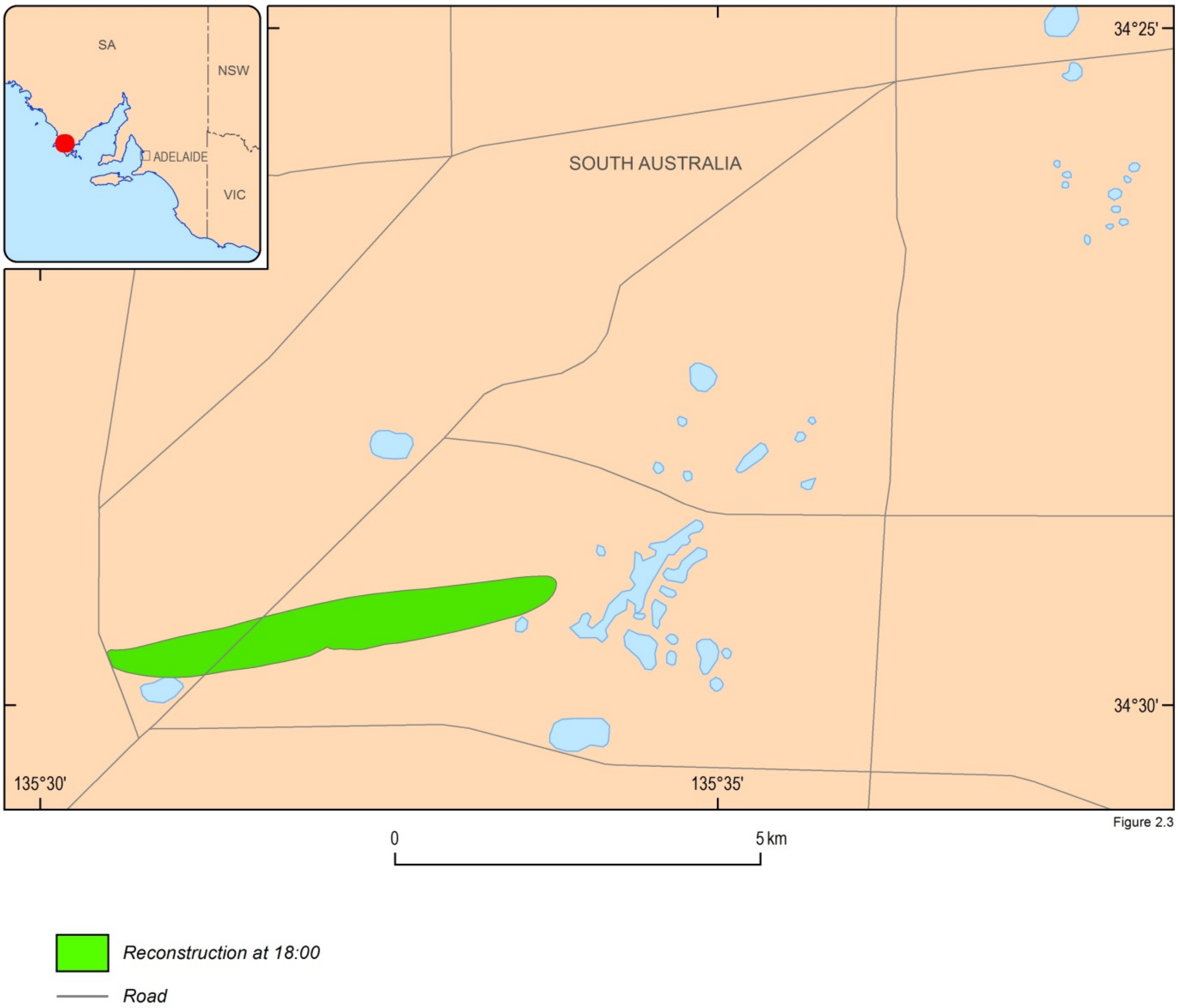

Figure 2.3.Reconstruction of the Wangary fire as it progressed to 18:00 on 10/1/2005

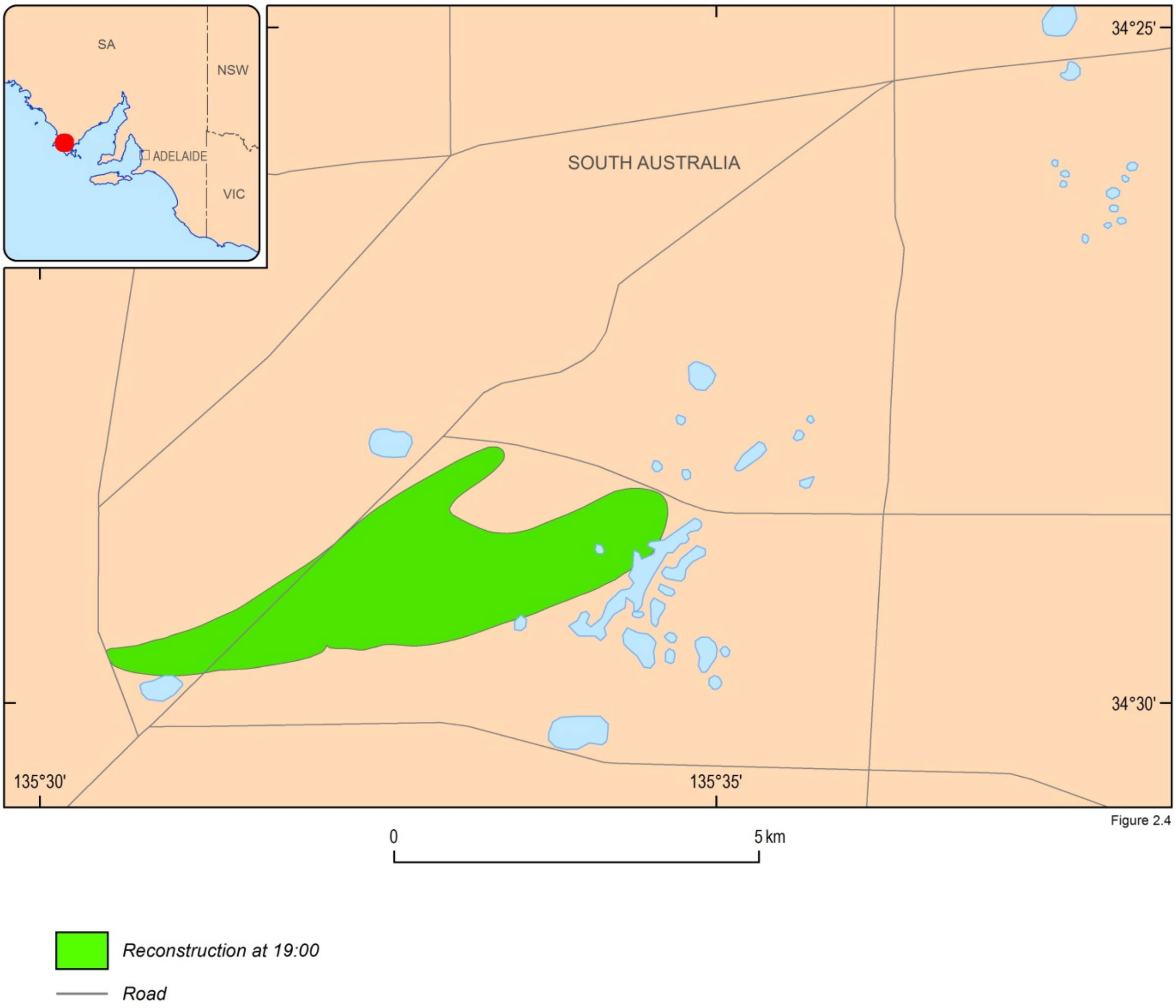

Figure 2.4 Reconstruction of the Wangary fire as it progressed to 19:00 on 10/1/2005

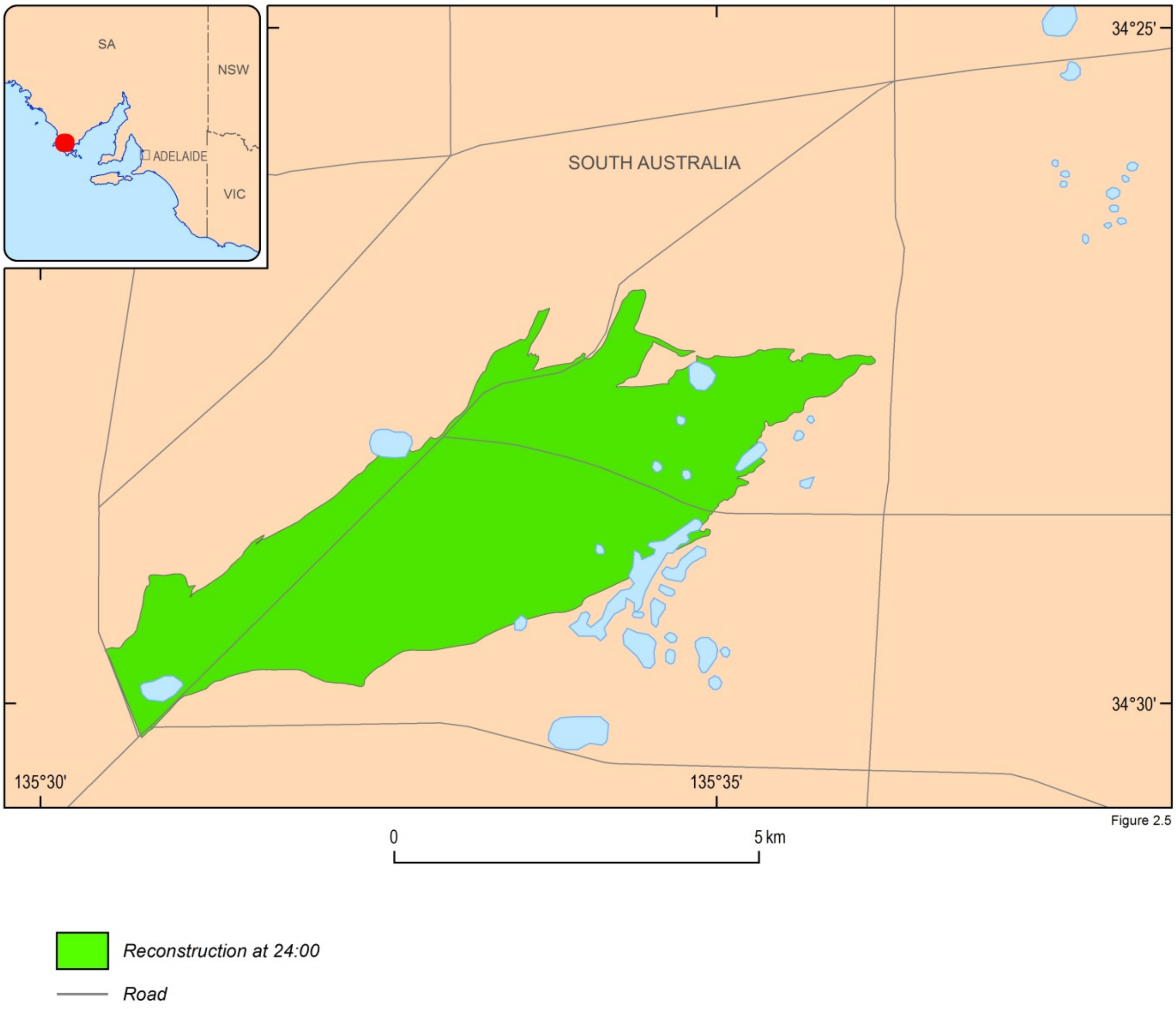

Figure 2.5 Reconstruction of the Wangary fire at midnight on 10/1/2005

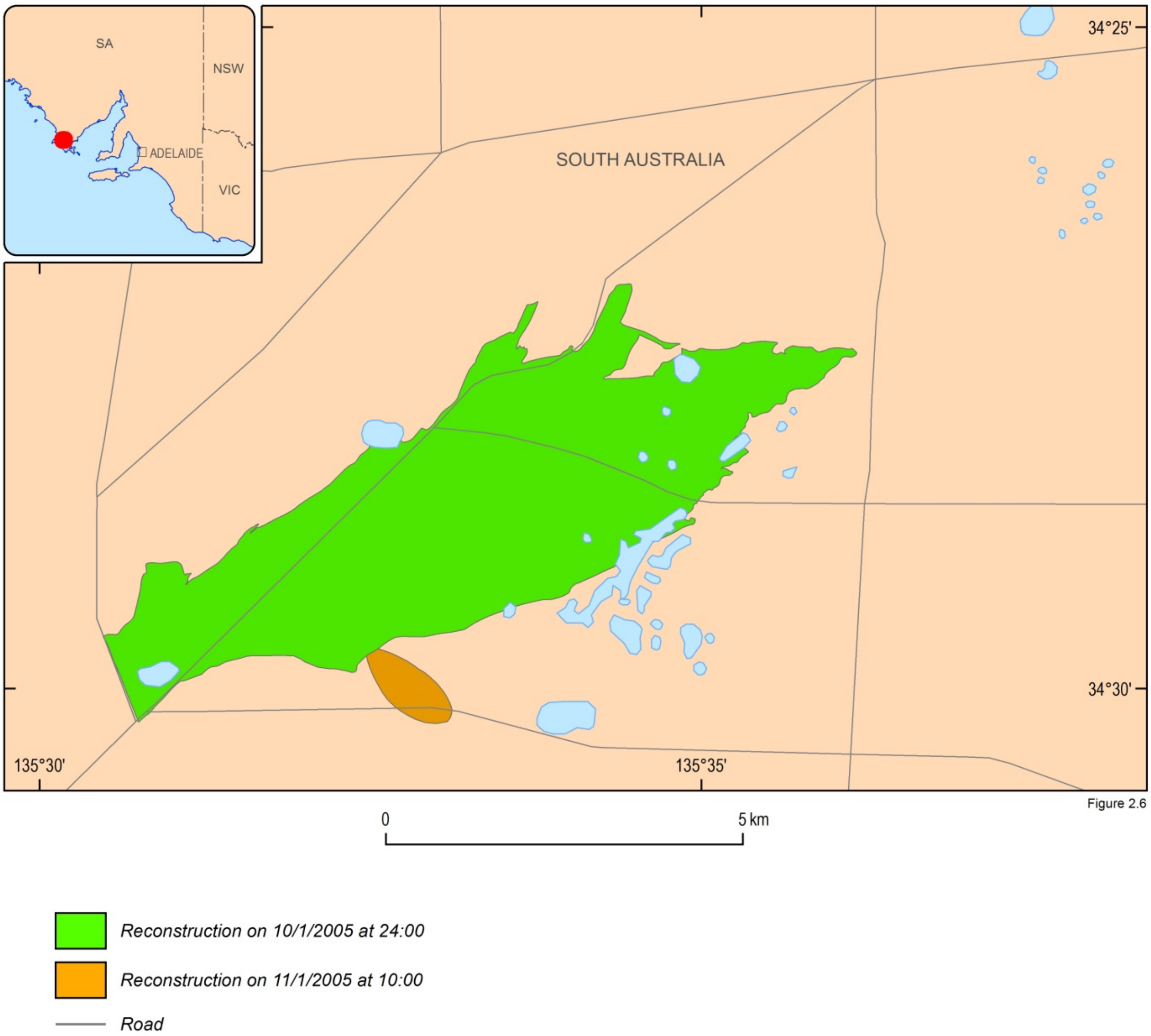

Figure 2.6 Reconstruction of the Wangary fire at 10:00 on 11/1/2005 showing initial outbreak

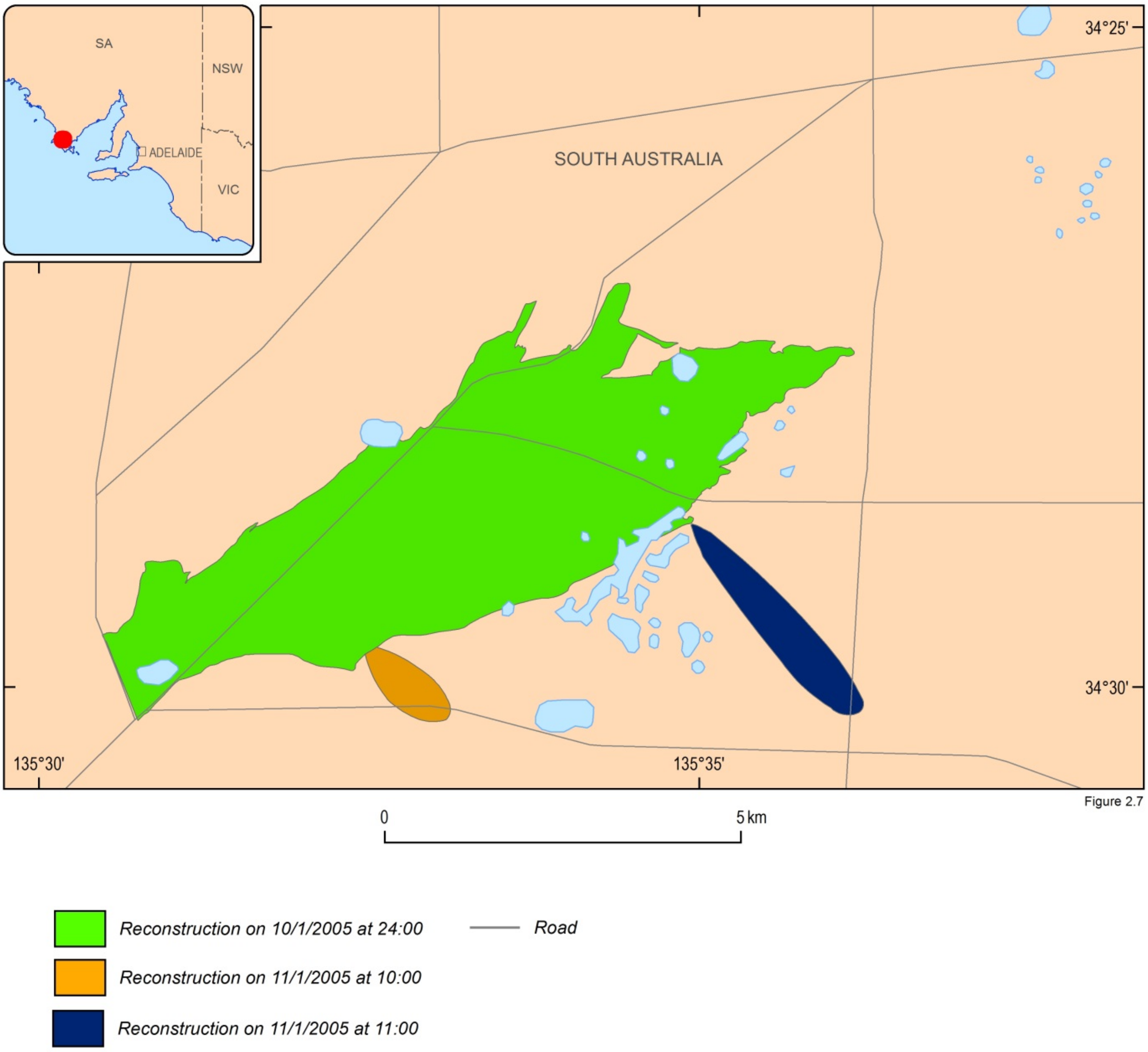

Figure 2.7 Reconstruction of the Wangary fire at 11:00 on 11/1/2005 showing second outbreak

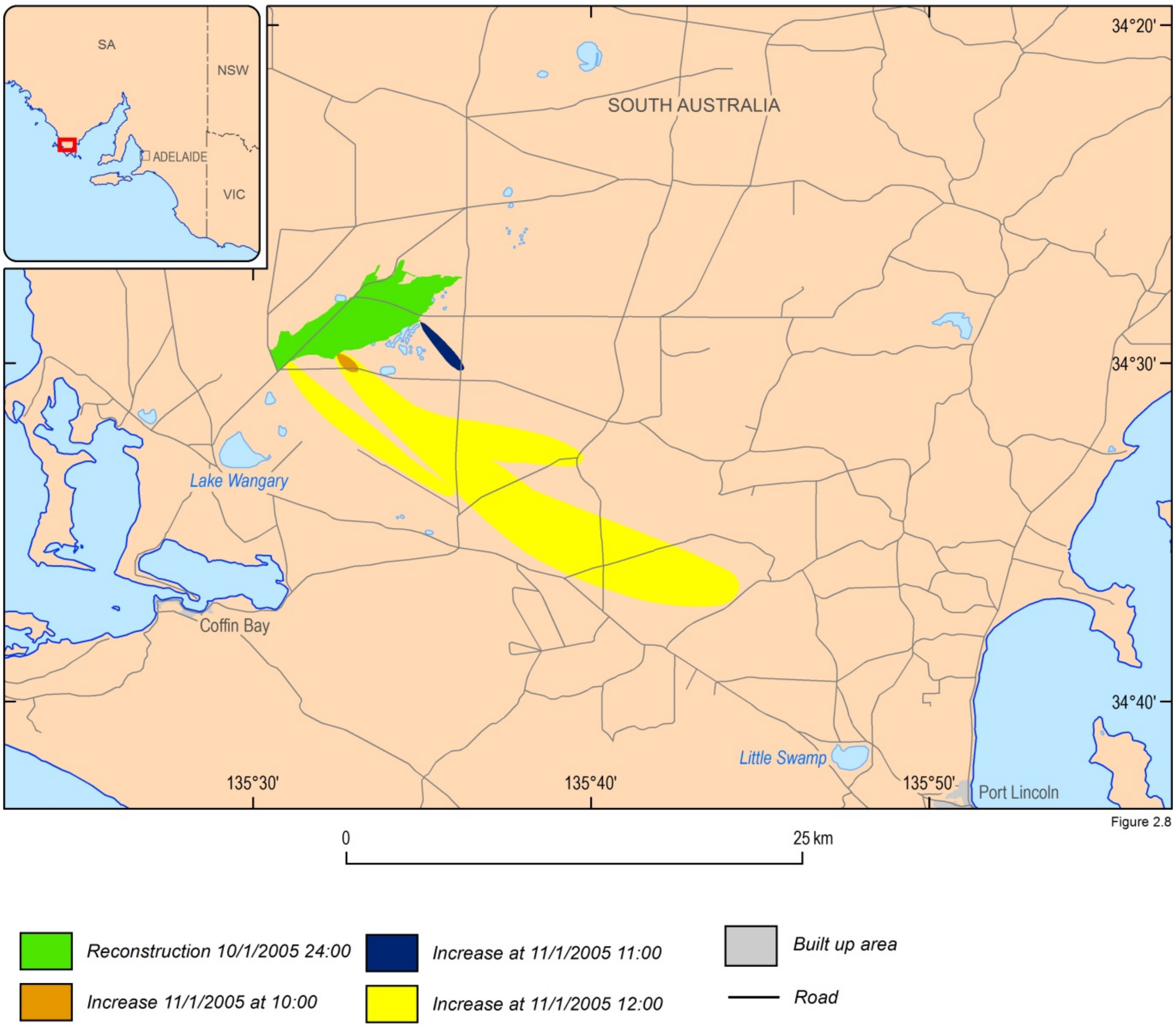

Figure 2.8 Reconstruction of the Wangary fire at 12:00 on 11/1/2005

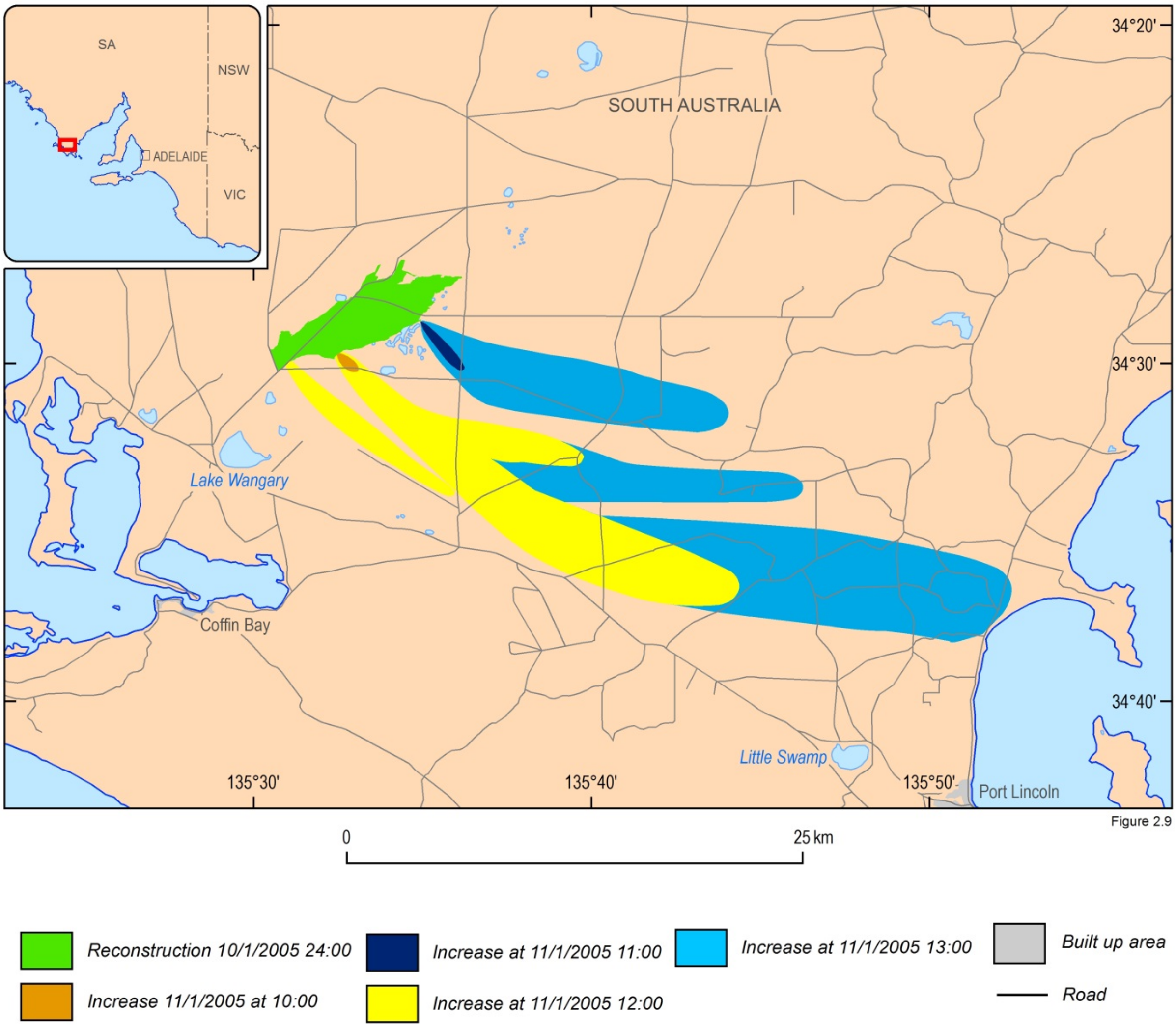

Figure 2.9 Reconstruction of the Wangary fire at 13:00 on 11/1/2005

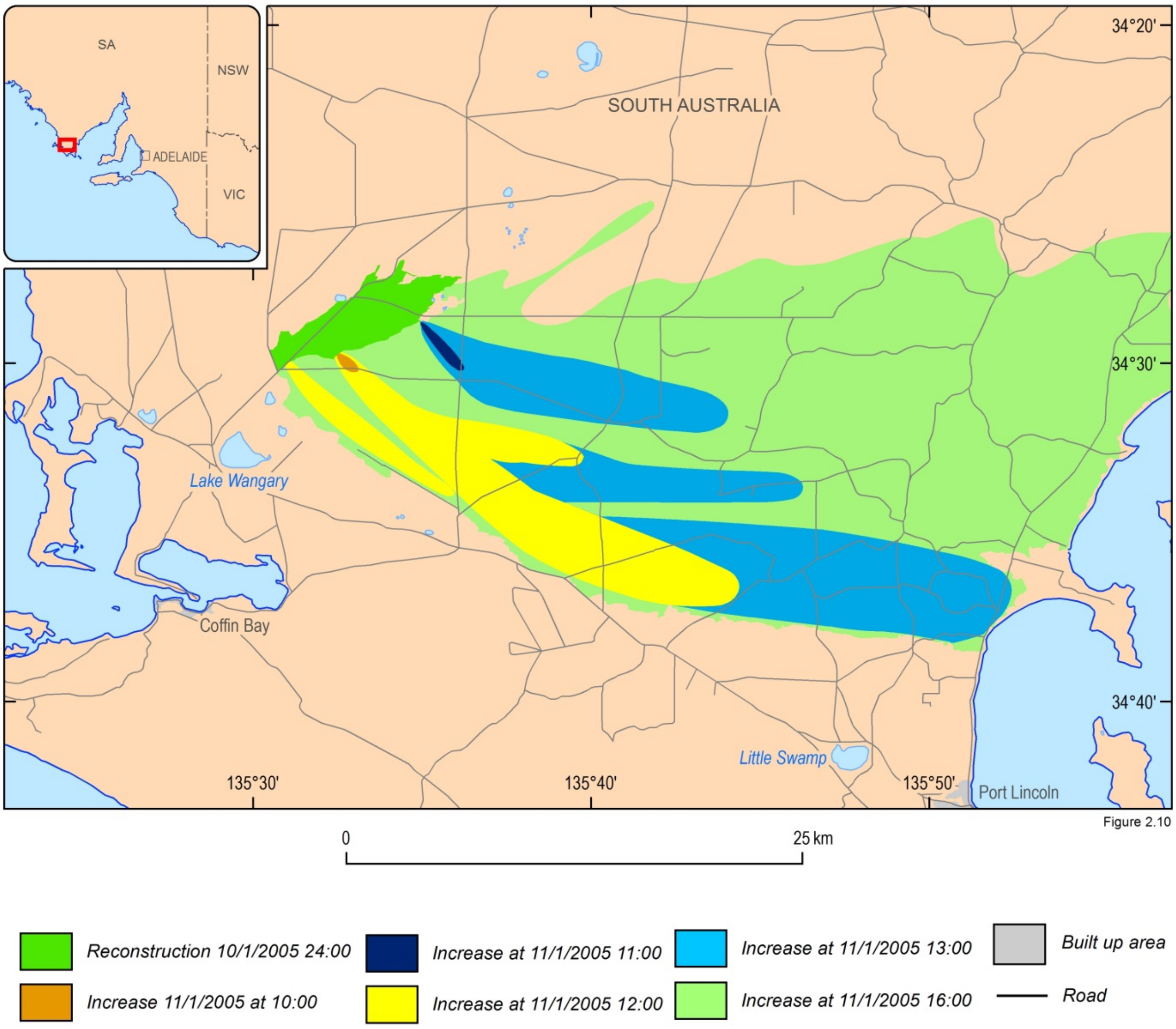

Figure 2.10 Reconstruction of the Wangary fire at 16:00 on 11/1/2005

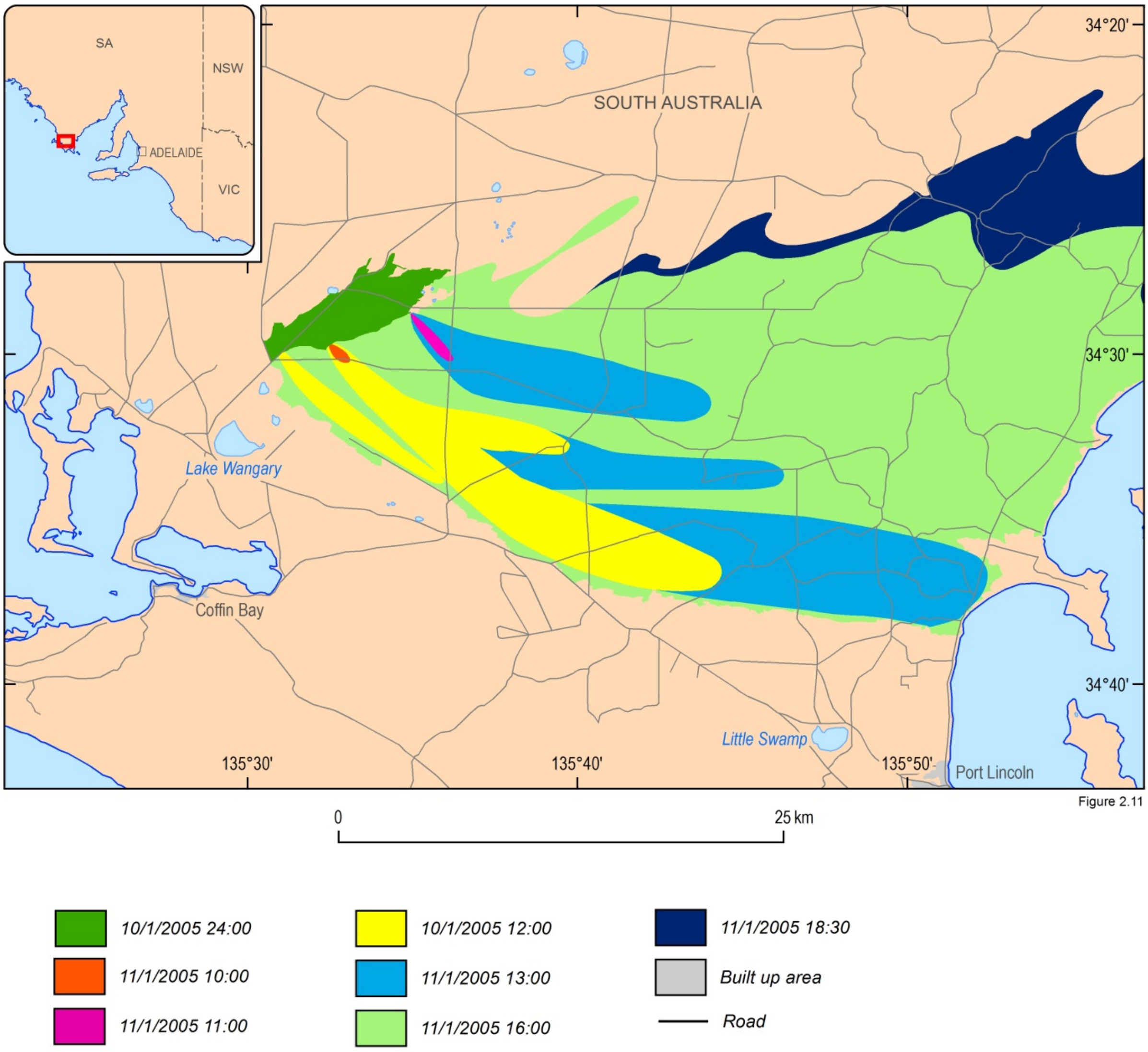

Figure 2.11 Reconstruction of the Wangary fire at 18:30 on 11/1/2005

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.

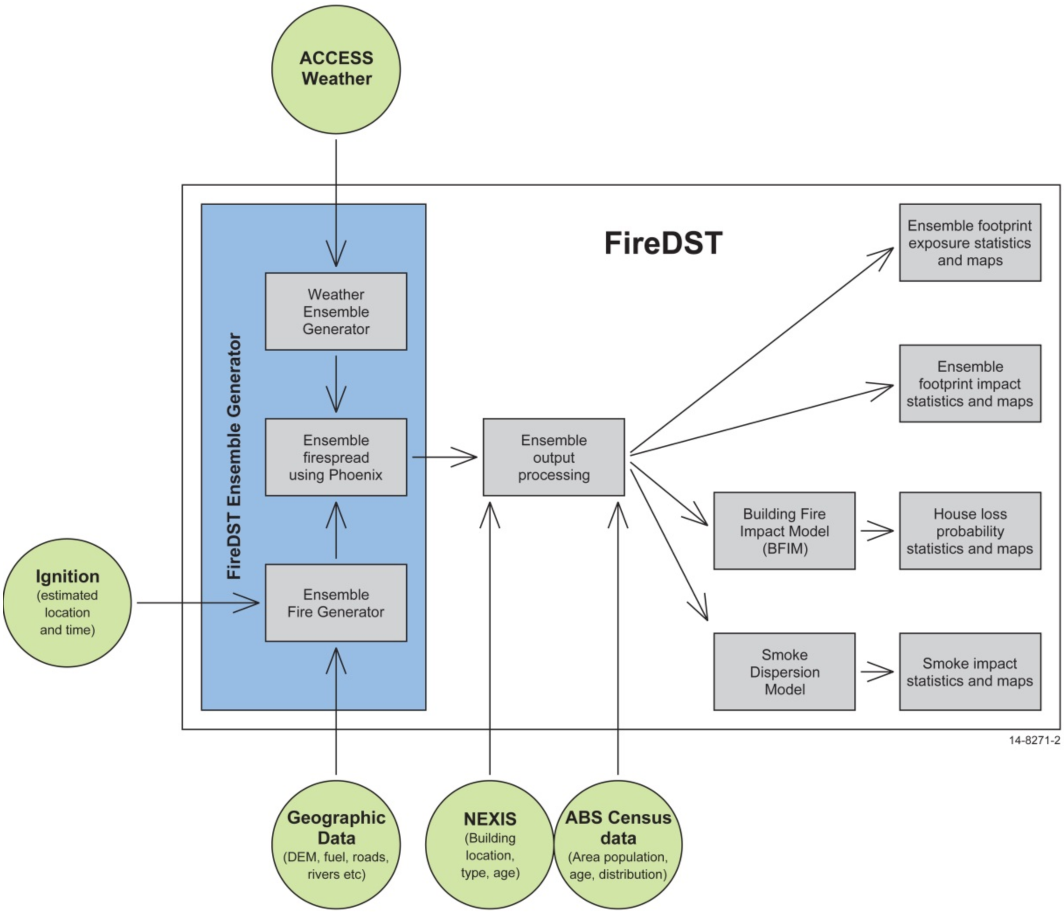

Figure 3.1 Information flow in FireDST.

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 Wangary 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 every six hours with national output at twelve km resolution with hourly time steps. A set of files is produced for the temperature, humidity, wind speed and wind direction at 10 m height. For this case study, research ACCESS files were specifically generated for a 48 hour period from 10:30am on 10/1/2005 at grid resolutions 0.036^{o,} 0.012^{o} and 0.004^{o} (which is approximately 4000 m, 1200 m and 440 m) 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 Wangary case study by the University of Melbourne.

The visualisation data consists of ArcGIS shape files showing roads, rivers, railways and lakes. This information was supplied 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 Wangary region.

Ignition location and timing was sourced from the Wangary fire reconstruction conducted by the University of Melbourne.

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. 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.

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, 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 5 m/s, or increasing the temperature by 2ºC. 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 Wangary fire, as specified in the ACCESS files. 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 6 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).

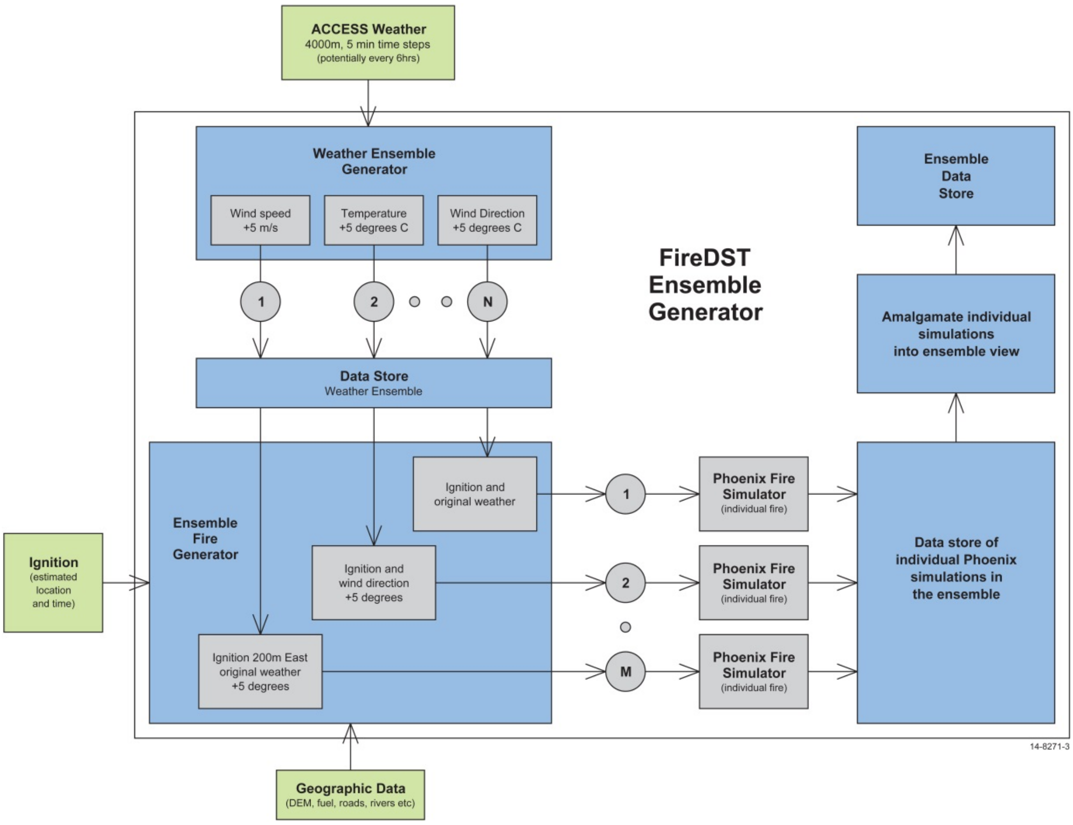

Figure 3.2 The FireDST Ensemble Generator.

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 Wangary 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 then 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), 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 examines the sensitivity of the modelled fire spread to the fuel 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 here 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 determined 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. Locations within each fire shape are allocated a value of one; locations outside the shape are set to zero. Values in the final ensemble shape are determined by the percentage of individual simulations that overlapped with each location. The percentage overlap shape is then displayed as shape files in percentage intervals (e.g. increments of 5%, 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 the assessment and visualisation of the ensemble fire spread for the Wangary fire.

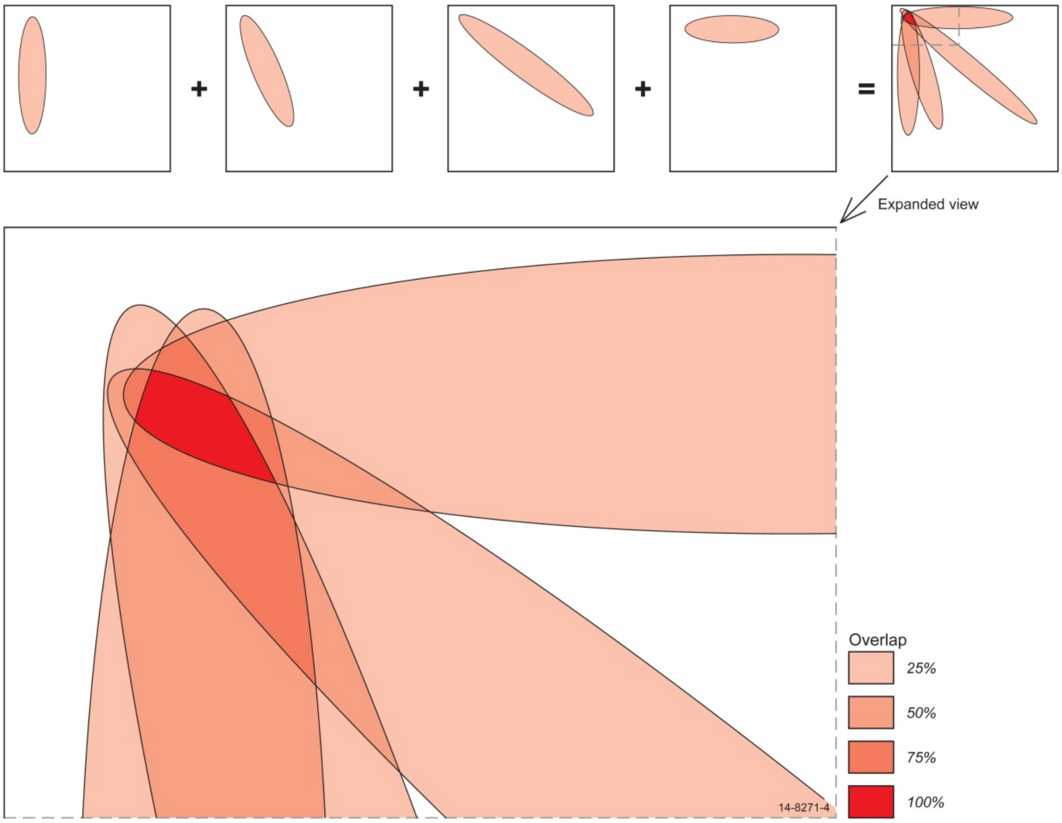

Figure 3.3 Example of how an ensemble shape of a burn extent is produced. The polygons show the fire spread of individual simulations.

3.4 FireDST system implementation

This section provides a brief overview of the implementation of the proof-of-concept FireDST system. FireDST was constructed using Python v2.6.2, 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 (developed in .NET, with limited or no option of deployment 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 prompted to select a case study and then an ensemble of scenarios that make up an ensemble fire spread. FireDST then 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 as this was a common platform in emergency service agencies.

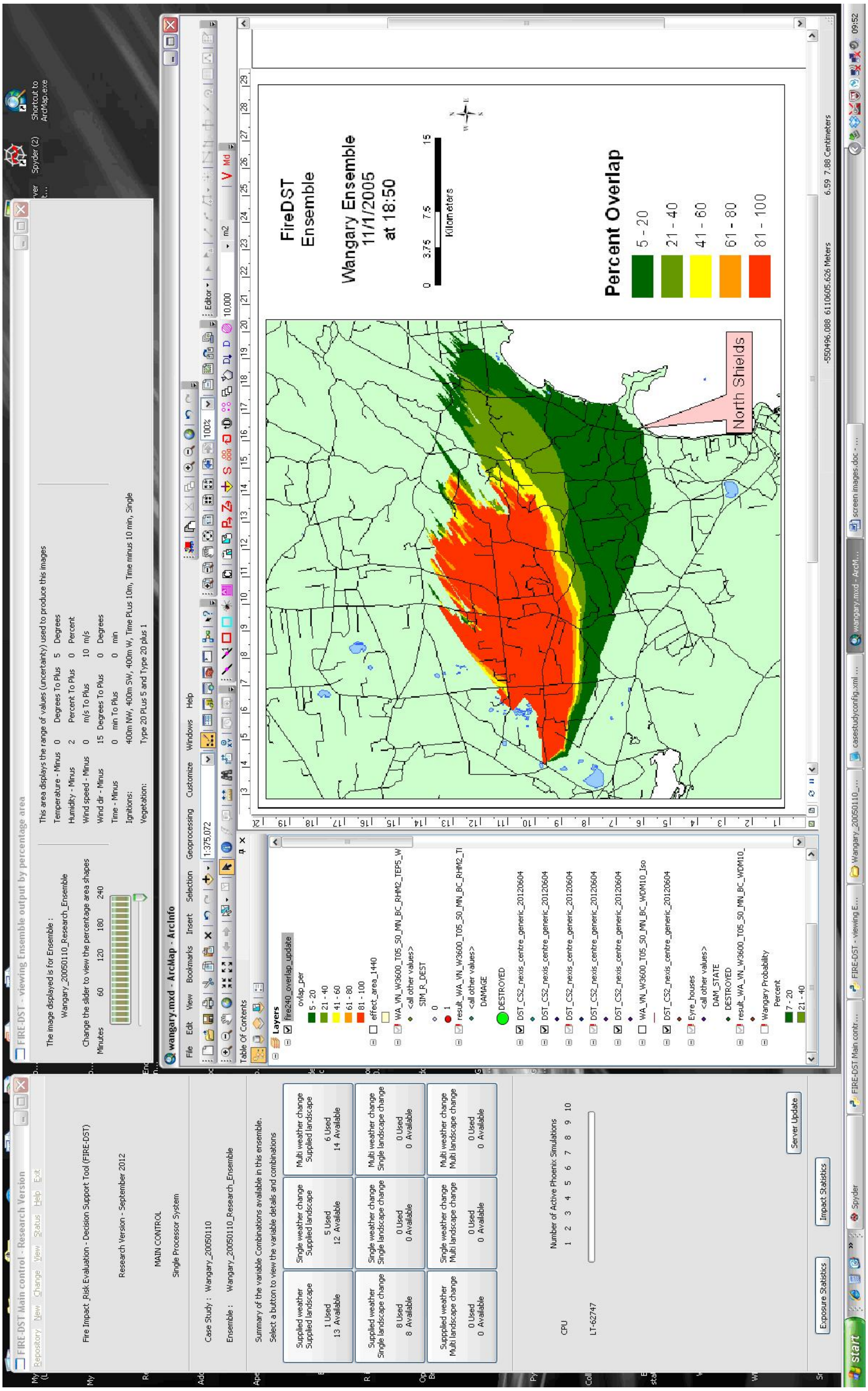

Figure 3.4 Full screen layout for FireDST.

The FireDST main control panel (Figure 3.5) 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

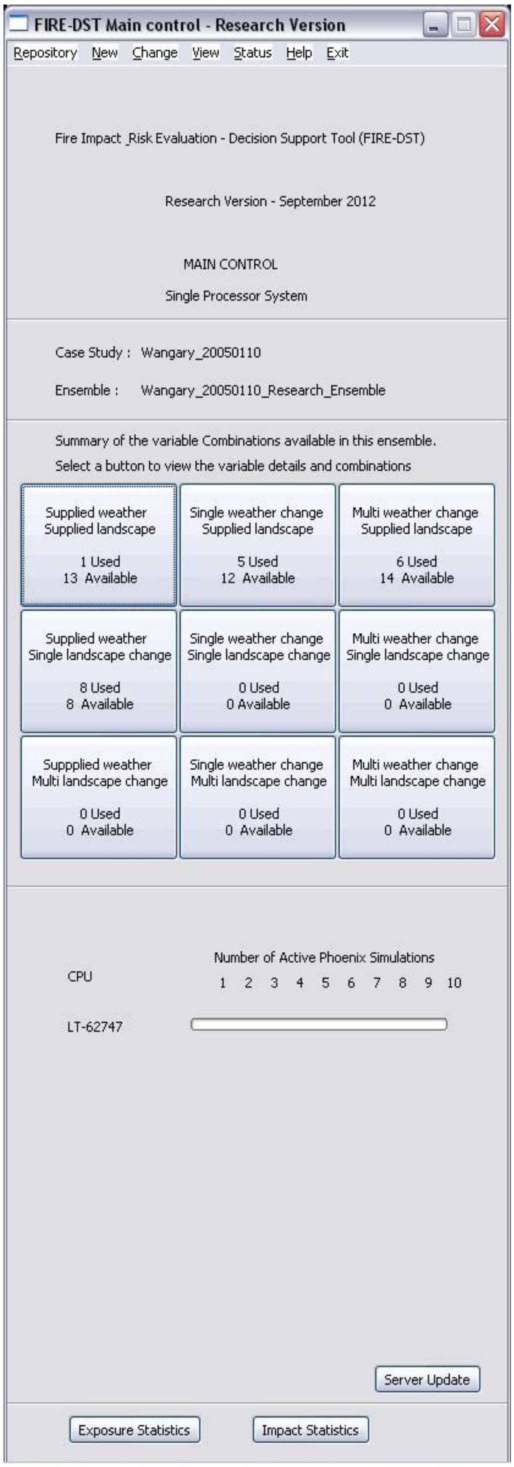

Figure 3.5 FireDST Main Control Panel. 'Landscape' refers to ignition and fuel parameters.

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.

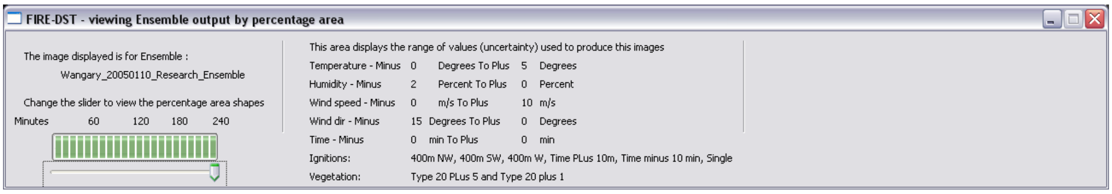

Figure 3.6 Viewing ensemble control panel.

3.5 FireDST research code

The F.I.R.E-D.S.T Project was funded by the Bushfire CRC. The FireDST research code 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 provided 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 integrate 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 Wangary fire as a case study for:

- Evaluating the techniques used to create an ensemble simulation of bushfire spread.
- Validating the ‘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

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 each of 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%; where it is burnt in some but not all scenarios, the location value is proportionally lower.

4.3 Results & Discussion

4.3.1 Ensemble visualisation

Figure 4.1 shows a fire ensemble of 33 scenarios for the Wangary fire (assuming a single ignition on 10/1/2005). The ensemble is shown to 13:00 Central Daylight Time (CDT) on 11/1/2005 to allow the full eastern extension of the simulation to be examined before the south westerly pushed the fire to the north east. The ensemble footprint is displayed in intervals of 20% overlap of the individual scenarios (see Appendix C for detail). The next section describes a comparison of the ensemble and the reconstruction.

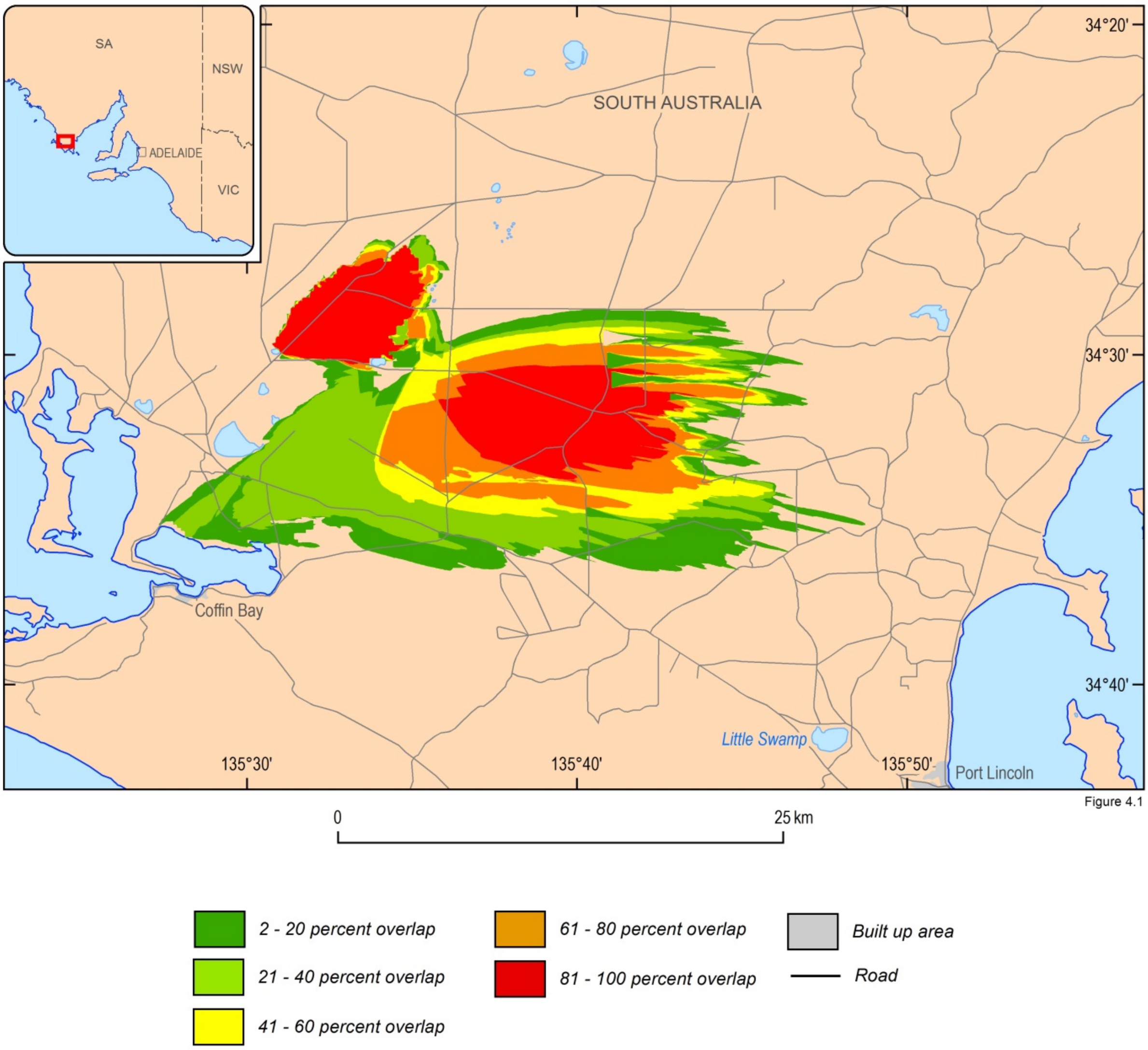

Figure 4.1 An ensemble view of the Wangary fire based on a 33 member ensemble up to 13:00 on 11 January 2005.

4.3.2 Comparison of ensemble and reconstruction

A reconstruction of the Wangary fire is described in Chapter 2. Figure 4.2 displays the reconstructed fire spread at 13:00 on 11 January 2005 against the 33 member ensemble view. All the simulations showed the fire to be contained to the swamp area on 10 January 2005, which matches what actually occurred (see Figure 2.6). The ensemble includes accurate simulations of two of the three breakouts of the Wangary fire on 11 January 2005, although the actual timing was different. The third breakout was not simulated in the ensemble, leading to an underestimate in the southerly reach of the ensemble fire spread. Also the ensemble produced quite a distinct fire spread to the south west that is not evident in the reconstruction. This is most likely because the ensemble simulations did not include any suppression effort on the southern flank, and the simulated southerly breakout occurred earlier than the actual breakout, so the simulations spread the fire in a south westerly direction.

Despite these differences between the modelled and historical event, this ensemble highlights the potential value provided by an ensemble approach to predicting the potential fire spread. This ensemble would have highlighted to fire managers that there was a high likelihood the fire would breakout on the morning of 11 January 2005.

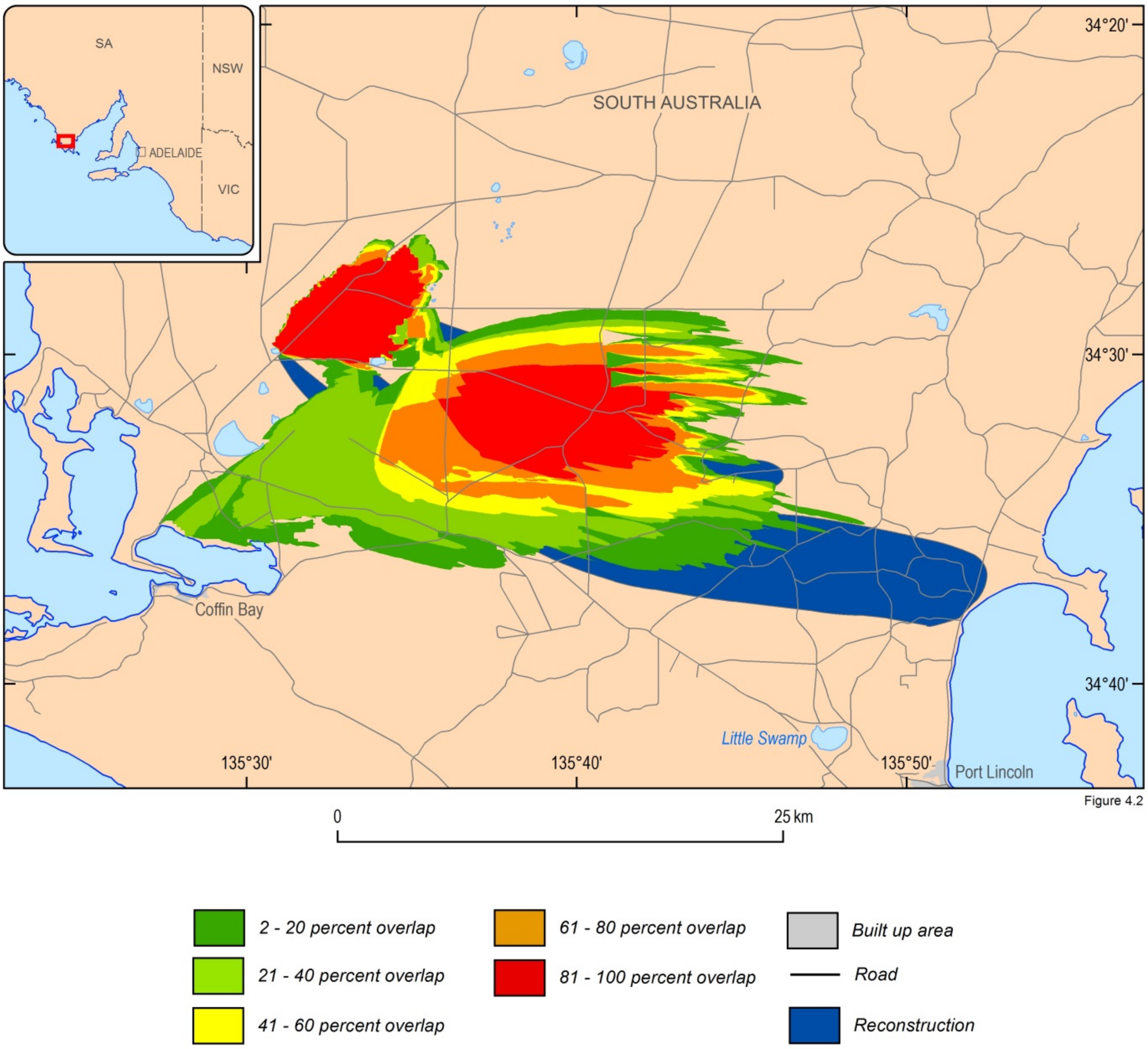

Figure 4.2 Fire spread in a 33 member ensemble for Wangary overlayed with the reconstruction of the Wangary fire to 13:00 CDT on 11 January 2005.

The FireDST ensemble approach is not static; information can be assimilated to improve the accuracy of the ensemble fire spread while an event develops. For this case study, an ensemble fire spread was produced that assimilated the actual times and locations for the breakouts that occurred on the 11/1/2005. This 45 member ensemble is shown in Figure 4.2 (using simulations listed in Appendix C). Comparison with Figure 4.2 shows the increased accuracy of the ensemble footprint that assimilates event information, which now impacts on North Shields.

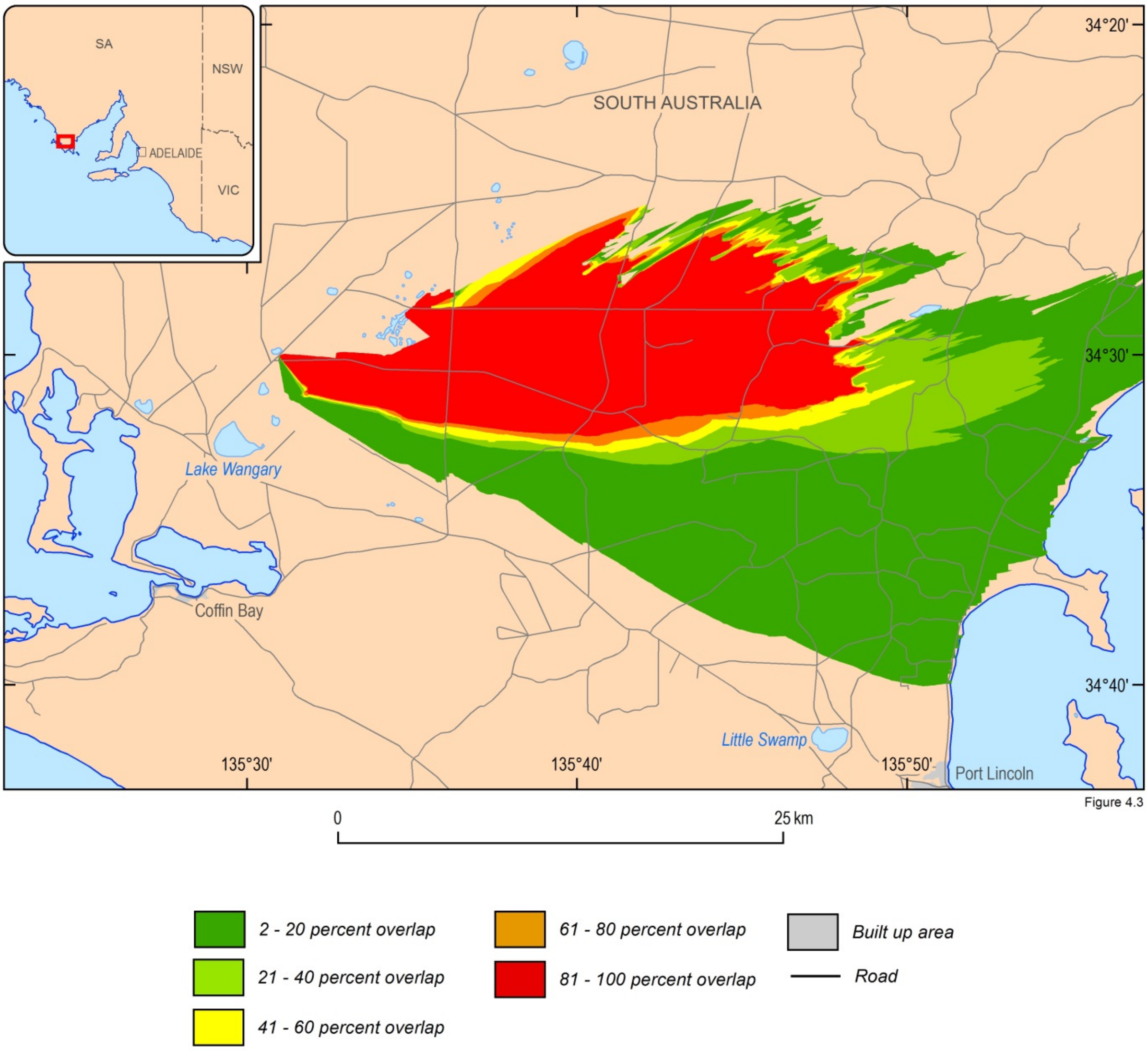

Figure 4.3 Fire spread for a 45 member ensemble for the Wangary fire from 9:50 to 15:50 CDT . The individual simulations used the actual location and time of the three fire breakouts on 11/1/2005.

4.3.3 Ensemble visualisation through time

FireDST can display the ensemble spread at selected time intervals. Figure 4.4 displays hourly time step ensemble output for the 45 member ensemble fire shape shown in Figure 4.3. Figure 4.4 demonstrates that the range of predicted fire spread increases between ensemble members as time progresses. This is because the difference in conditions between ensemble members, as set by the variation in input parameters, has an incremental impact over time.

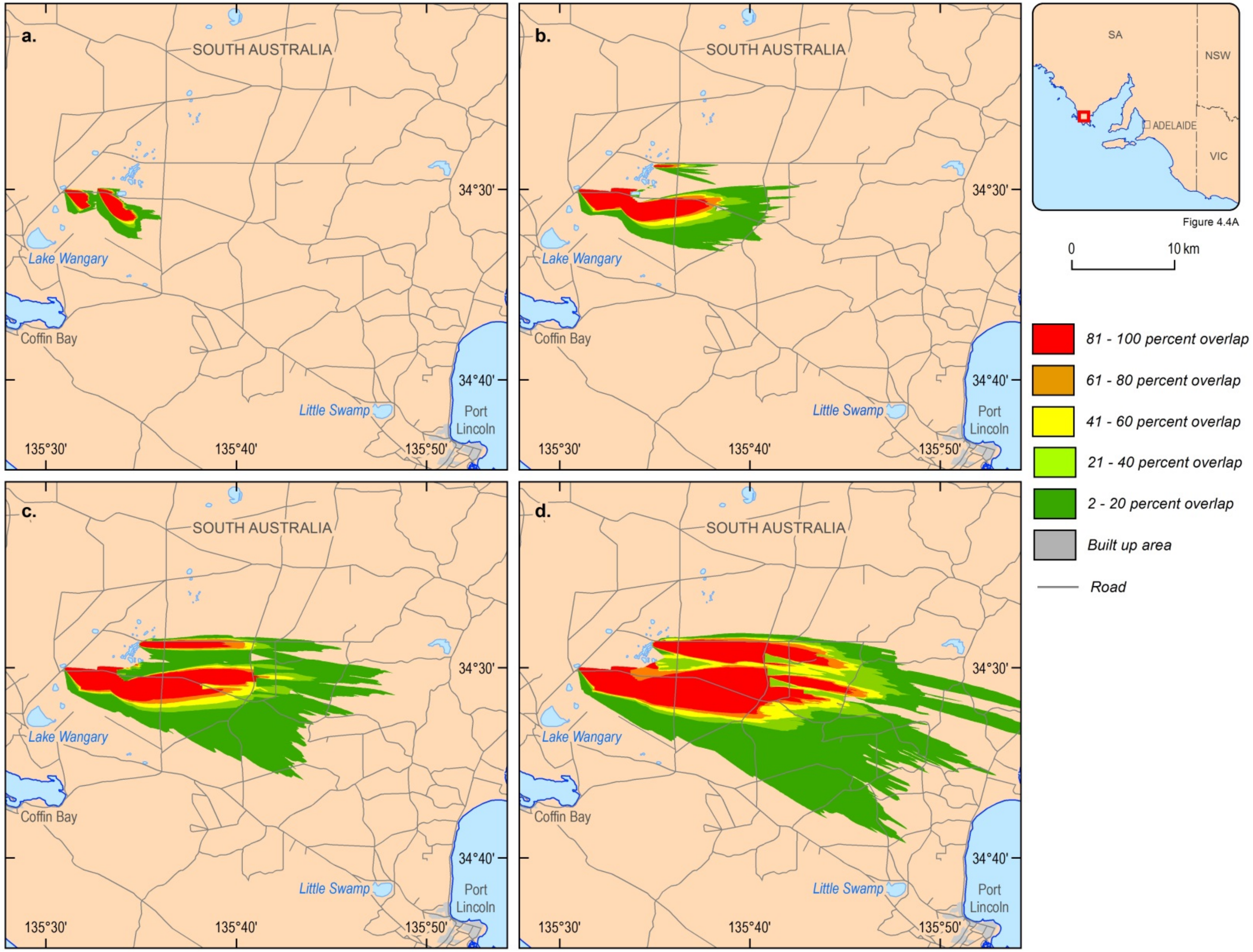

Figure 4.4(a) Ensemble views of the potential fire spread at hourly intervals through time, a. 10:50, b. 11:50, c. 12:50 and d. 13:50.

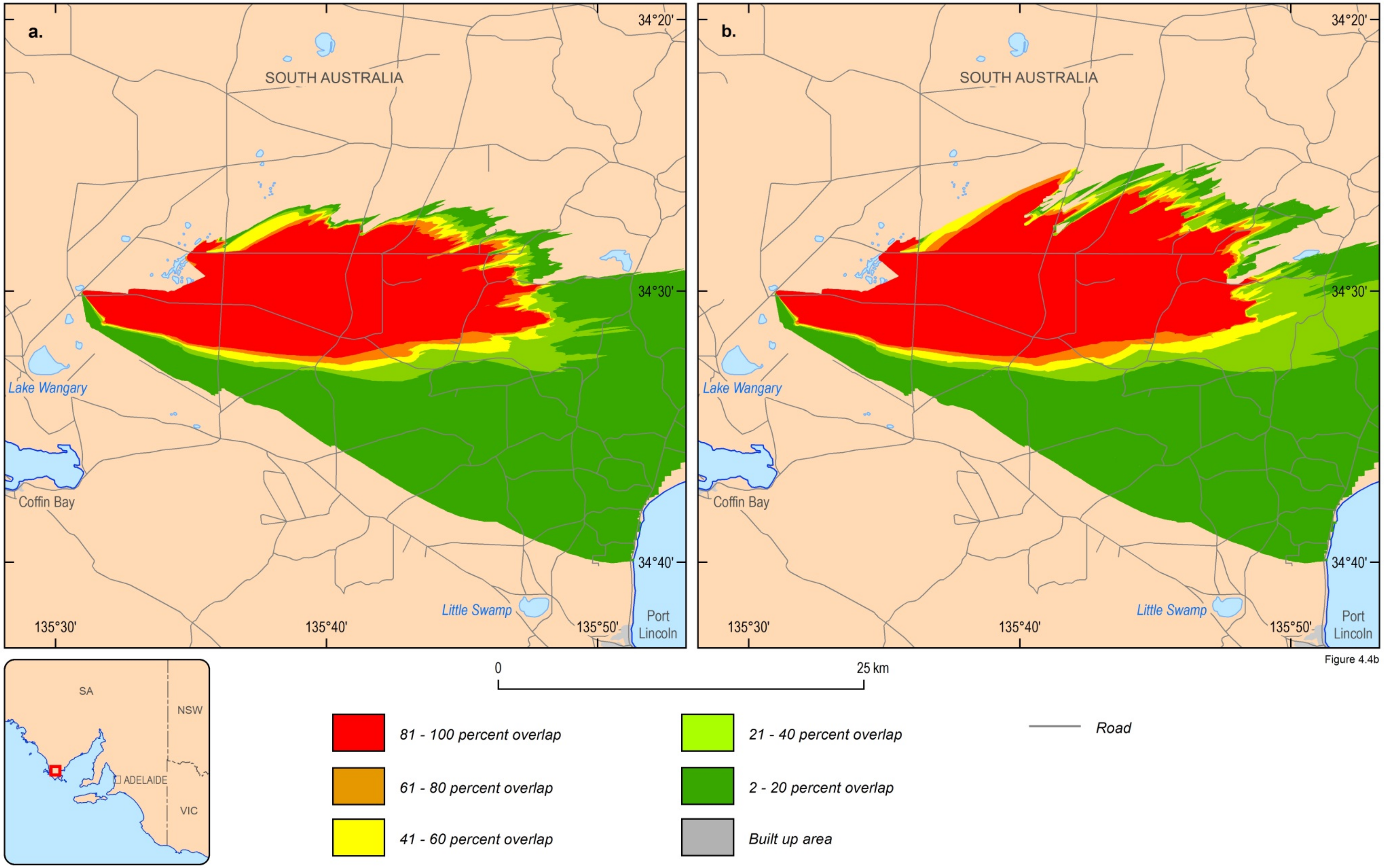

Figure 4.4 (b) Ensemble views of the potential fire spread at hourly intervals through time, a. 14:50 and b. 15:50.

4.3.4 Ensemble fire spread – sensitivity to weather parameters

Figure 4.5 and Figure 4.6 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 4.5) and wind speed variability (Figure 4.6), 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 4.5 shows that the fire spread is sensitive to a change in temperature. However, the sensitivity is small, as using an ensemble with +/- 5°C produces only a slightly smaller shape than that using +/- 10°C. In context of this event, this is not too surprising because there was a period of marked drying lasting several hours prior to the wind change (Cechet *et al.,* 2014).

Figure 4.6 however shows that the ensemble was also not very sensitive to changes in wind speed over the lifetime of the event. The +/-5 m/s ensemble shape is different to the +/-10 m/s ensemble shape at 11:50 and yet at 18:50 they are almost the same.

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* of 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°C might be 90% probable while a temperature variation of 10°C 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.

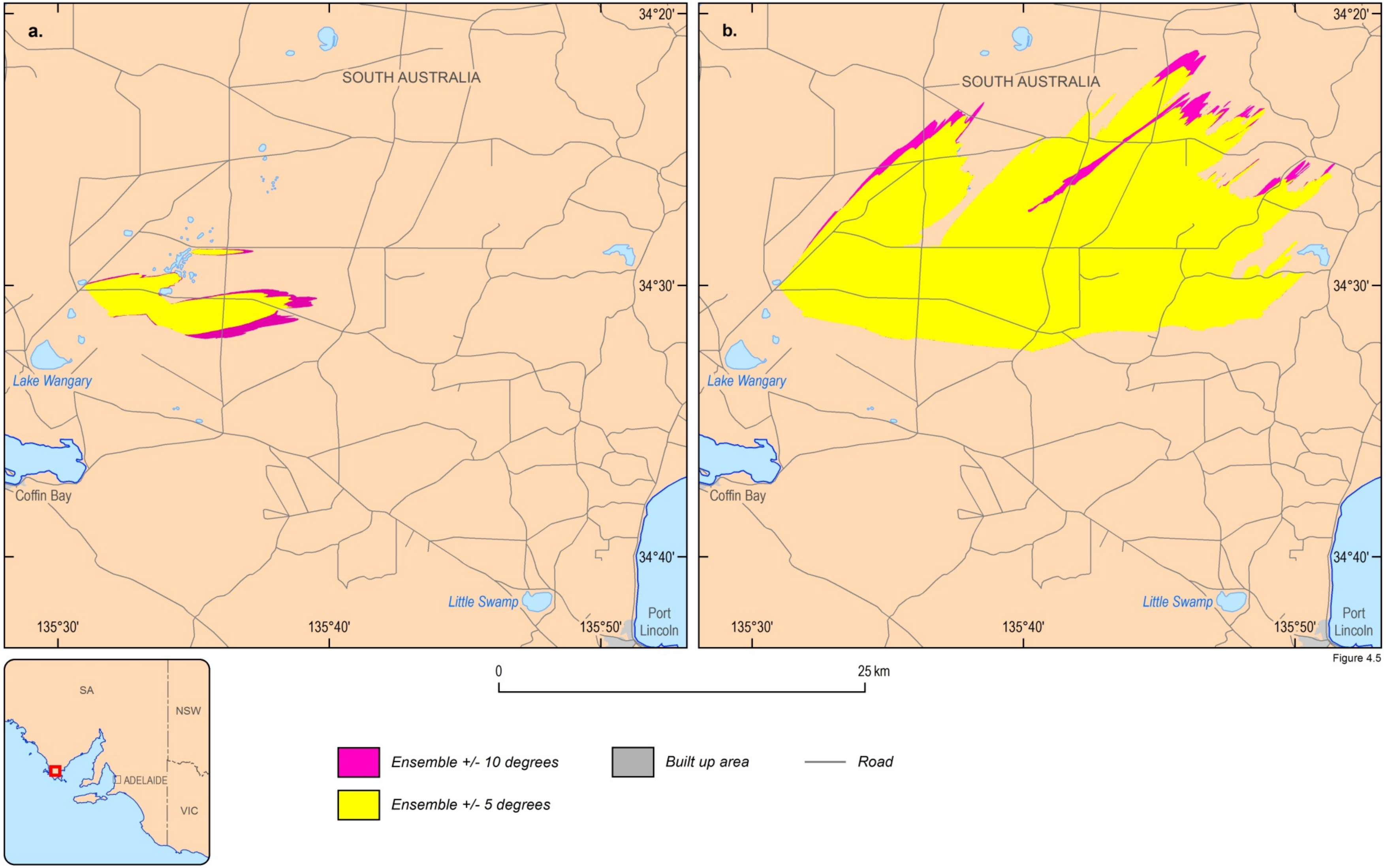

Figure 4.5 Sensitivity of the ensemble envelope to ranges in temperature at two different time steps a. 11:50 and b. 17:50.

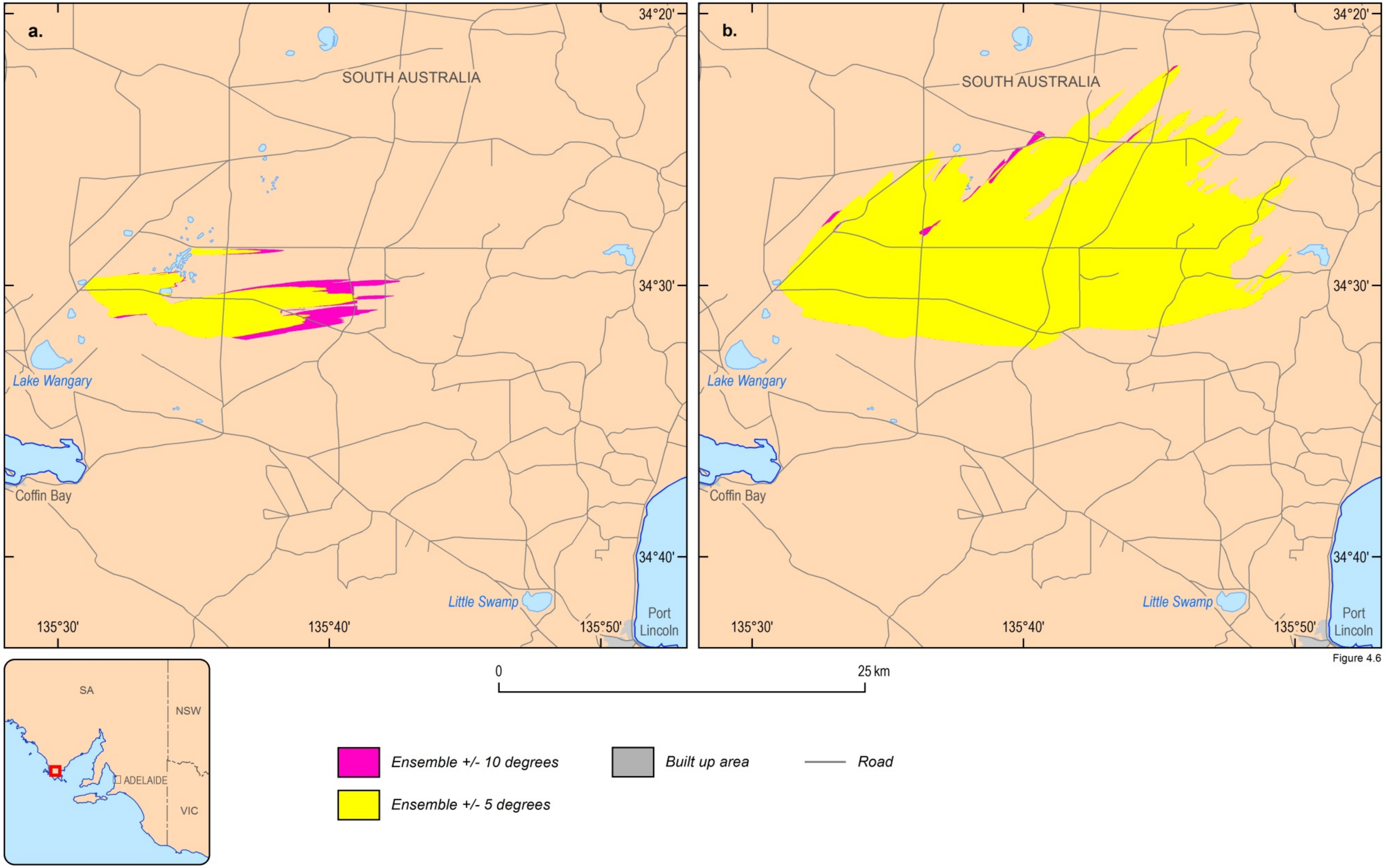

Figure 4.6 Sensitivity of the ensemble envelope to ranges in wind speed at two different time steps a. 11:50 and b. 17:50.

4.3.5 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. For the Wangary fire there is not a good match between modelled and historical fire spread if the fire spread is modelled deterministically, i.e. as a single model run based on the conditions at the time the fire occurred. This is due to uncertainties and inaccuracies in the parameter estimates of those historical conditions (this is discussed further in Chapters 5 and 6), as well as the internal parameterisation of the fire spread. However, an ensemble envelope using the breakout information on 11/1/2005 and based on limited perturbation of the parameters is able to produce a footprint that is close to the reconstruction. This shows that 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 simulations through the footprint of the fire spread envelope.
- Even a 'pseudo-probabilistic' sensitivity ensemble such as shown here gives information on the potential development of an event that cannot be provided by a single deterministic model run.

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

4.3.6 Future Work

- Specifying the uncertainty in the various FireDST parameters, and building this into the Ensemble Generator is key to generate a fully probabilistic fire spread ensemble that could be interpreted in terms of uncertainty of the outcome of an event.
- Understanding the decision making processes of operators would define the user requirements to enable suitable interaction with the ensemble information. Such business analysis could flag for example, 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 the potential sensitivity to weather conditions in the higher layers of the atmosphere.

The objective was 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 enable 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 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 10 m height. These files represent the standard weather forecast for the forty eight hours from 10:30am on 10/1/2005 at grid resolutions 0.036°, 0.012° and 0.004° (approximately 4000 m, 1200 m and 440 m) at five minute time steps.

The FireDST Weather Ensemble Generator perturbs weather conditions in the ACCESS files and use 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 Port Lincoln airport and 43°C at Wangary, then that particular scenario specifies that the temperature for 2pm at Port Lincoln airport is 30°C and 41°C at Wangary.

FireDST imposes restrictions to ensure that scenarios are physically realistic when sampling potential bushfire scenarios. For example, the humidity cannot be set to 0% and the temperature cannot go below 0°C.

Six tests were used to assess 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 5.1Weather perturbations for Wangary generated by the FireDST Weather Ensemble Generator

Parameter	Unit	Range	Comment
ACCESS Grid Resolution	metres	4000,1200,440	Supplied
ACCESS Temporal Resolution	minutes	5,15,30,60	Only 5 minutes was supplied
Wind Direction	°	-5 to +25	Clockwise from north
Wind Intensity (speed)	m/s	-10 to +10	
Temperature	°C	-10 to +10	
Humidity	%	-5 to +5	

In reality, there will be uncertainty in all of the weather parameters at once, so FireDST was also tested with various parameter combinations. For example, the Weather Ensemble Generator was used to produce a scenario with the temperature increased by 2°C, the humidity down by 1% and the wind speed increased by 2 m/s.

For each of the scenarios in the respective weather ensembles, the simulated fire shape was visually compared with the Wangary reconstruction fire shape. All ignition assumptions and fuel 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 (Cechet *et al.,* 2014).

Therefore, 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 Wangary event at each ACCESS file resolution are given in Table 5.2.

Table 5.2 Wangary fire wind speed bias correction

Dir.	Angle segment (Degrees)	4000 m grid resolution	1200 m grid resolution	400 m grid resolution
N	338 – 22	1.1	1.1	0.95
NE	23 - 67	1.05	1.05	0.95
E	68 – 112	1.0	1.0	1.0
SE	113 - 157	1.0	1.0	1.0
S	158 – 202	1.0	1.0	1.0
SW	203 – 247	1.05	1.0	1.0
W	248 – 292	1.1	1.1	1.0
NW	293 – 337	1.2	1.15	0.95

5.2.3 Further correction of the ACCESS wind speed by using wind multipliers

The bias correction approach described above did not take into account variation in the topography. Topography effects are included in the supplied ACCESS weather model, but at a relatively large scale (Table 5.3) using a grid resolution that matches the grid resolution of the ACCESS files. For example, the 4000 m ACCESS weather has used a 4000 m topographic grid.

Table 5.3 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 uses the Wind Ninja[1] wind modifier system, in which the terrain is resolved on a 100 m grid to 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 Wangary fire at three grid resolutions, 4000 m, 1200 m and 440 m. Irrespective of grid resolution, all simulations underestimated the size of the fire compared to the reconstruction of the historical Wangary fire.

The 4000 m simulation (Figure 5.1) shows a breakout of the fire to the south around midnight on 10/1/2005. This simulated breakout just after midnight was probably caused by an increase in wind speed at this time as (Figure 6.2) shows that for a few hours prior to midnight there was little or no wind speed and that the wind speed jumped to 3.2 m/s by 1:15 on the 11/1/2005.

The 1200 m simulation (Figure 5.2) appears to be the most accurate relatively speaking when compared to the reconstruction, with the breakout occurring at almost the same location as the real breakout (in the north east) just after 7:00 on 11/1/2005. The real breakout was around 11:00.

The 440 m simulation (Figure 5.3) shows two breakouts. The first breakout is to the west at about 01:37 on 11/1/2005. This breakout occurred in the simulation because there is no suppression acting on the simulated fire while in reality there was active suppression on the west which kept the fire contained to the swamp area (see Figure 5.4). The second simulated breakout was to the east at about 6:15 on 11/1/2005 at almost the same location as the historical breakout (which occurred around 11:00).

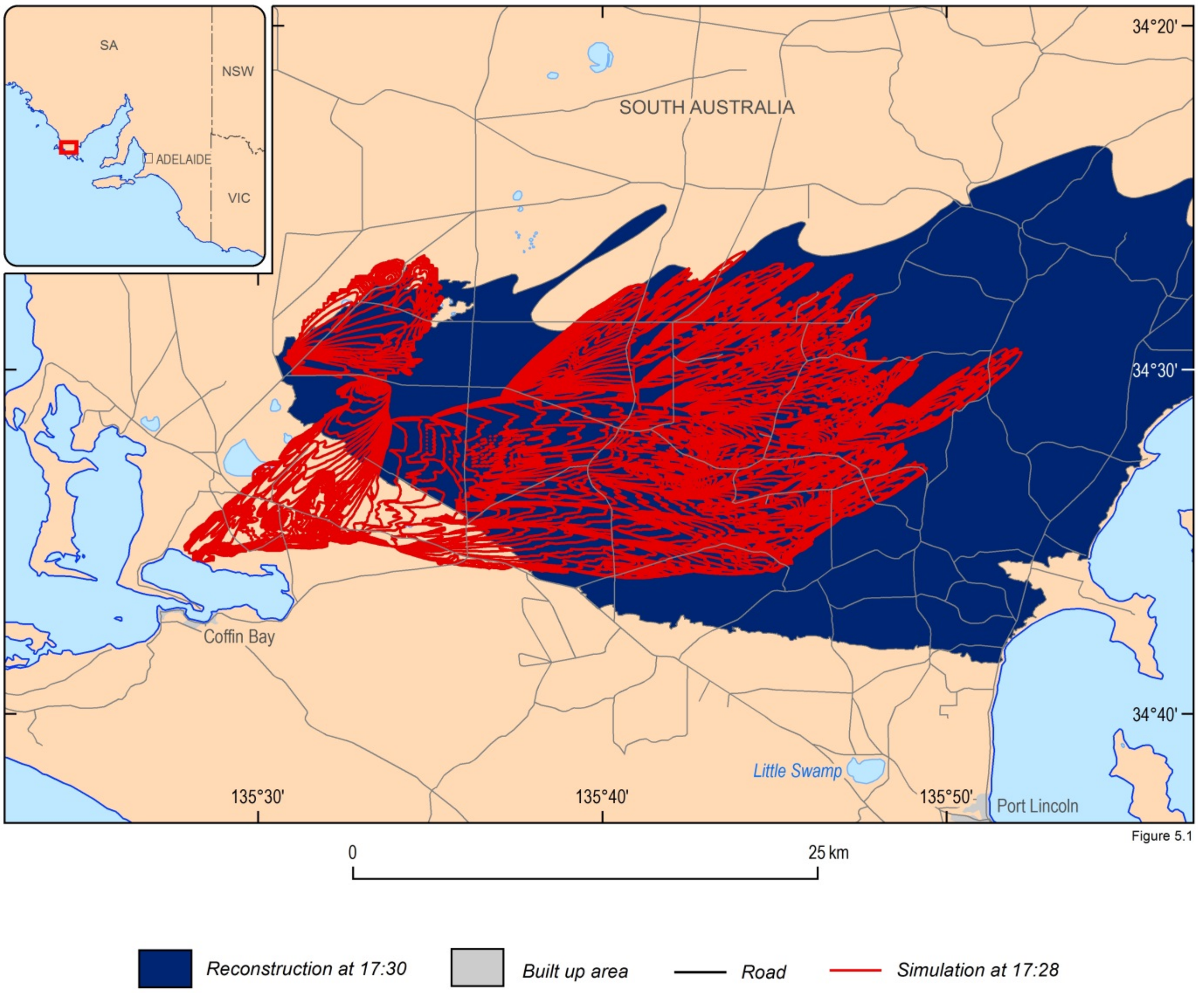

Figure 5.1 Simulation of the Wangary fire up to 17:30, based on the ACCESS 4000 m 5 minute (red), and the reconstruction of the fire at that time (blue).

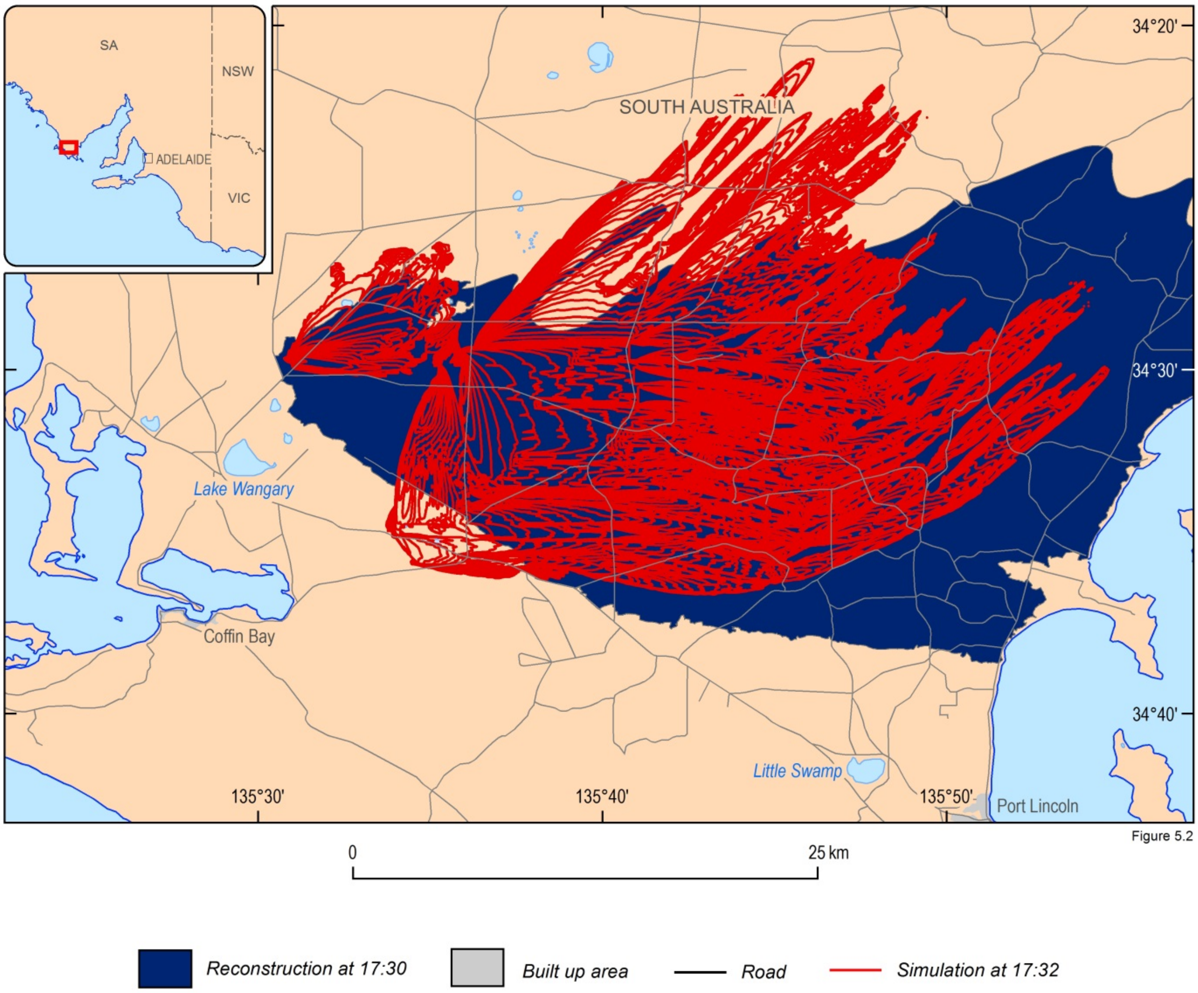

Figure 5.2 As for Figure 5.1, for 1200 m ACCESS resolution.

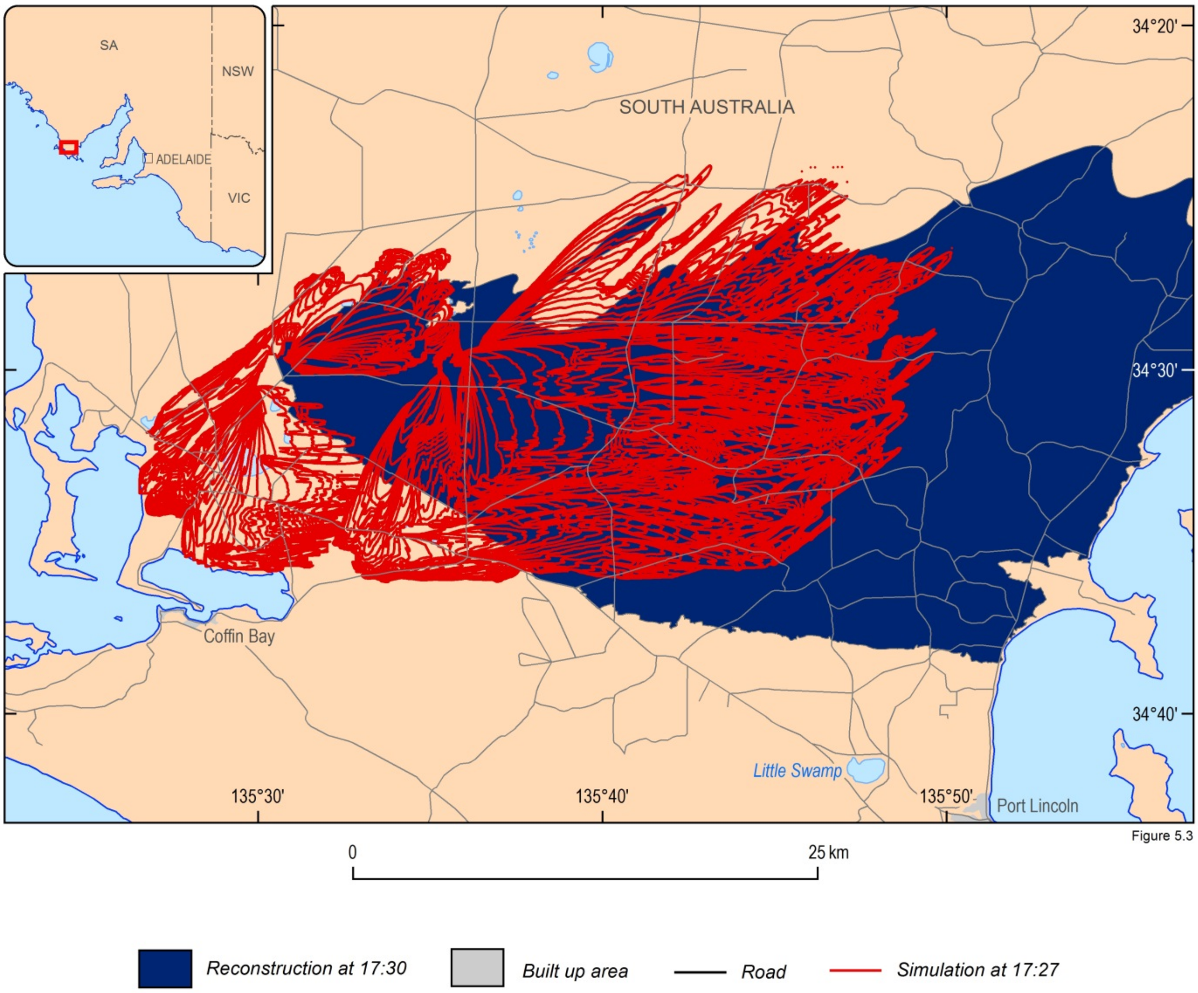

Figure 5.3 As for Figure 5.1, for 440 m ACCESS resolution.

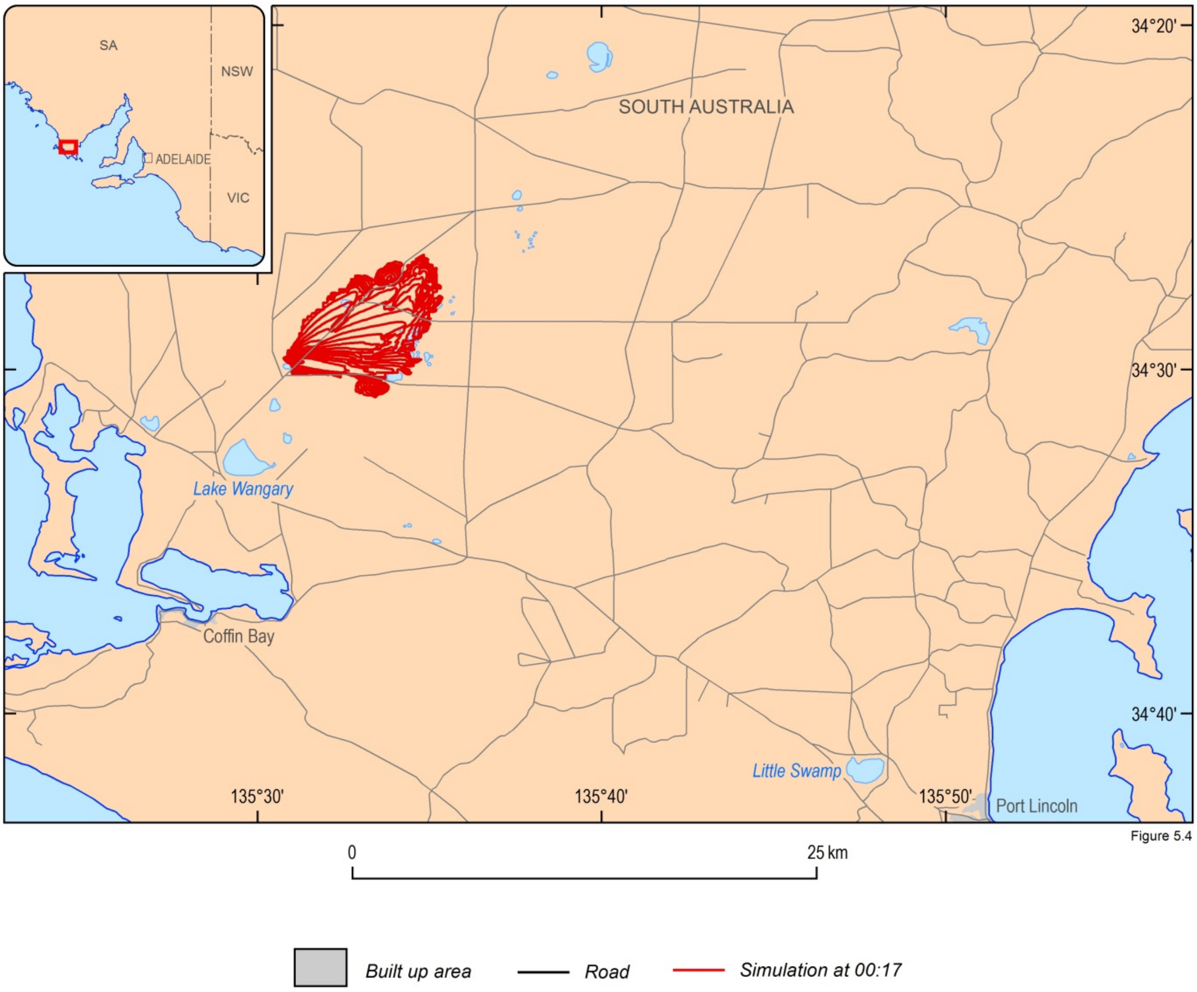

Figure 5.4 Simulation of the Wangary fire up to 00:17, based on the ACCESS 4000 m 5 minute weather input, showing that the simulation reflects the actual fire being contained to the area of the swamp and the start of the breakout to the south.

These results demonstrate the potential benefit of ensemble information, in suggesting that breakouts were likely. This could have prompted fire managers to consider deploying resources to mitigate the effect of a breakout to the east.

The reconstruction of the fire contains the locations and times of the actual breakouts that occurred. The simulations in the following chapters in this case study report used the reconstruction breakout information in order to produce more accurate simulations of the Wangary fire. Figure 5.5 to 5.7 show the simulation results for using ACCESS 4000m 5 minute weather, displaying the northerly breakout based on the reconstruction information.

An interesting observation is that, of all resolutions assessed, the simulations based on the 1200 m resolution weather produced results that came closest to matching the actual fire. The sensitivity analysis conducted by the University of Melbourne also concluded at the 1200 m resolution simulations produced the most accurate results (Cechet *et al.*, 2014).This is possibly due to PHOENIX RapidFire parameterisation of the while environment (including the fuel, terrain and weather). Nevertheless the rest of the Wangary study used 4000 m resolution weather for consistency across all simulations in this report and as this resolution is most likely to be the next resolution operationally produced by the Bureau of Meteorology.

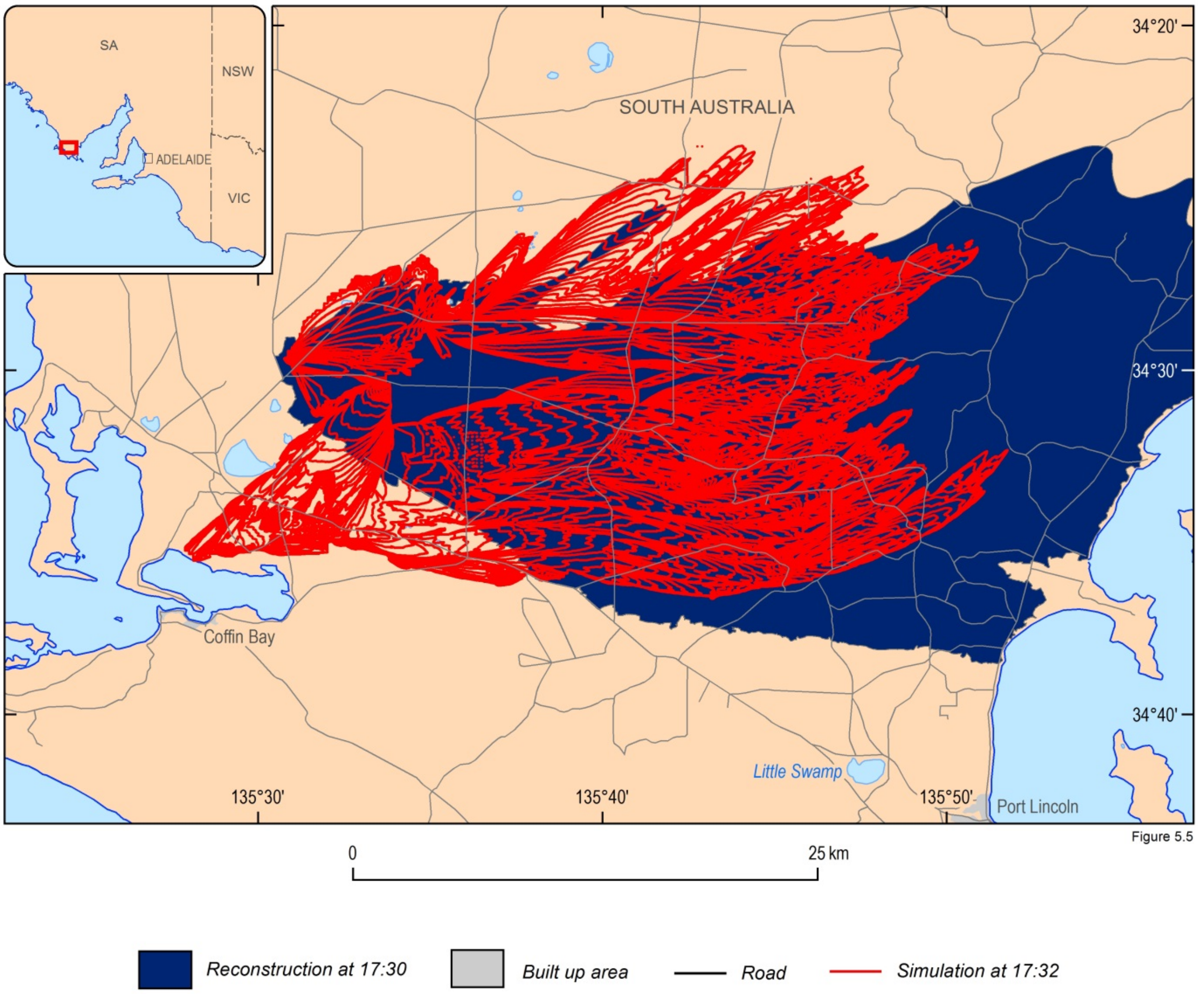

Figure 5.5 Simulation of the Wangary fire up to 17:30, based on the ACCESS 4000 m 5 minute incorporating the reconstruction breakout information (red), and the reconstruction of the fire at that time (blue).

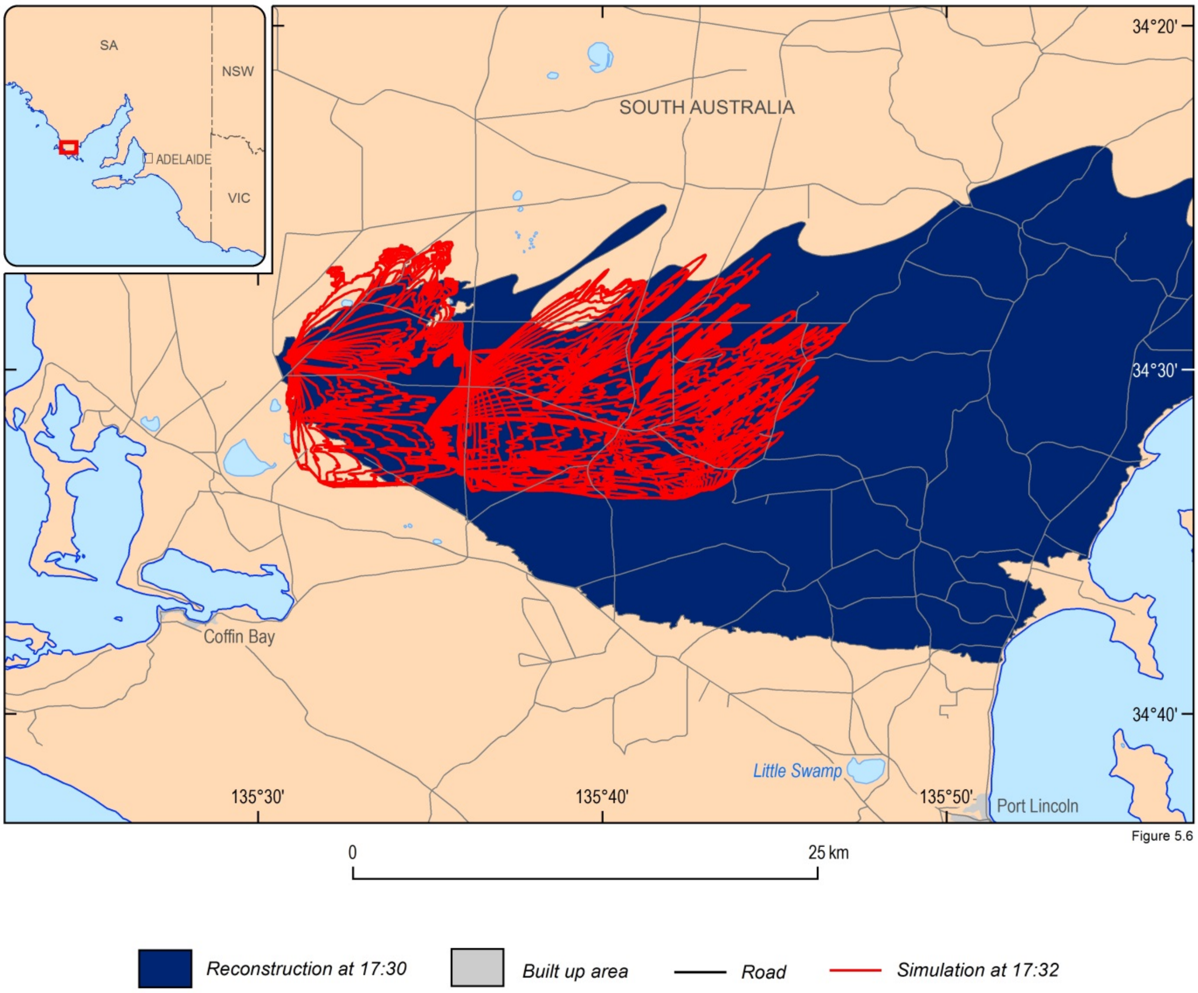

Figure 5.6 As for Figure 5.5, for 1200 m ACCESS resolution.

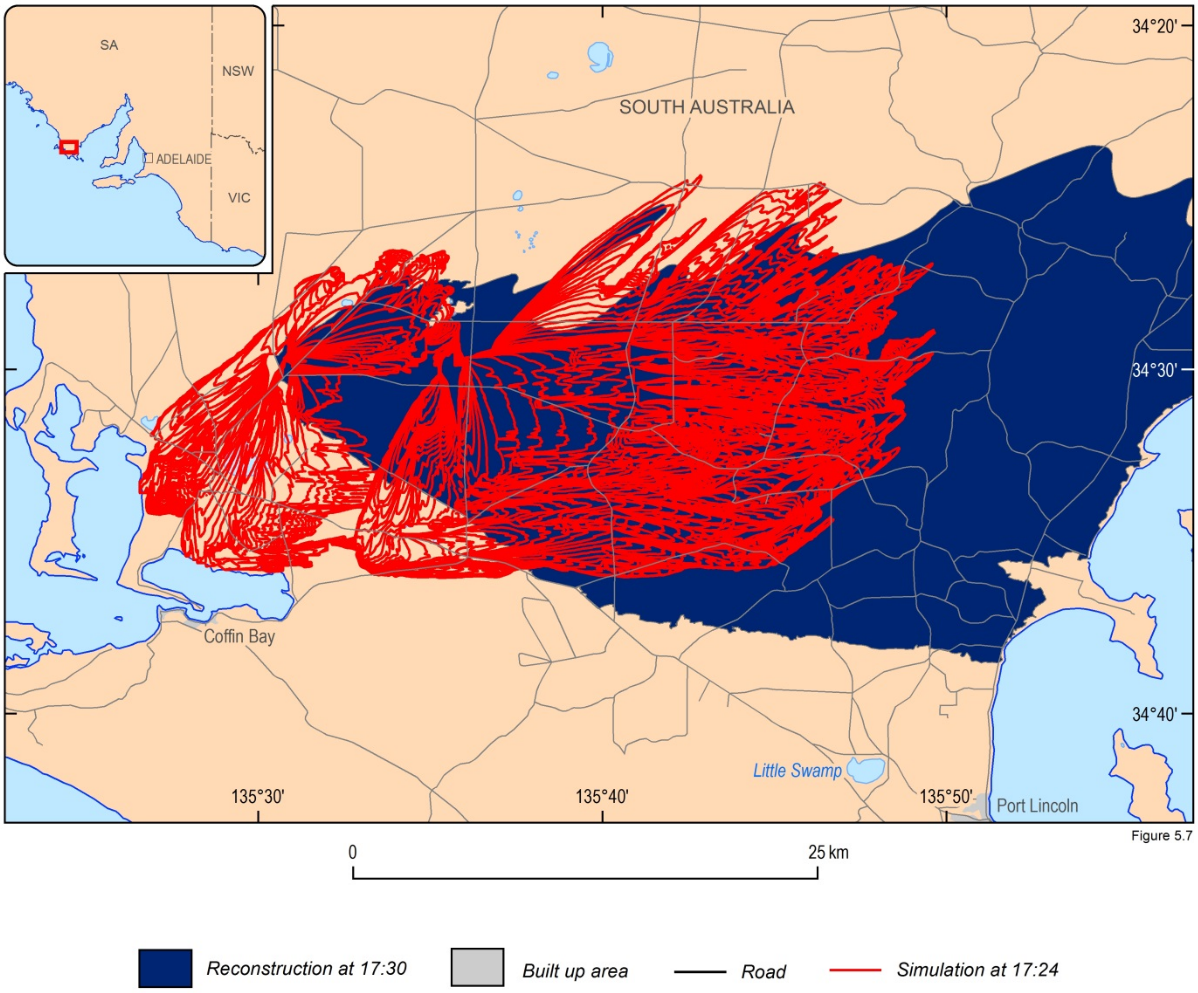

Figure 5.7 As for Figure 5.5, for 440 m ACCESS resolution.

5.3.1.1 Bias correction of wind strength

Figure 5.8 to Figure 5.10 show the impact of the bias correction on the fire simulation for each resolution of ACCESS file. Across all resolutions, bias correction increased the fire spread area. Nevertheless, the modelled fire spread did not attain an equivalent shape or size 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.

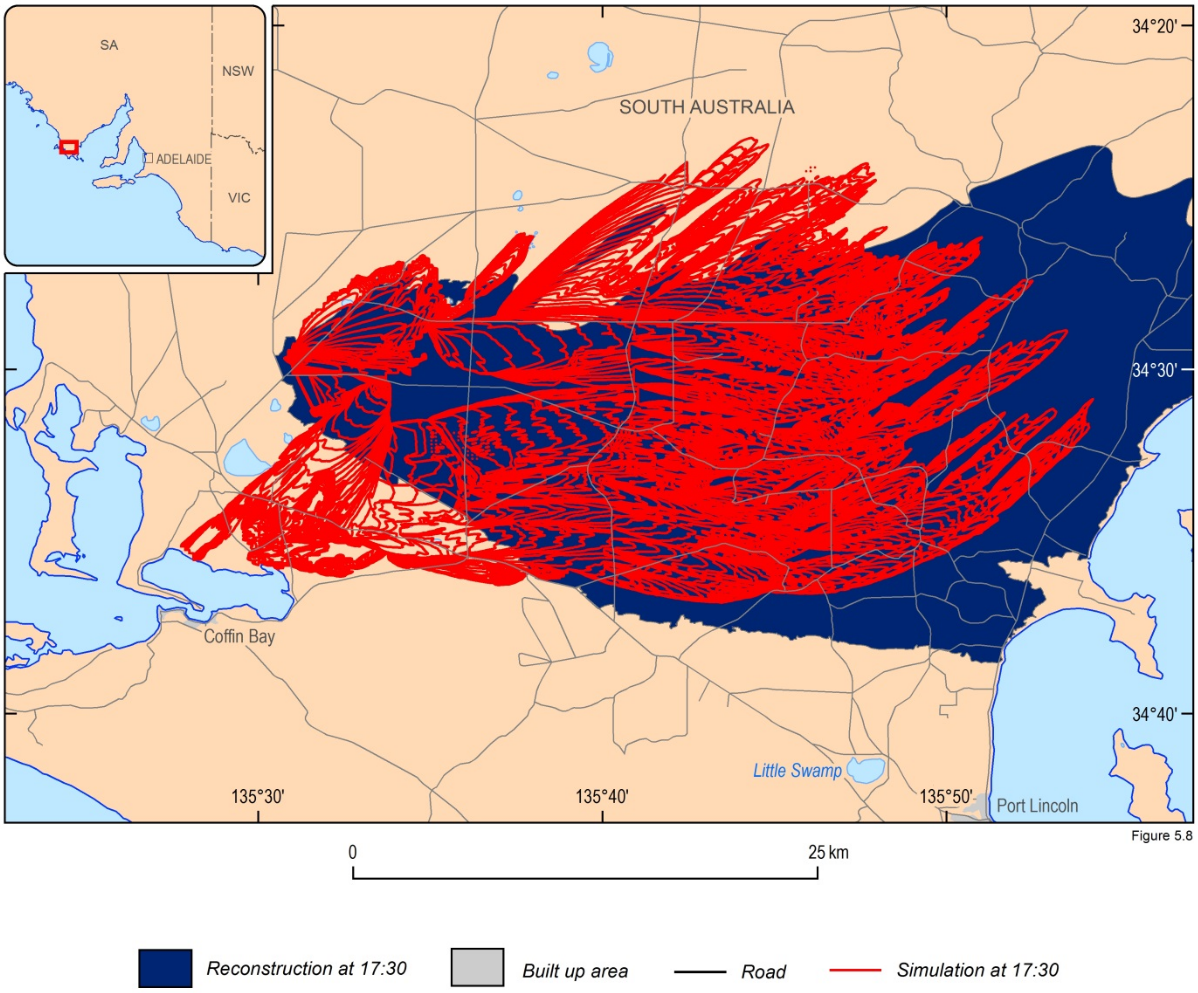

Figure 5.8 Simulated fire spread for the Wangary fire based on 4000 m 5 minute bias corrected weather, incorporating the reconstruction breakout information (red), and the reconstruction of the fire (blue).

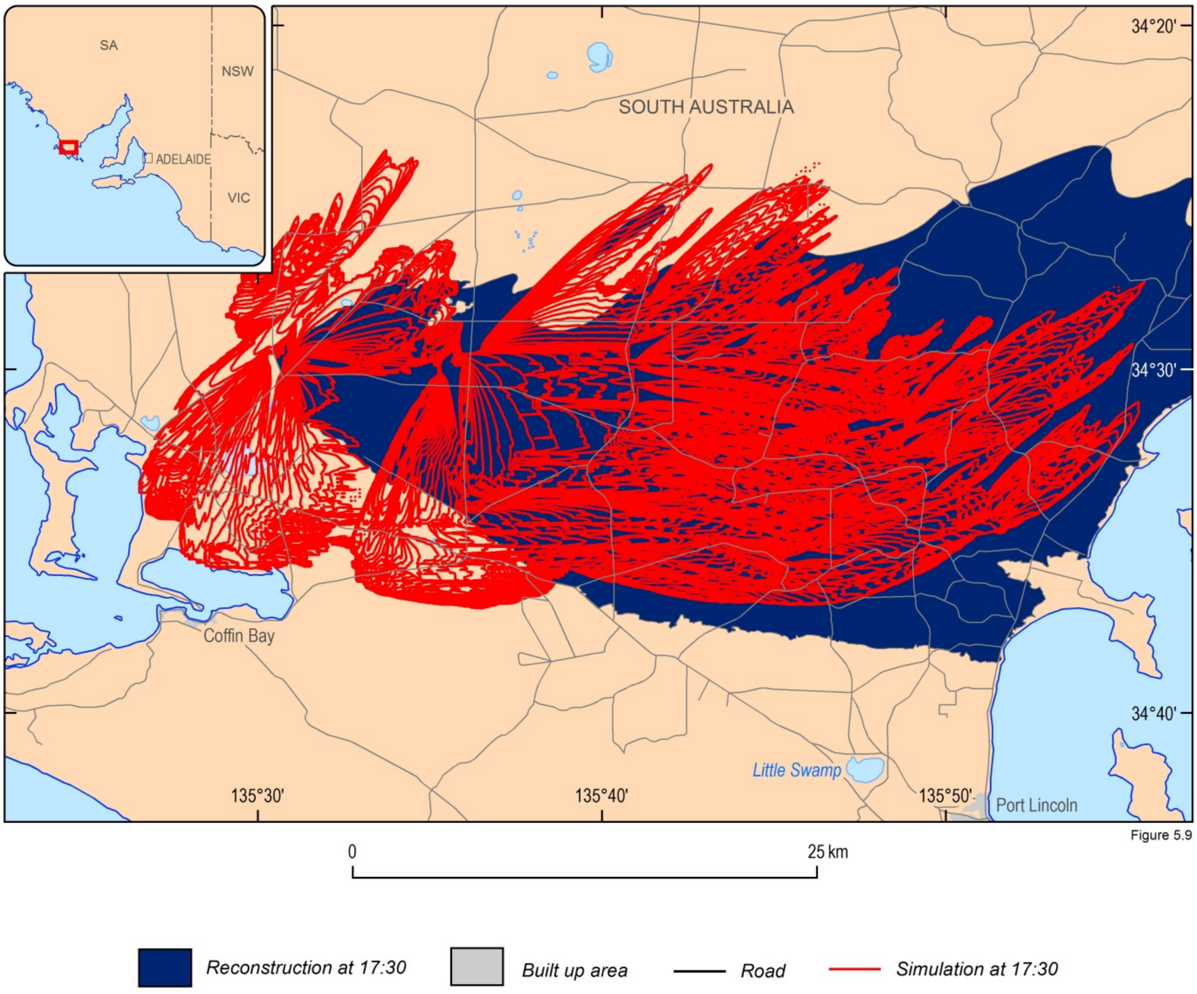

Figure 5.9 As for Figure 5.8, for 1200 m ACCESS resolution

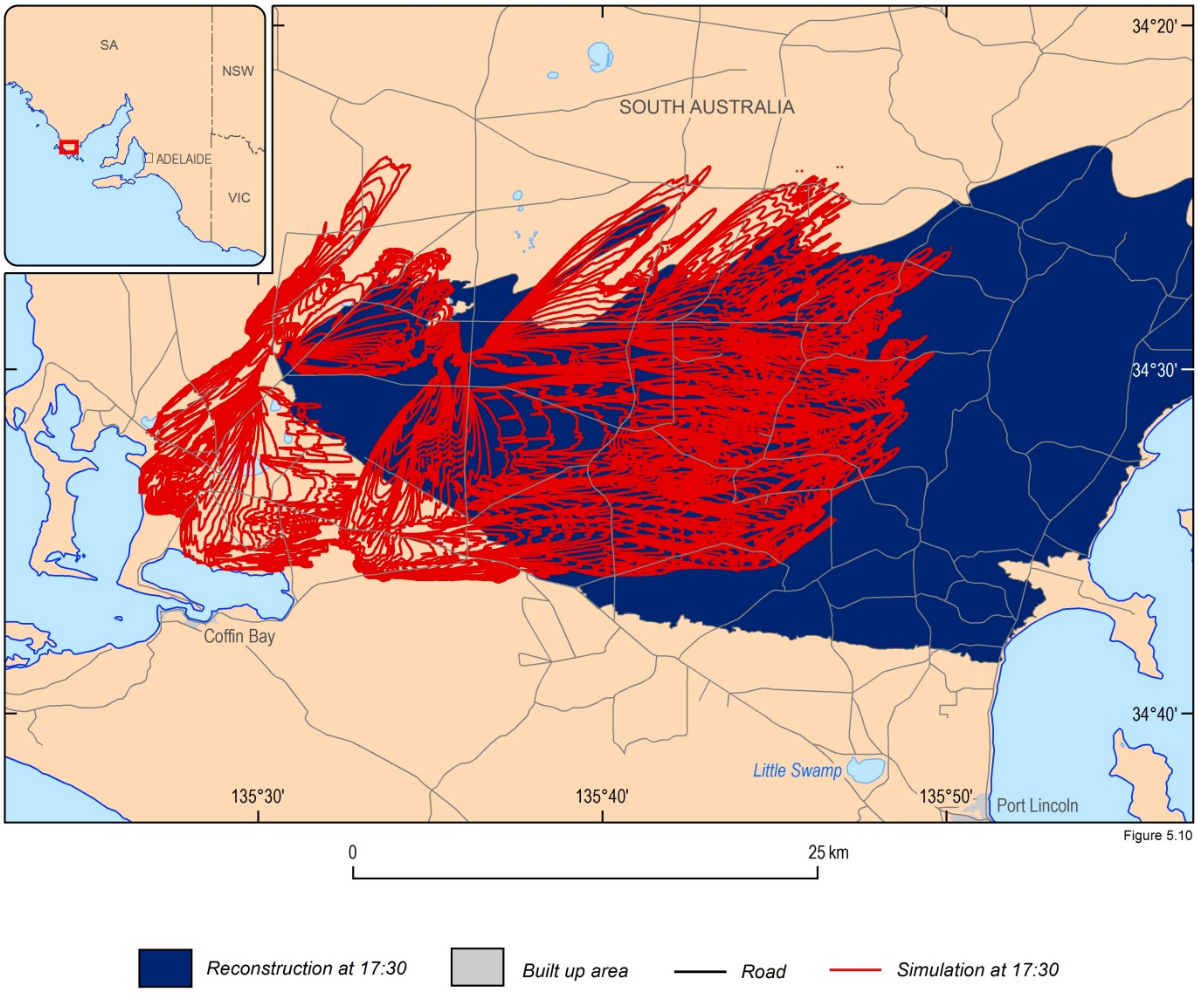

Figure 5.10 As for Figure 5.8, for 440 m ACCESS resolution.

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 good 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 5.11 (4000 m), Figure 5.12 (1200 m) and Figure 5.13 (440 m) show the simulation based on surface wind speed and direction generated by winds modified with Wind Ninja modifiers. All show little or no increase in accuracy in the fire shape compared with the simulations purely using the ACCESS bias corrected wind. This is not unexpected, as the terrain on the Eyre Peninsula is fairly uniform and so the Wind Ninja modifiers will have little impact.

The relatively large difference between the modelled and historical fire spread despite adjustments to the modelled weather conditions suggests that the uncertainty in the weather data is not the dominant factor affecting the accuracy of the simulated fire spread. Further work is needed to better understand the limitations of the fire spread modelling for conditions such as the Wangary fire.

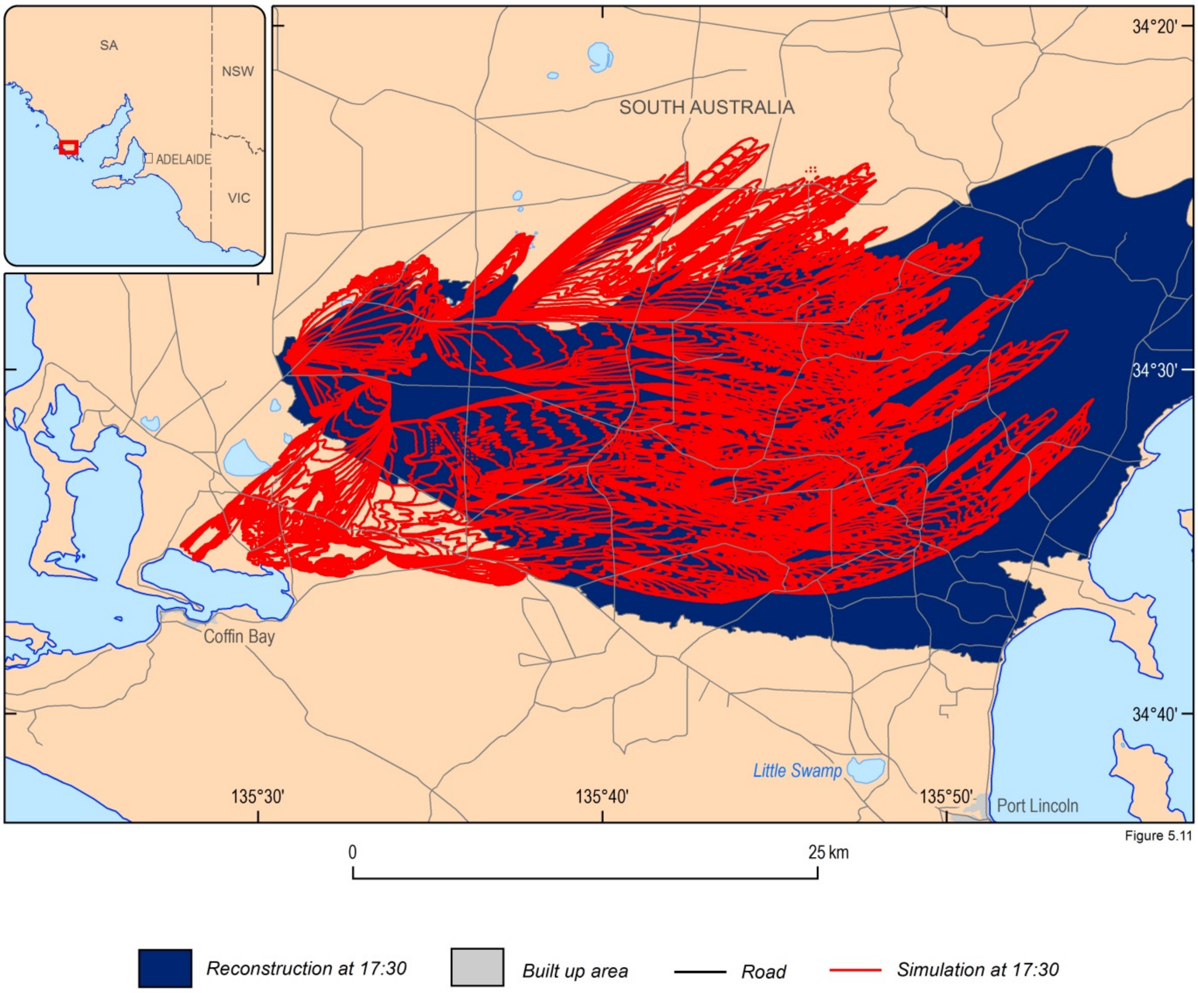

Figure 5.11 Simulated fire spread for the Wangary fire based on 4000 m 5 minute bias corrected Wind Ninja weather, incorporating the reconstruction breakout information (red), and the reconstruction of the fire (blue).

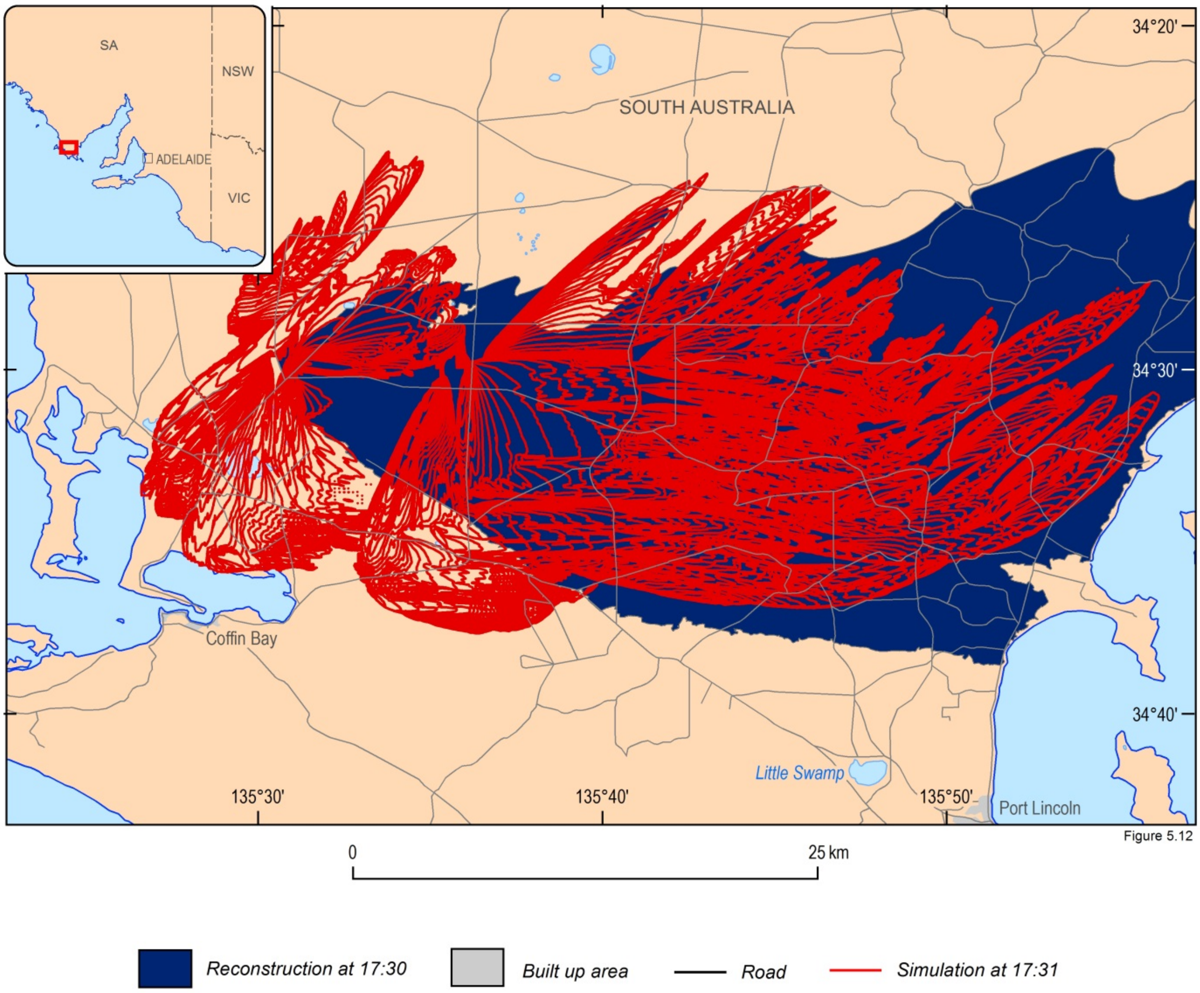

Figure 5.12 As for Figure 5.11, for 1200 m ACCESS resolution.

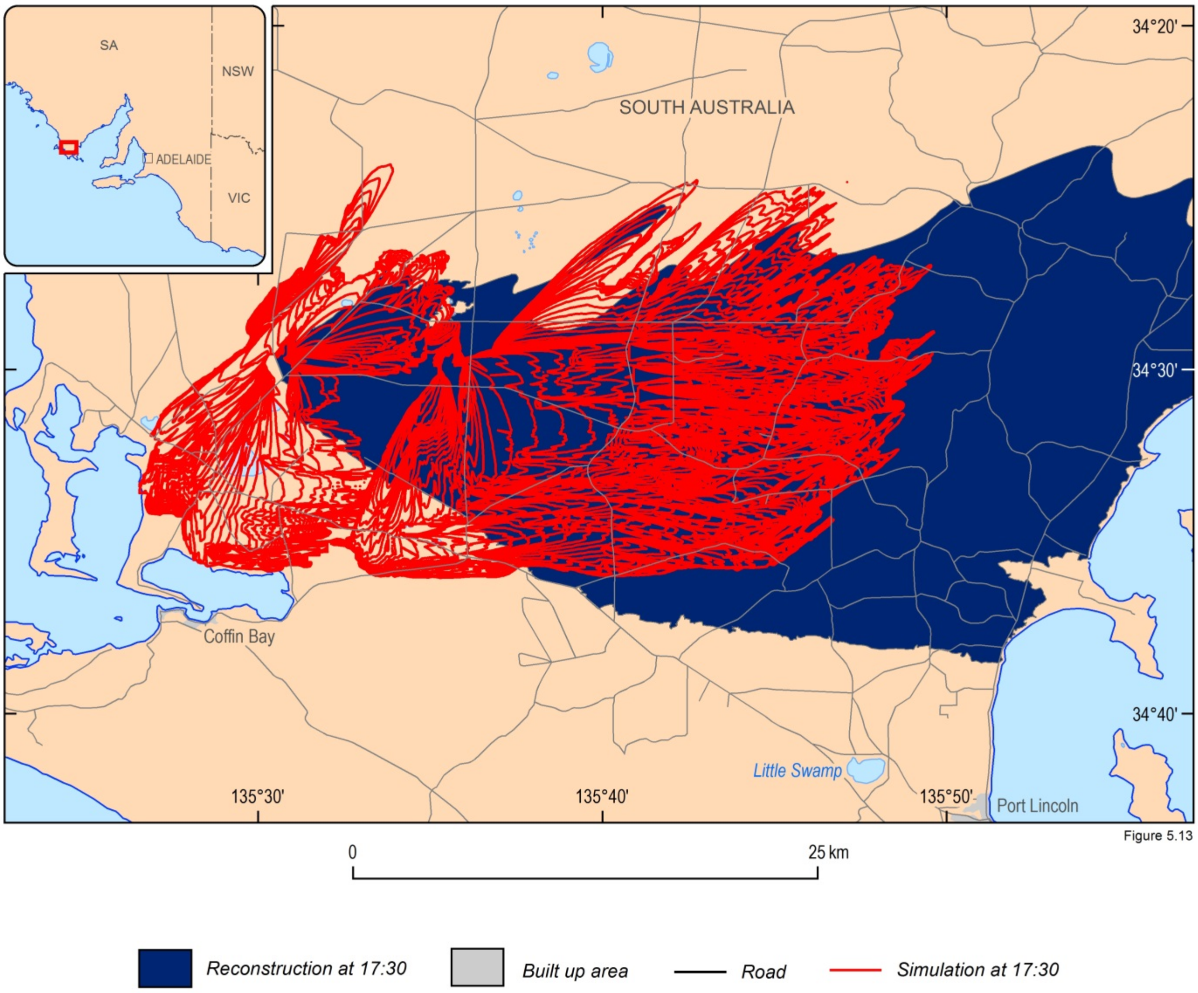

Figure 5.13 As for Figure 5.11, for 440 m ACCESS resolution.

5.3.2 Sensitivity to temporal resolution

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 5.14 to Figure 5.16 show the results of simulations with the respective time intervals.

All the simulations at 15, 30 or 60 minutes produce smaller shapes than the 5 minute time step simulations. This confirmed expectations, as the weather at these times is just an extract of the conditions and any variability between the times is removed. Thus the 5 minute time step weather should always be used.

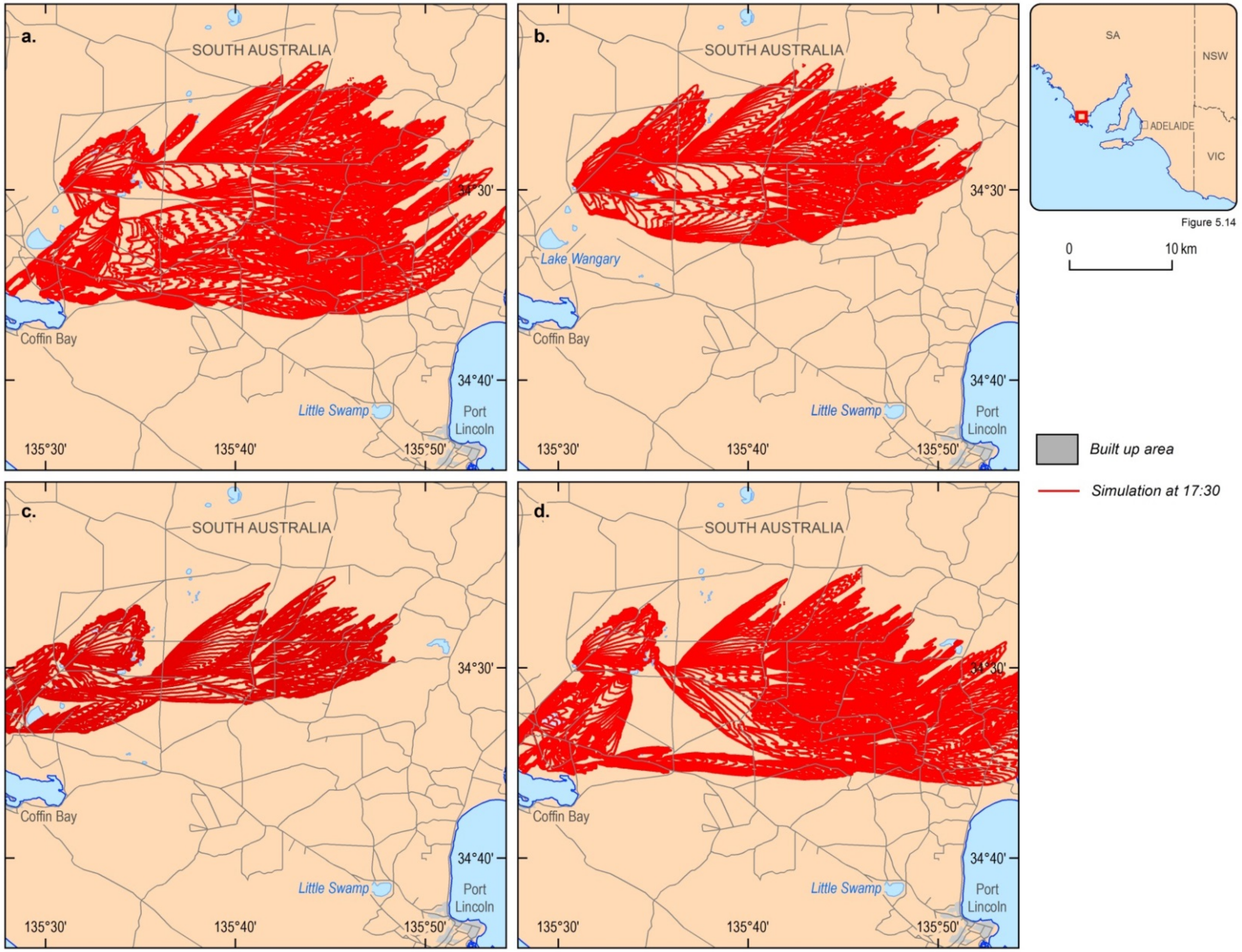

Figure 5.14 Comparison of a.5, b.15, c.30 and d.60 minute time step weather data. The red shape shows the simulated fire spread for the Wangary fire based on 4000 m bias corrected time step weather input with Wind Ninja, incorporating the reconstruction breakout information.

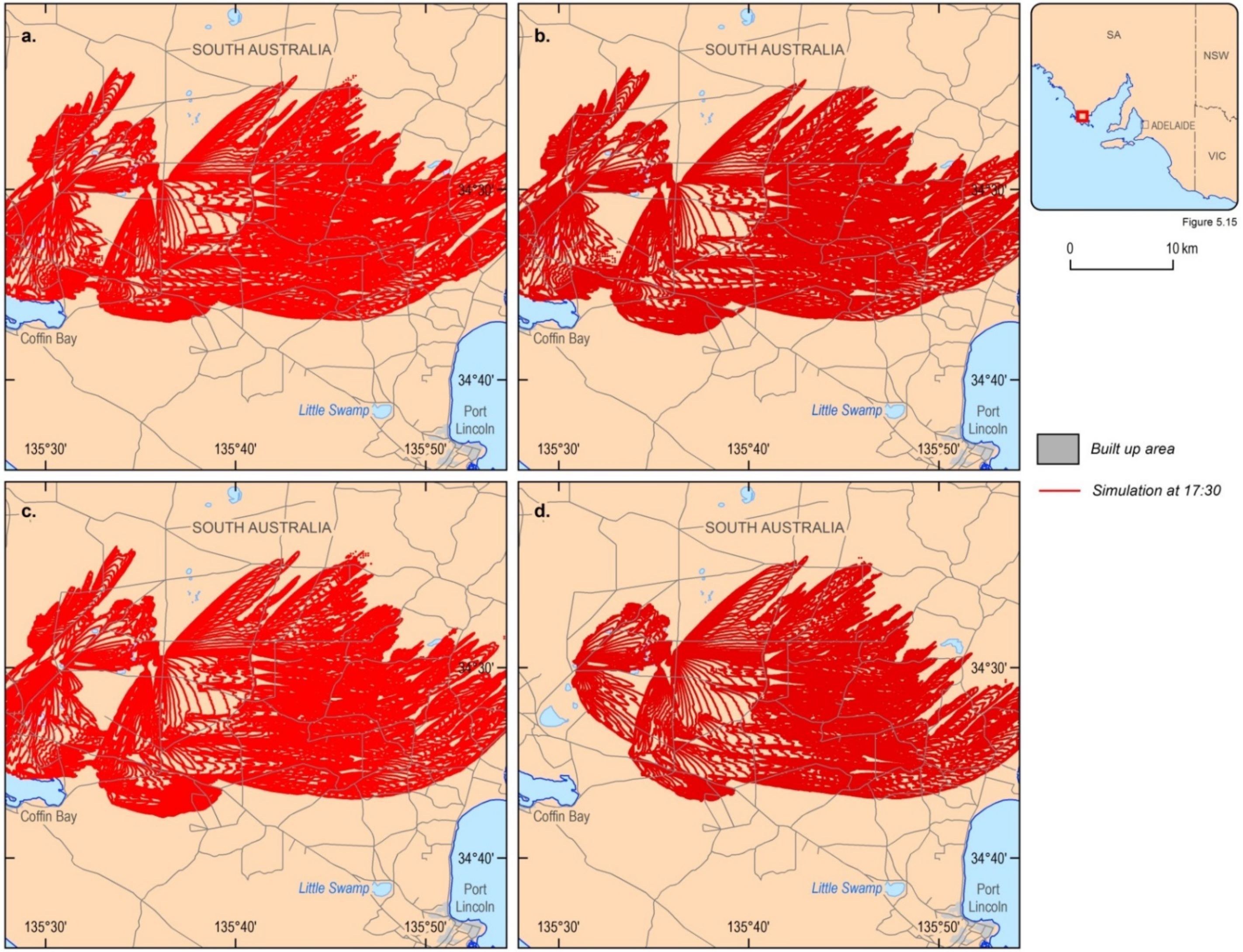

Figure 5.15 As for Figure 5.14, for 1200 m ACCESS resolution.

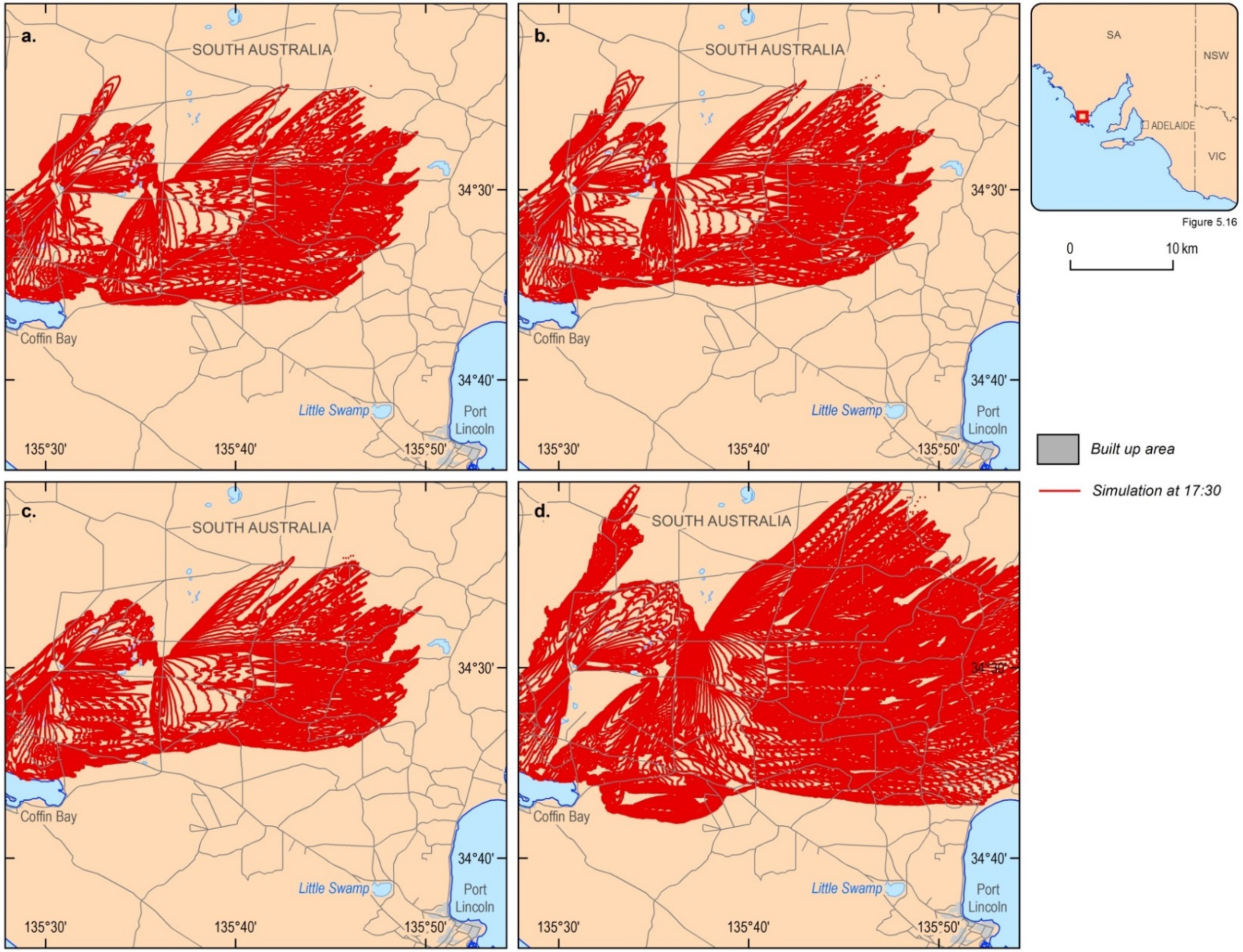

Figure 5.16 As for Figure 5.14 for 440 m ACCESS resolution.

5.3.3 Sensitivity to wind direction

Figure 5.17 andFigure 5.18 show two direction shifts in the wind speed (-10º and +10º respectively). The figures demonstrate a marked change in the direction of the simulated fire as a result of the perturbed wind direction, as expected indicating significant sensitivity.

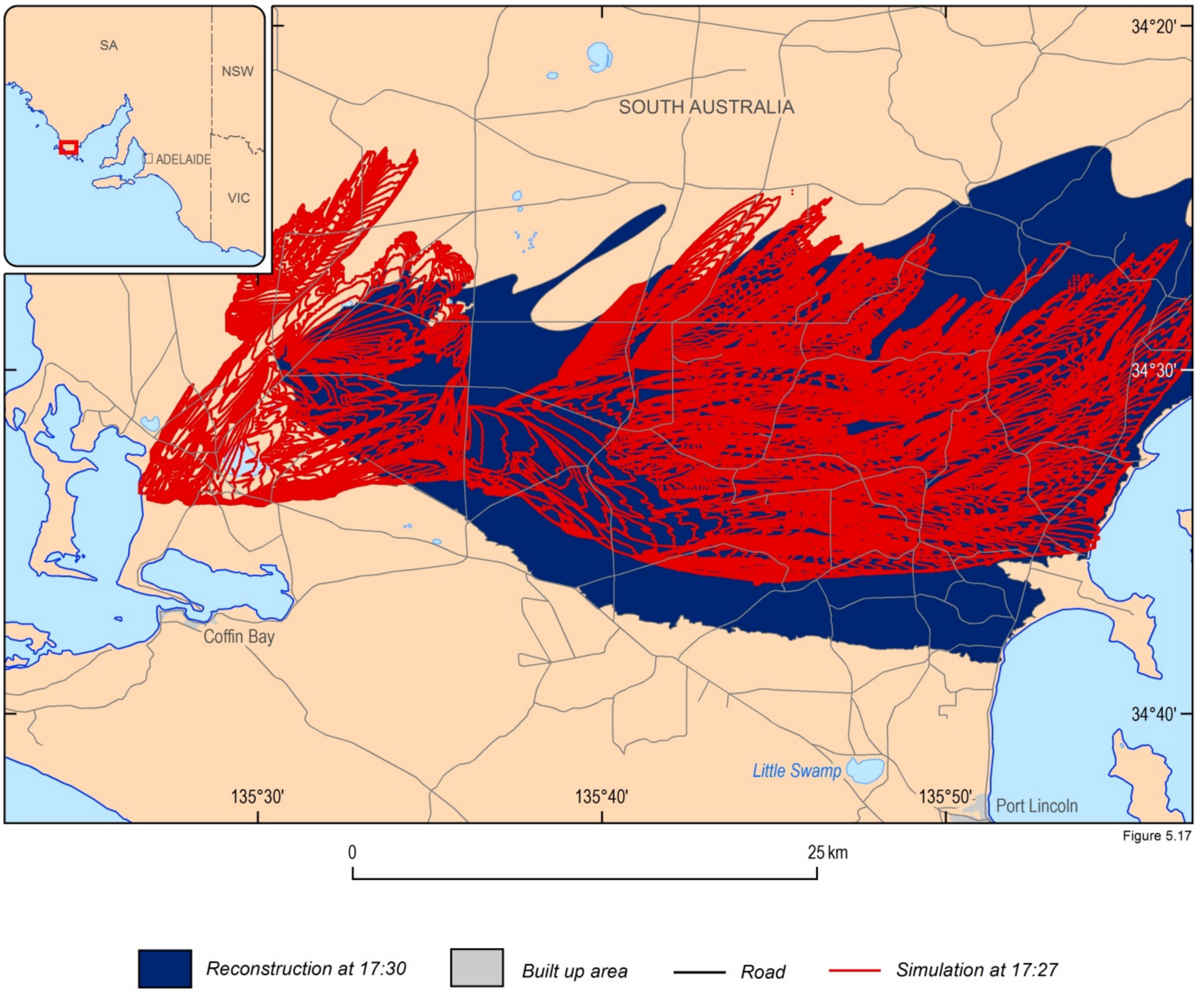

Figure 5.17 Simulated fire spread based on 4000 m 5 minute Wind Ninja, bias corrected ACCESS weather with wind direction -10o (red); Wangary fire reconstruction (blue).

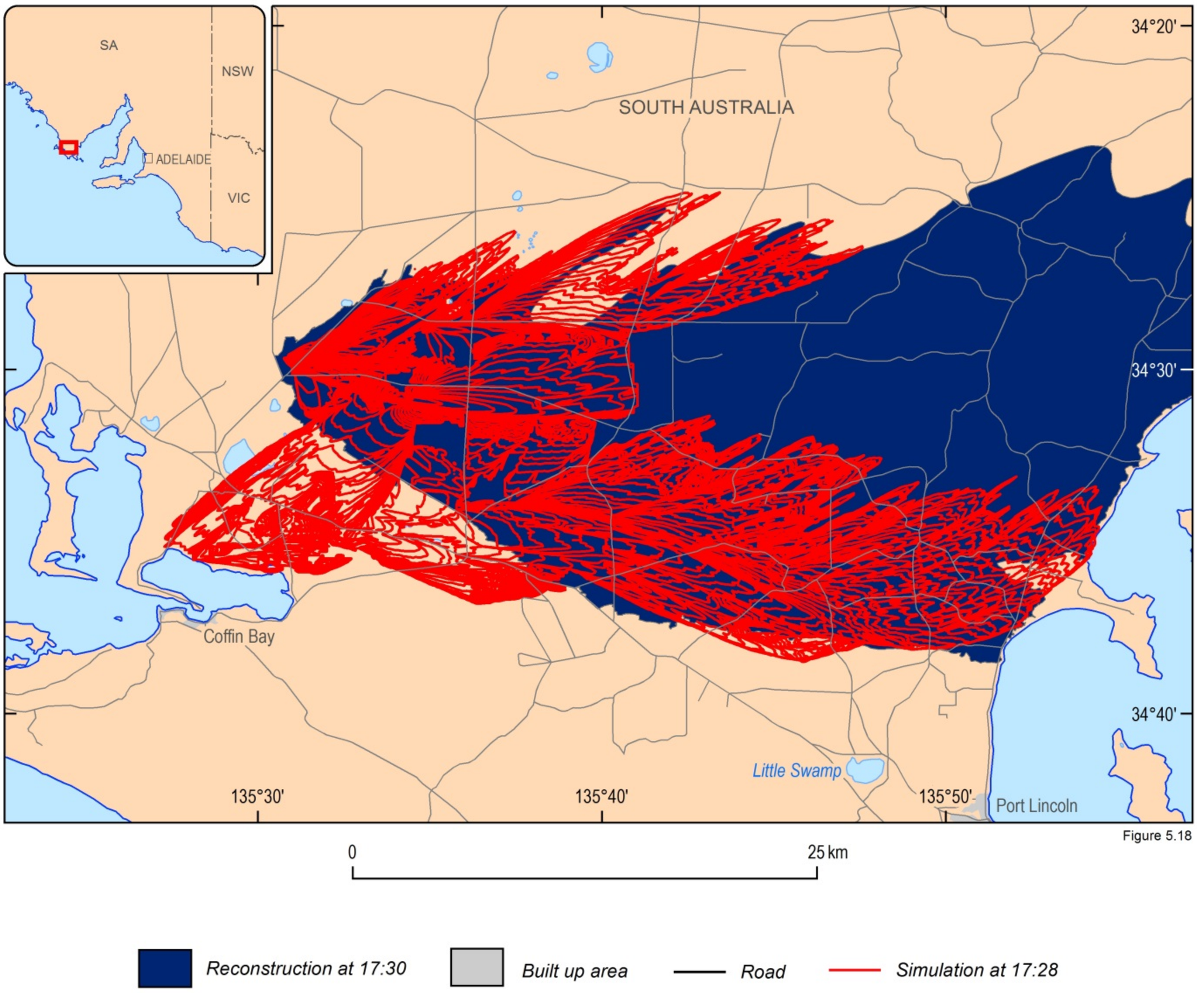

Figure 5.18 As for Figure 5.17, with +10º ACCESS wind direction.

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 5.19 (all wind speeds +5 m/s) and Figure 5.20 (all wind speeds +10 m/s). The difference in fire spread between the two figures shows the sensitivity of the fire spread simulation to the variation in wind speed.

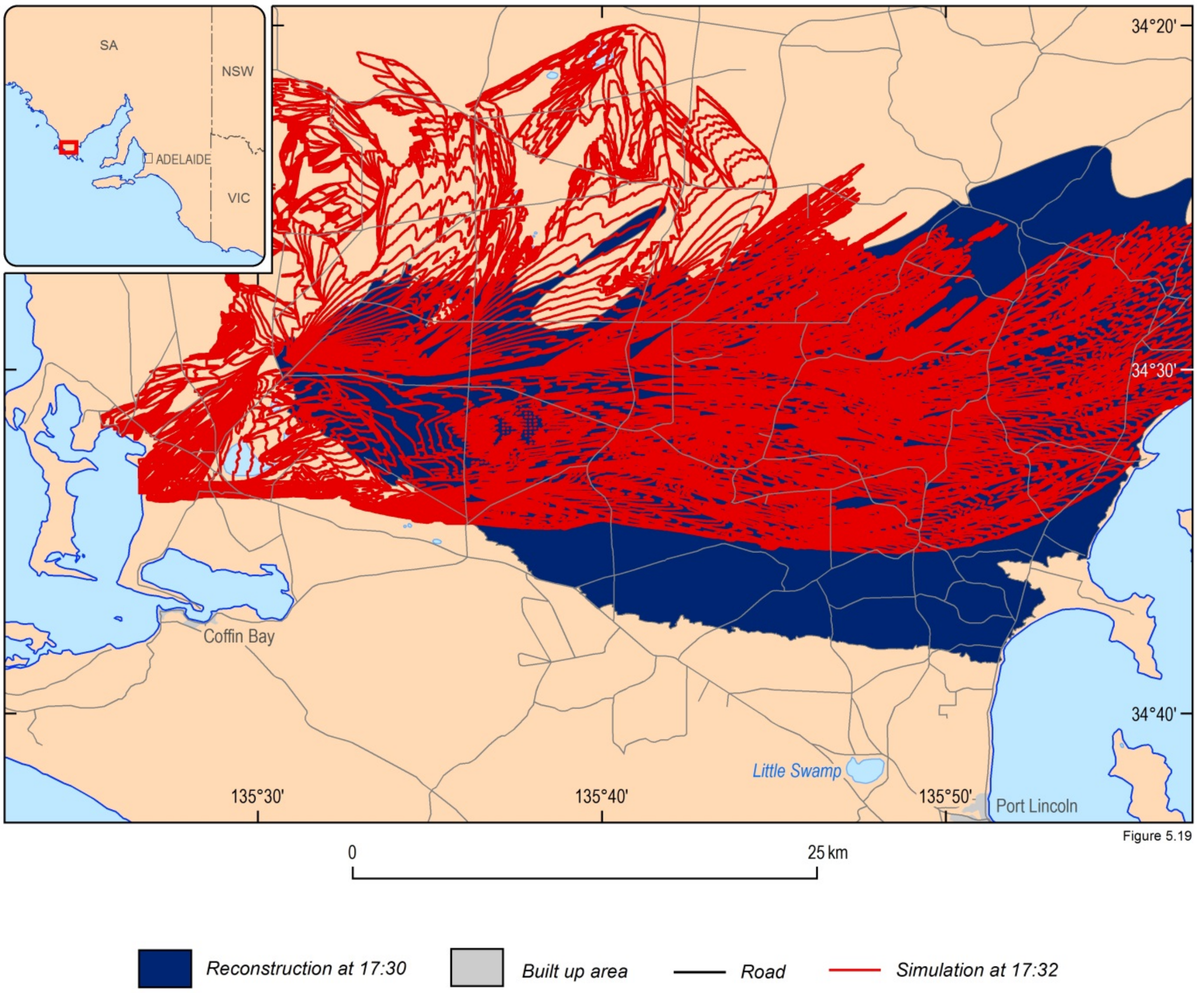

Figure 5.19 Simulated fire shape based on 4000 m 5 minute Wind Ninja, bias corrected ACCESS wind speed +5 m/s (red); Wangary fire reconstruction (blue).

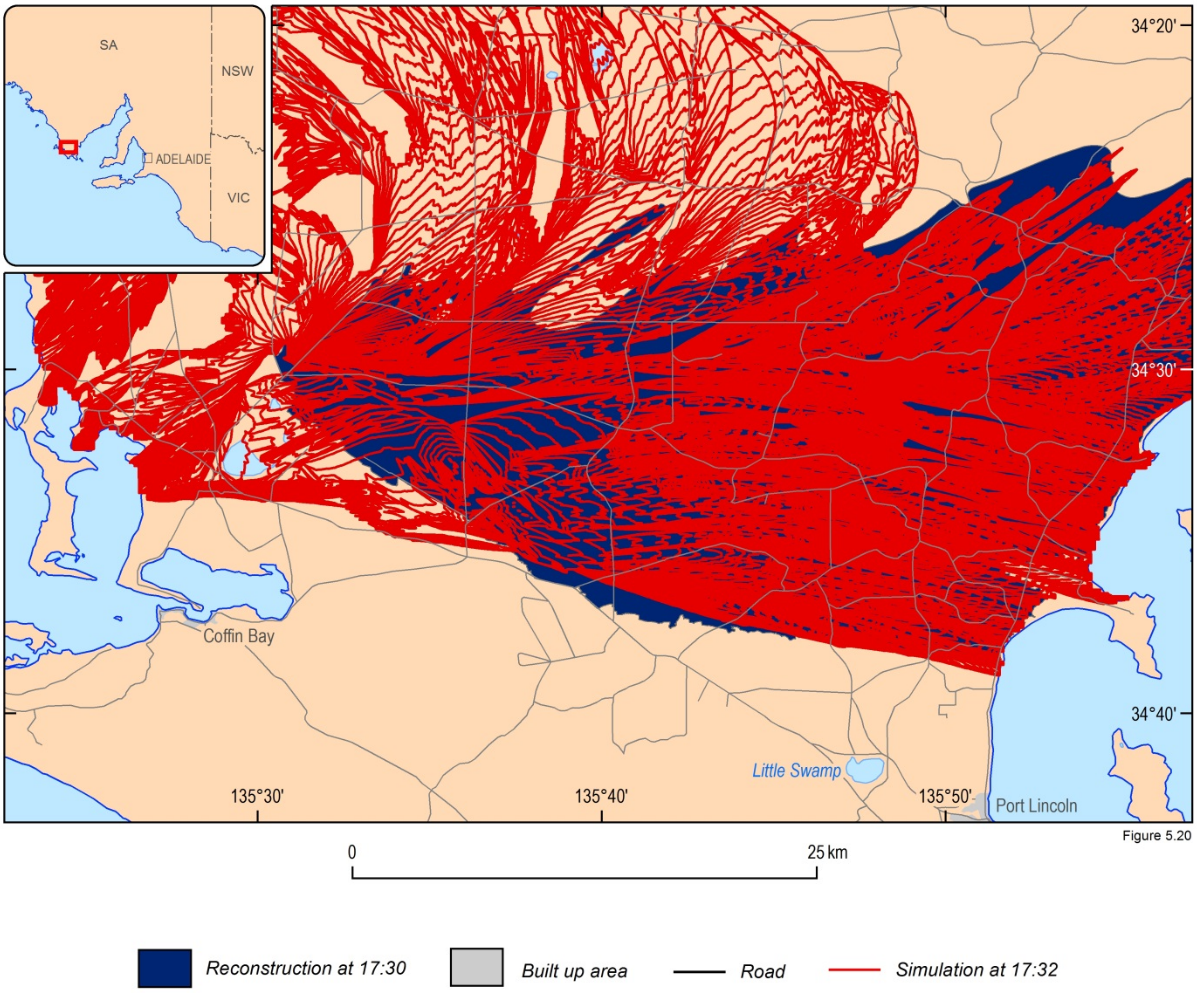

Figure 5.20 As for Figure 5.19, for +10 m/s ACCESS wind speed.

5.3.5 Sensitivity to temperature

The fire spread for two temperature scenarios are shown in Figure 5.21 (temperature -2°C) and Figure 5.22 (temperature +2°C). A decrease in temperature is reflected in a slight decrease of the size of the fire shape.

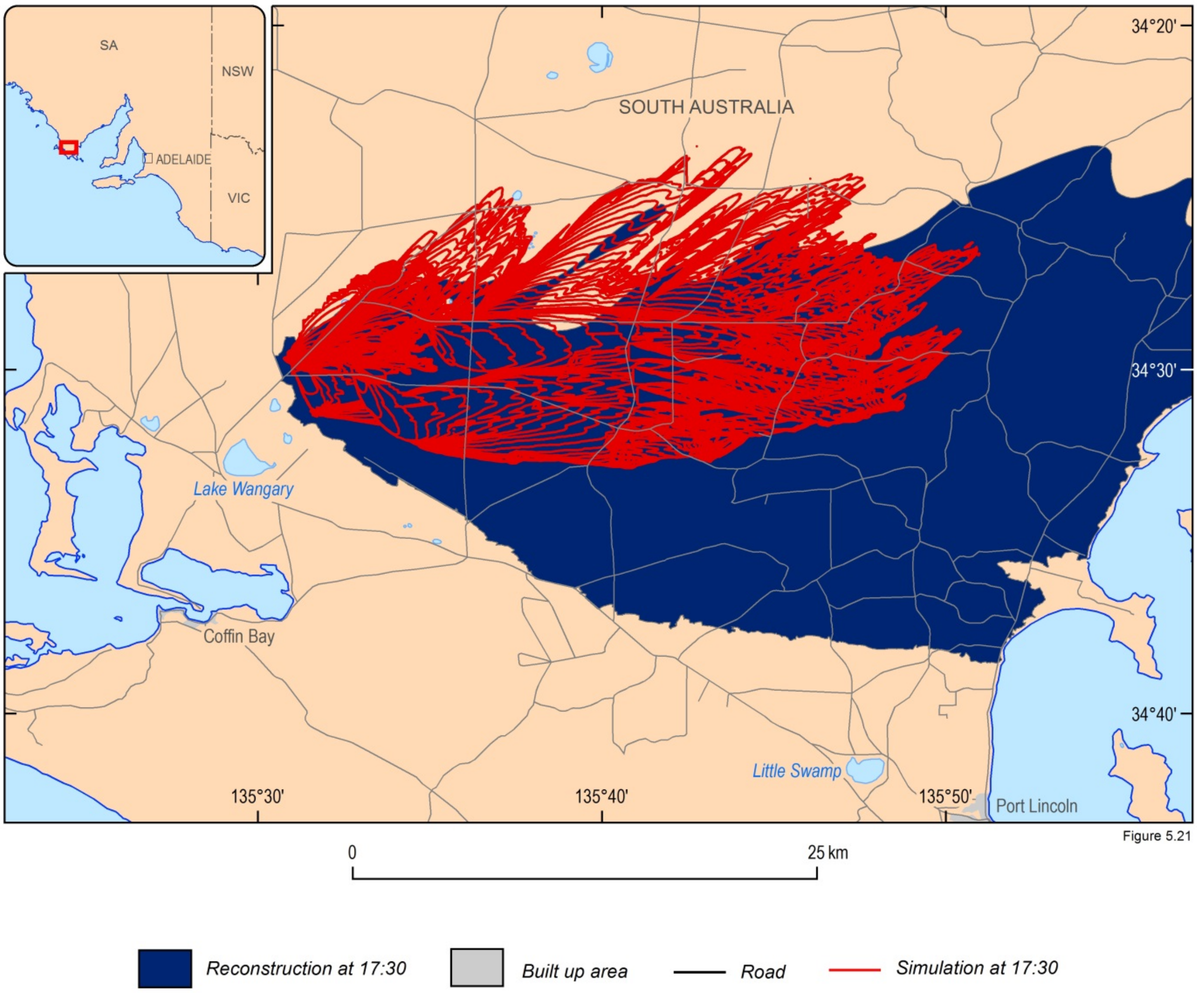

Figure 5.21 Simulated fire spread based on 4000 m 5 minute Wind Ninja, bias corrected ACCESS weather with temperature -2oC (red); Wangary fire reconstruction (blue).

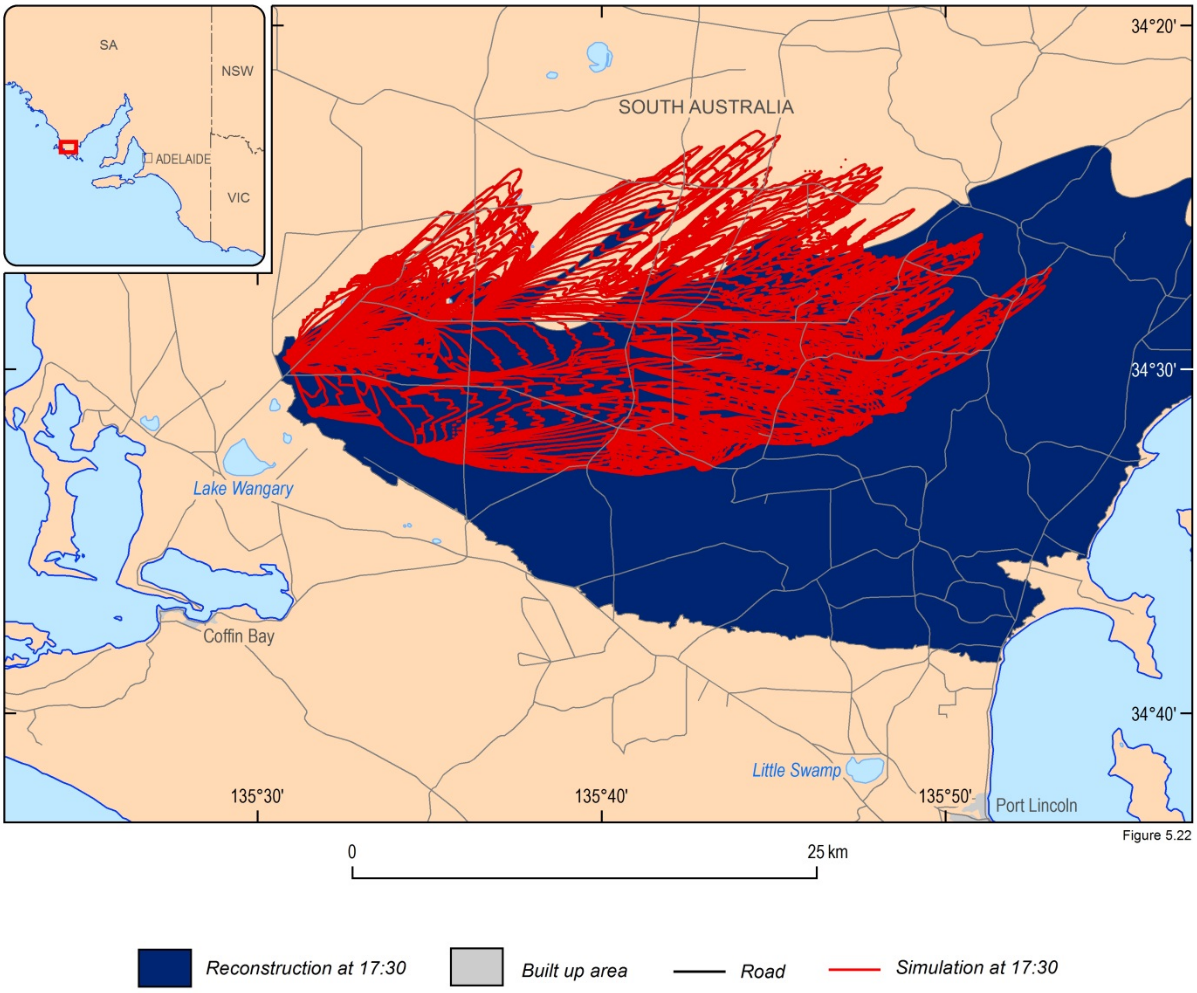

Figure 5.22 As for Figure 5.21, for +2oC ACCESS temperature.

5.3.6 Sensitivity to humidity

To demonstrate an assessment of the sensitivity of fire spread to humidity, two humidity shifts are shown in Figure 5.23 (humidity -2%) and Figure 5.24 (humidity +5%). These two values were chosen because on the day of the Wangary Fire there was low humidity. Consequently, introducing large perturbations in the simulations would not be realistic. As expected, a decreased humidity results in a larger fire shape that in this case (humidity -2%) almost matches the reconstruction area in the east (Figure 5.23). This result could either indicate an error in the modelled humidity, or it suggests the impact of a humidity decrease compensates for errors in the fire spread parameterisation or other input parameters. A global increase of humidity of +5% (Figure 5.24) resulted in a fire shape that was smaller than a simulation using the actual humidity which was expected.

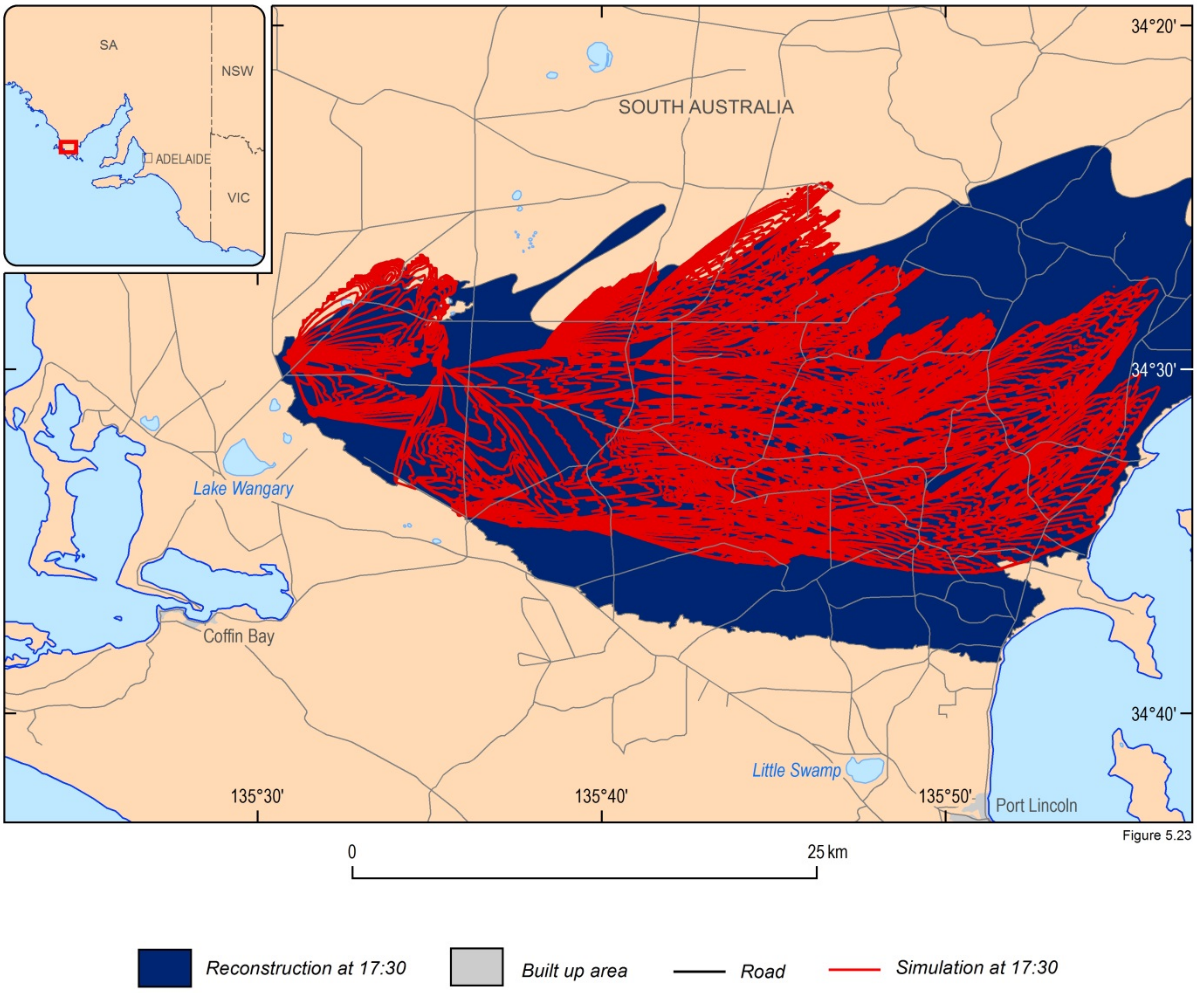

Figure 5.23 Simulated fire shape based on the 4000 m 5 minute Wind Ninja bias corrected ACCESS weather with humidity -2% (red); Wangary fire reconstruction (blue).

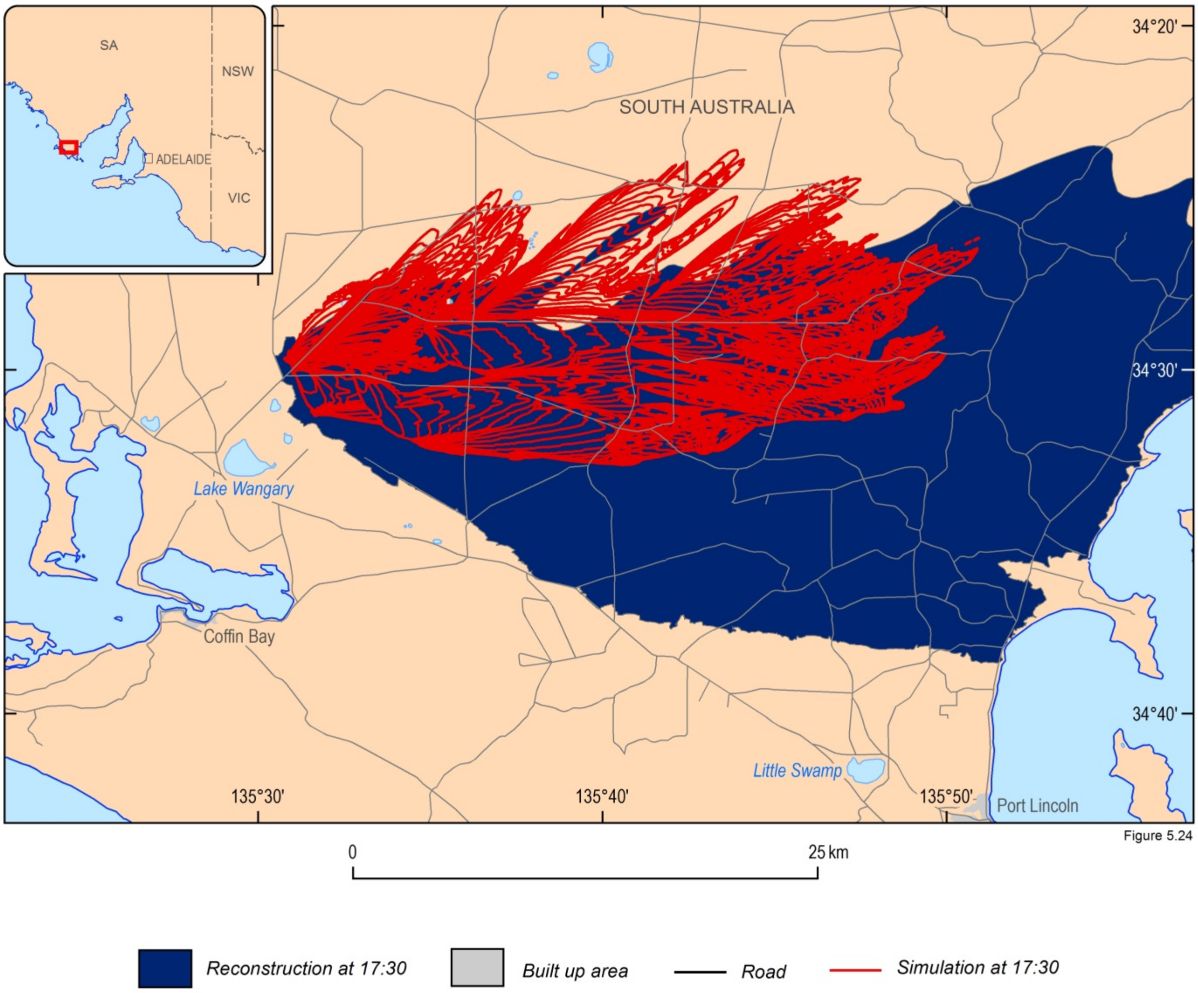

Figure 5.24 As for Figure 5.23, for +5% ACCESS humidity.

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 5.25 shows a scenario where the following modifications were made to the conditions of the original Wangary fire:

- Wind speed +5 m/s
- Wind direction +15^o
- Temperature +5^{o}C
- Relative humidity -2%

Multiple variations in weather meant the fire spread incorporated more complex interactions between weather variables. This is illustrated by comparing the results of this scenario with those shown in the previous sections of this chapter. The resulting fire spread shown in Figure 5.25 does not closely reflect the influence of single individual parameter that defines the scenario. For example, the change in the fire shape and size exceeds that caused by the similar perturbation to the humidity and temperature in isolation (compare to Figure 5.22 and Figure 5.23). 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.

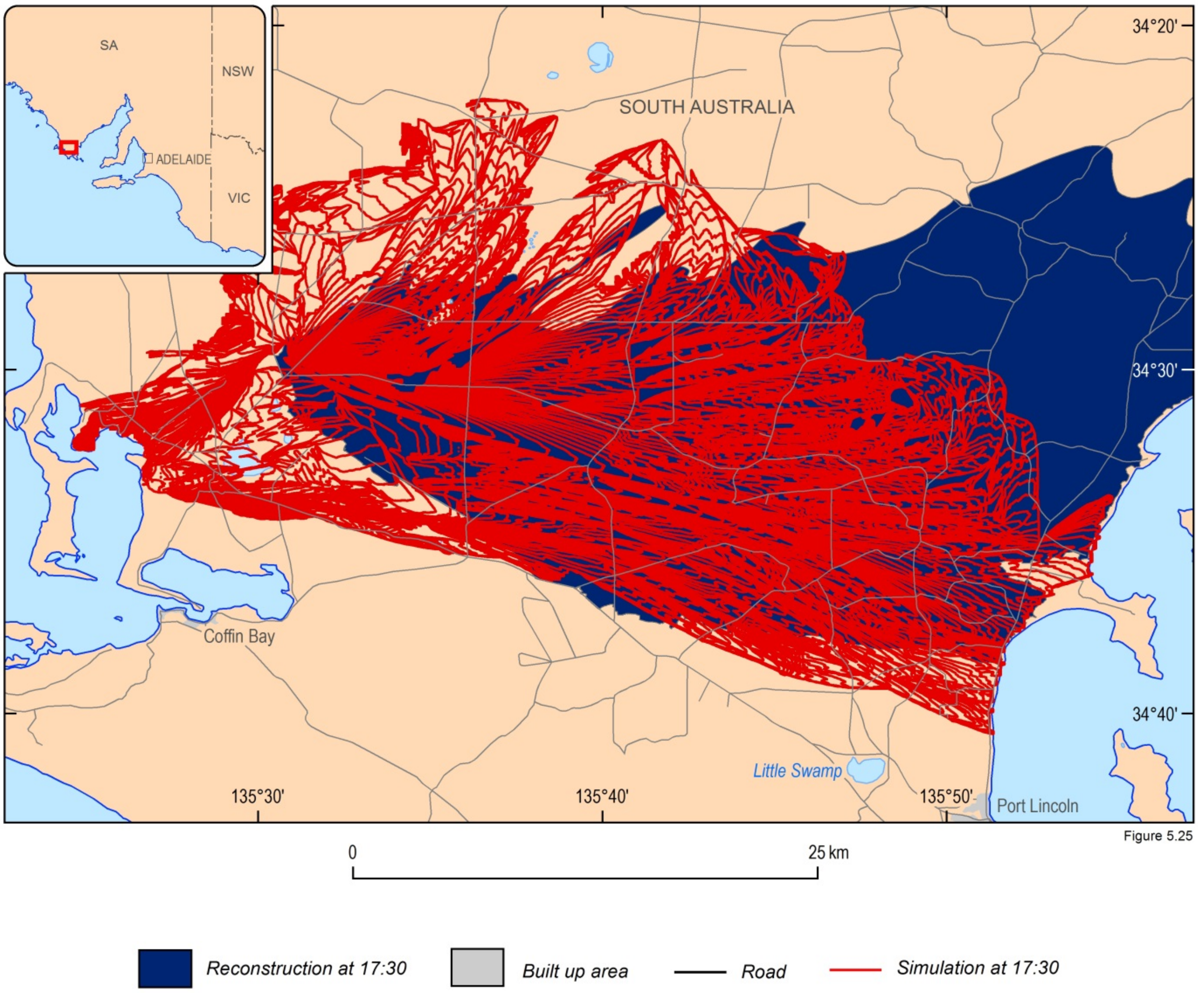

Figure 5.25 Wangary fire spread simulation with ACCESS weather at 4000 m 5 min interval, bias correction of wind speed, humidity -2%, temperature +5°C, wind direction +15°, wind speed +5 m/s.

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 Wangary fire underestimated the size of the historical event, based on the reconstruction of that event. The relatively large difference between the modelled and historical fire spread despite adjustments to the modelled weather conditions suggests that the error produced by the uncertainty in the weather data is not the dominant factor limiting the accuracy of the simulated fire spread. Further work is needed to better understand the limitations of the fire spread modelling for conditions such as the Wangary fire.

- The FireDST Weather Ensemble Generator can generate any range of simultaneous modifications of temperature, humidity, wind speed and wind direction. All the changes apply equally across the whole landscape. Thus, the Weather Ensemble Generator 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.
- Finally, the results in this chapter demonstrate the potential benefit of ensemble information in suggesting that breakouts were likely if ensembles had been completed prior to the 11 January. In the context of a fire, this could prompt a consideration to deploy resources to mitigate the effect of a breakout in the most likely area.

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.
- Also the selection of the variability in the input conditions is critical to ensuring that a realistic ensemble is produced. This requires further research into the combinations of weather variations that are most likely. In the future it may be possible for the Bureau of Meteorology to introduce probabilities of variations in the ACCESS weather parameters.

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. 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 aim of this research was to evaluate the vertical atmosphere weather conditions as a driver of the ember transport layer in the fire spread modelling. This was achieved by simulating the Wangary fire using the ACCESS vertical atmosphere to specify the weather conditions for the event.

6.2 Methodology

6.2.1 Background

Bushfires have been known to generate convective columns up to 15 km and, once lofted by convection, embers can be transported over large distances by the winds that tend to be much stronger at such altitudes than at the surface (Cruz et al 2012). To investigate the effect of both ground ember generation and lofted embers on the modelled fire spread, the analysis described here tested different vertical layers up to the top of the simulated atmosphere as input for the fire spread modelling.

The standard PHOENIX RapidFire model parameterised the ember transport based on input weather data at 10 m. The PHOENIX RapidFire convection bubble model was modified by the University of Melbourne to incorporate an extra 'transport layer' based on wind direction and wind speed. The Bureau of Meteorology generated a simulated atmospheric profile from 10 m to 60 km above ground level for the Wangary 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.

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
32	20951.7
33	22136.7
34	23329.7
35	24538

Level	Altitude (m)
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 atmospheric profile to provide an overview of the simulated atmospheric wind speed conditions. The closest point in the ACCESS 4000 15 minute grid is in the southern portion of Salt Swamp (-34.500, 135.572) approximately 5.5 km to the east of the original ignition point (Figure 6.1). This point is just outside the fire boundary at midnight on 10/1/2005 to allow an examination of the weather conditions that caused the historical fire breakouts on 11/1/2005.

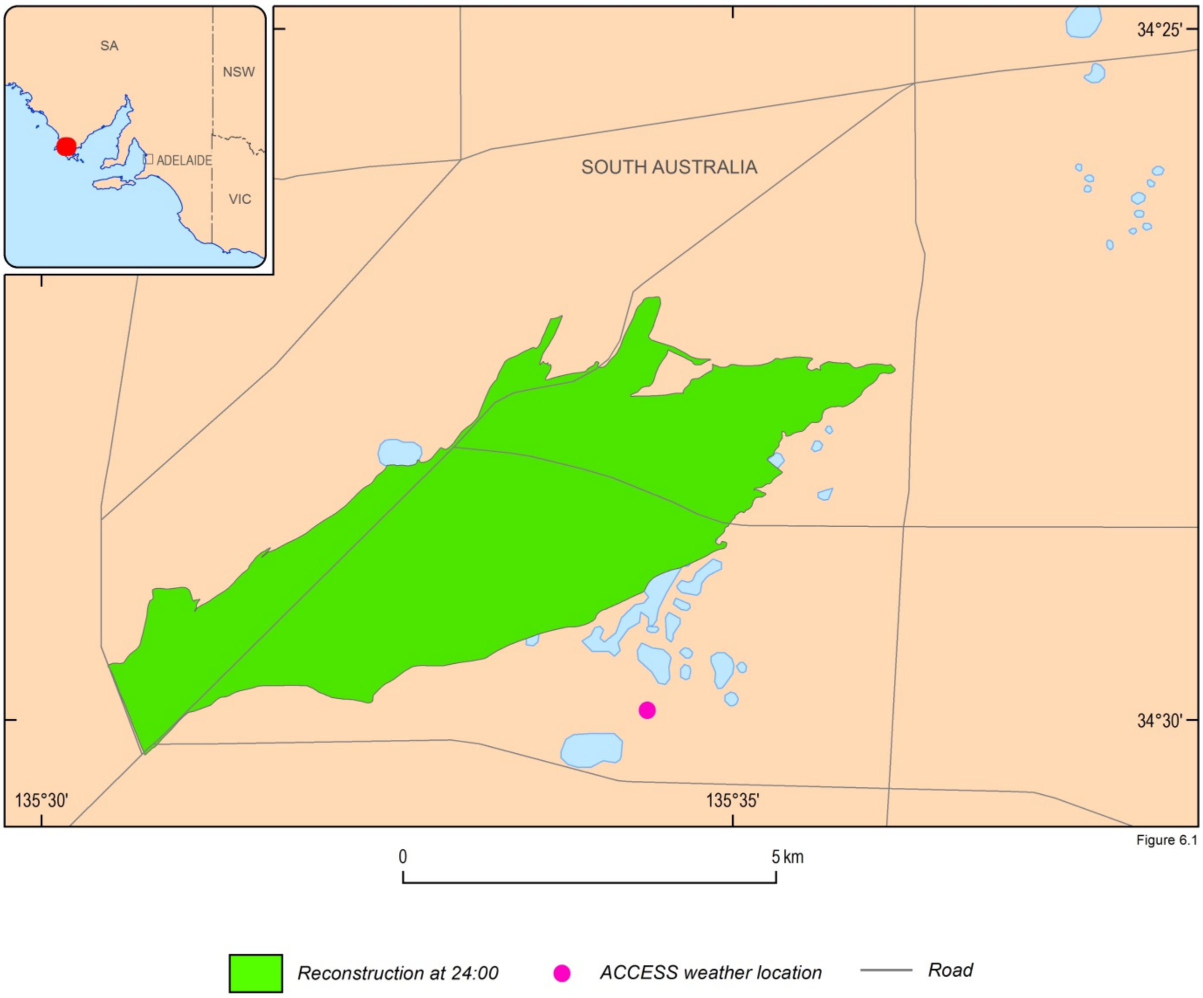

Figure 6.1 Map of the closest point in the ACCESS 400m 5 minute grid (-34.5, 135.572) to the fire boundary at midnight on 10/1/2005 (green area).

An extract of the ACCESS modelled atmospheric profile wind speed over time at the weather location is displayed in Figure 6.2 to Figure 6.4. Figure 6.2 shows the boundary layer wind speeds (10 m, 50 m (level 1), to 850 m (level 6)). The boundary layer is the part of the atmosphere that is directly influenced by the presence of the earth's surface. The depth of the boundary layer is quite variable in time, ranging from hundreds of metres to a few kilometres (Stull 1988).

The wind speeds in this figure follow the same pattern but have different intensities. The rapid drop in wind speed just before 10:00 and the instabilities in wind speed up until 15:00 are attributable to a change in wind direction as a south westerly change passed over the Eyre Peninsula (Cechet *et al.,* 2014). Figure 6.3 shows the layers just above the boundary layer (1130 m (level 7), to 3130 m (level 12)). Figure 6.4 shows the wind speeds above 10 km, which exhibited more consistency in wind speed than the lower levels.

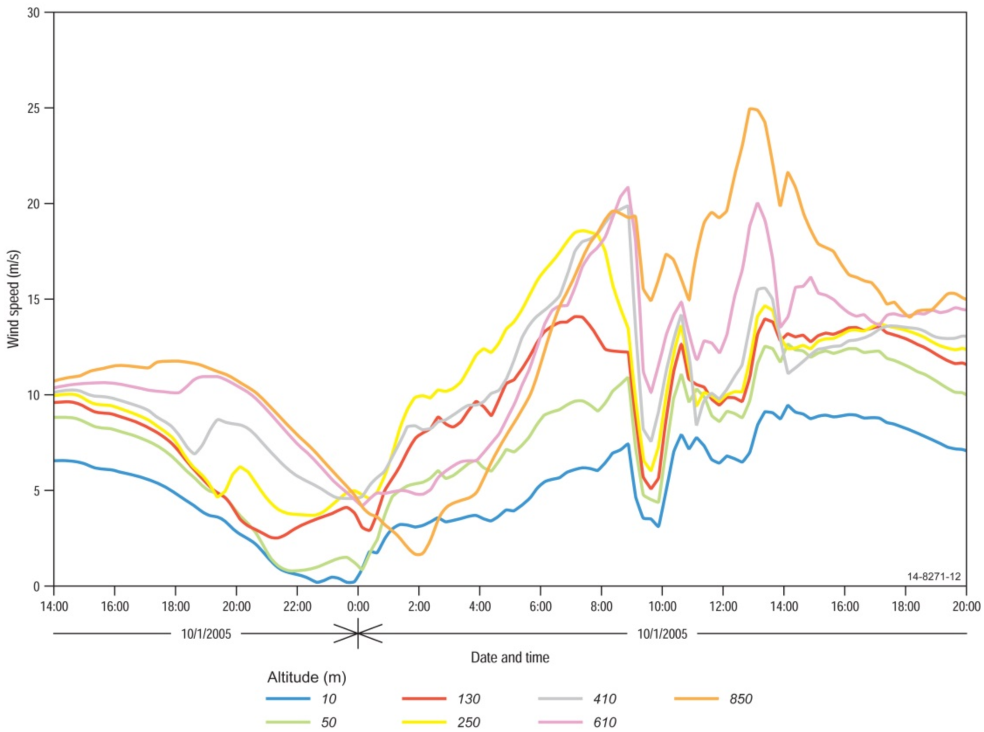

Figure 6.2 Wind speed at altitude (in boundary layer) by time for location -34.5, 135.572

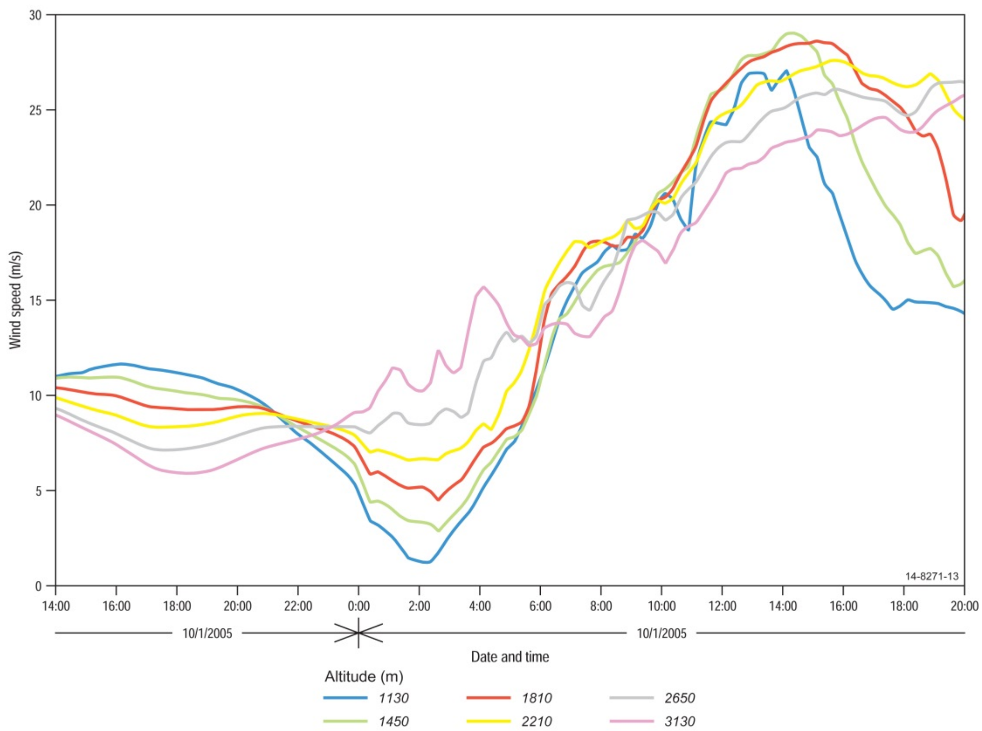

Figure 6.3 Wind speed at altitude (just above the boundary layer) by time for location -34.5, 135.572

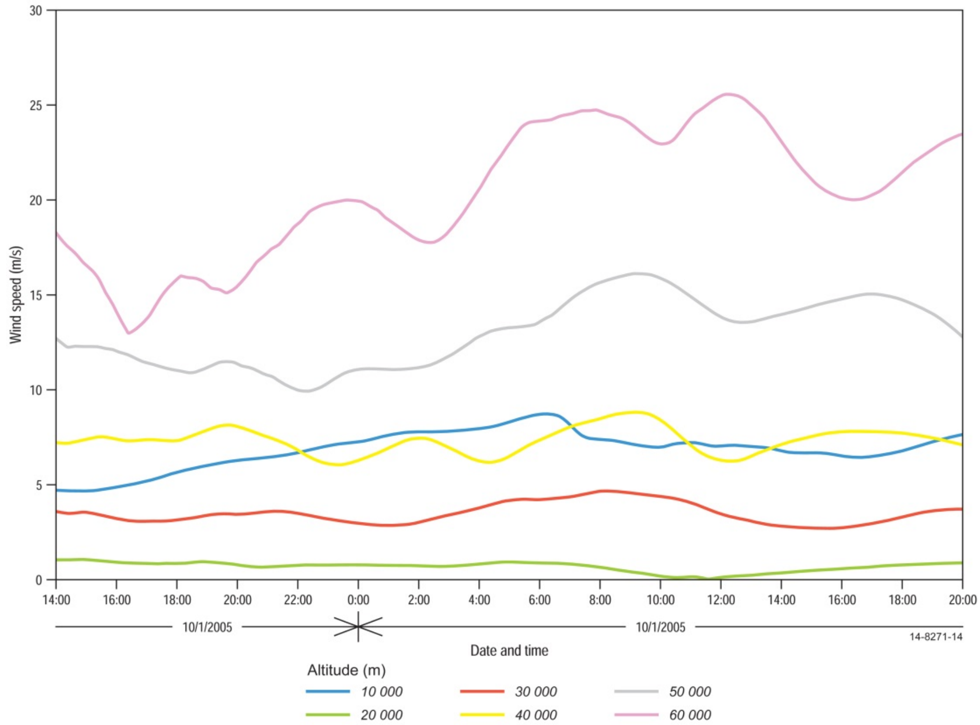

Figure 6.4 Wind speed at higher altitudes by time for location -34.5, 135.572.

Figure 6.5 displays the atmospheric wind speed profile for the first 60 km altitude at (-34.5, 135.572) at 10:30 CDT on 11/1/2005 just before the real fire breakouts. This shows the variation in wind speed as the altitude increases.

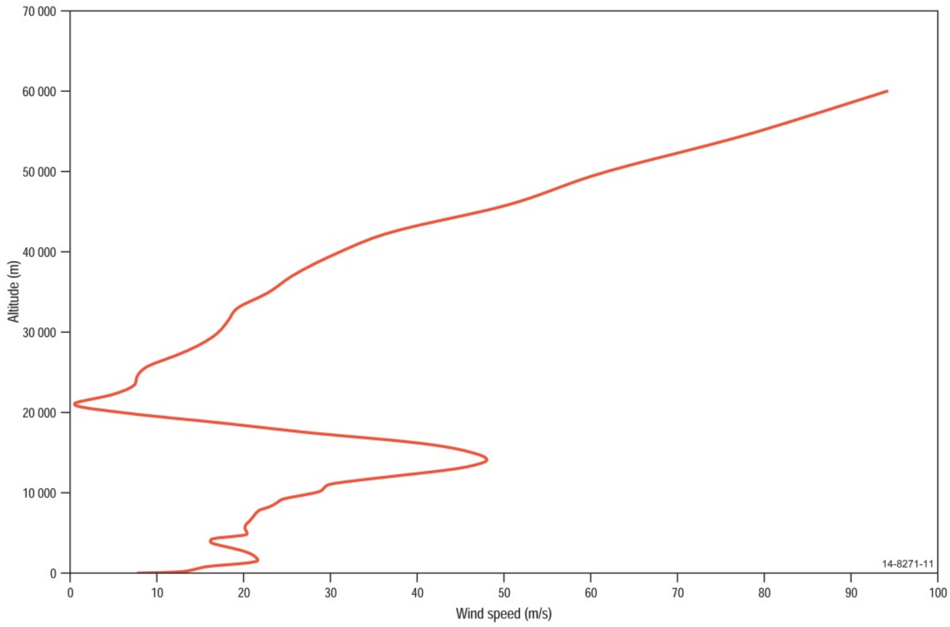

Figure 6.5 Altitude and wind speed for the first 60 km for location -34.5, 135.572.

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 data for temperature, humidity and surface wind speed and direction. Surface winds were both bias corrected and further adjusted using the Wind Ninja local wind modifiers (see Chapter 4). This is the only section in this document where the 15 minute surface weather from ACCESS is used, as the upper level atmosphere was modelled at a 15 minute resolution.

The upper level atmosphere conditions were specified by each of the respective vertical layers in turn. Bias correction of the upper level wind speed, as described in Chapter 4 for surface winds, was not possible for winds in the vertical profile. This is because there was only one historical observation for the Wangary case study.

The fire simulation was halted at 19:45 CDT on 11/1/2005. This time was selected to allow for the simulations to impact with North Shields (where most of the deaths occurred) and to allow for sufficient time after the south westerly change pushed the fire to the north west to simulate as many of the actual buildings destroyed.

The simulations discussed in Section 6.3 assess sensitivity to the vertical layer that was used to define ember transport.

6.3 Results and Discussion

6.3.1 Sensitivity to atmospheric conditions

The results showed little difference between the simulated fire spread using the 10 m weather and that based on winds from levels up to level 39 (29.8km). Figure 6.6 shows a simulation using Level 6 (850 m) where the average wind speed was 11.6 m/s as compared to the 10 m wind speed average of 4.7 m/s (Figure 6.2). With this difference in wind speed over time, simulations might be expected to yield a significantly larger fire spread. However, this was not the case.

It is likely that the reason for the comparative lack of sensitivity of the fire spread to higher wind speeds in the vertical atmosphere is that the predominant modelled fire spread mechanism in the Wangary fire was radiation rather than ember transport. The PHOENIX RapidFire results indicated there was little or no ember transport, and consequently few cells were ignited by embers. This was because most of the vegetation consisted of fairly low growing crops, which do not generate embers like a forest of large trees. The difference in wind between the vertical atmosphere and the surface conditions was not sufficient to impact the radiation significantly. This result is significantly different from that found in the Kilmore case study, where the fire did traverse forest, and significant sensitivity was found (French *et al.*, 2014a).

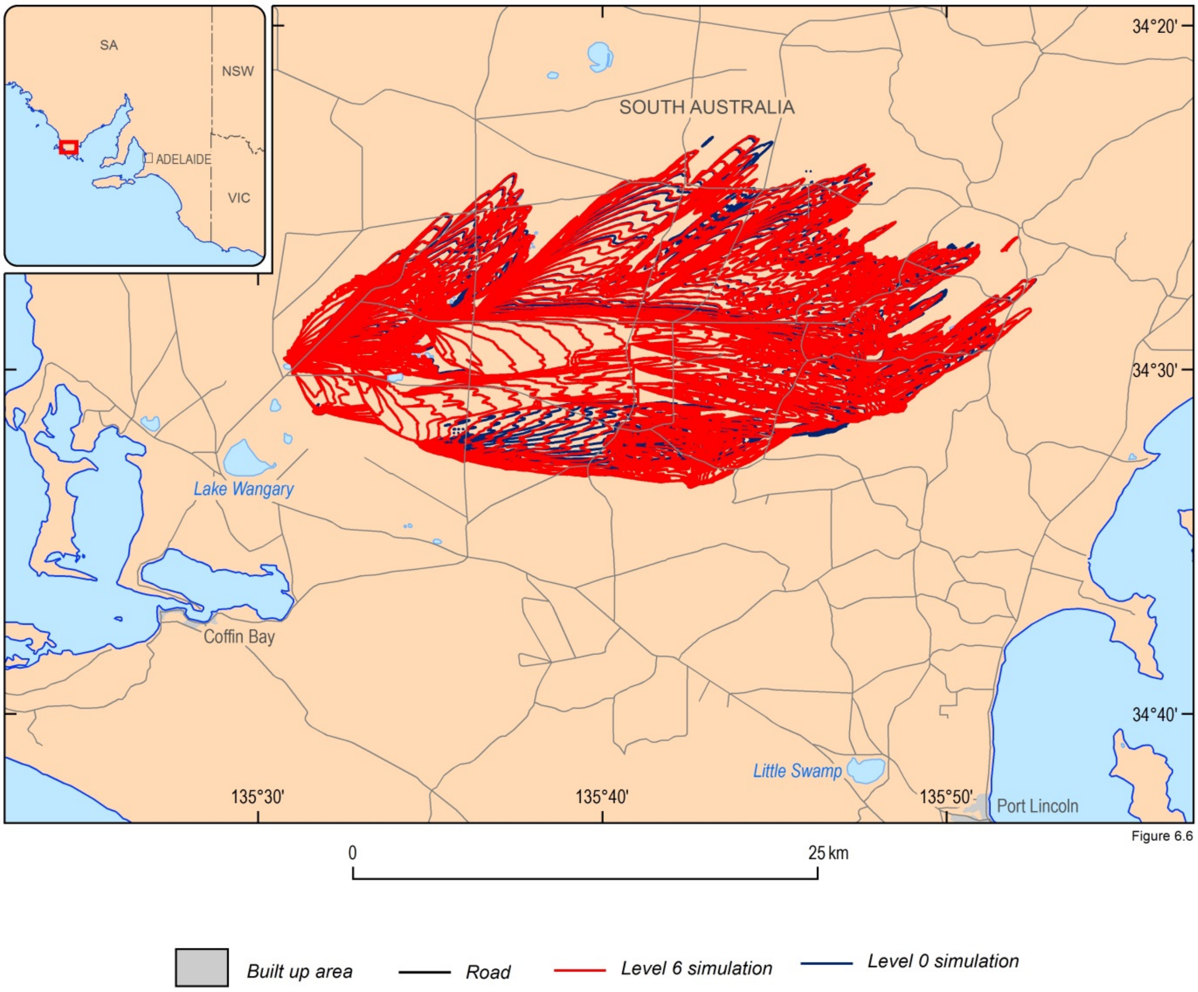

Figure 6.6 Simulated fire spread with transport layer winds based on ACCESS Level 6 (850 m) (red) and level 0 (10 m) (blue).The overlap between the fire shapes is so complete that it is difficult to see any differences.

The winds at level 39 (30 km) in the ACCESS atmosphere were the first that produced a simulation which was significantly different from the simulation based on the level 0 conditions (Figure 6.7). At this altitude, the wind speed and direction over time were sufficiently different from the conditions at the surface to affect the modelled radiation.

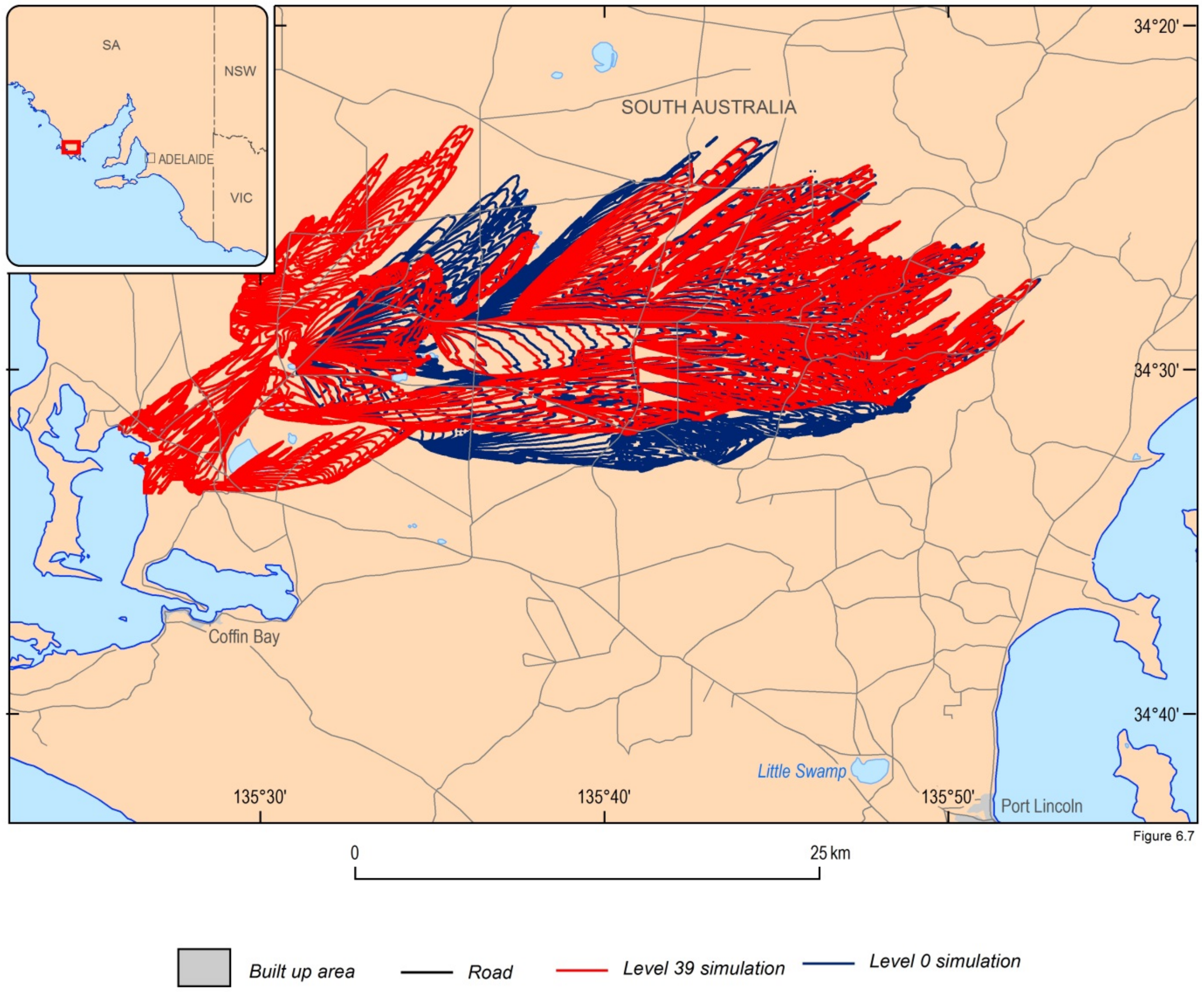

Figure 6.7 Level 39 as the transport layer (red) with level 0 (10 m) as the transport layer (blue).

6.4 Conclusions and Future Work

The work described in this chapter has yielded further insights of the sensitivity of the Wangary fire modelling to the upper level atmospheric conditions. Bushfire simulation has to consider the upper level wind direction, as it drives the transport of fire embers. However, the Wangary fire traversed predominantly grassland (crop) fuel, which generated few embers in the model. The radiation-driven fire spread was shown to be much less sensitive to difference in wind speed and direction.

The results in this chapter demonstrate the benefit of the FireDST approach for investigating sensitivity of fire modelling to uncertainty in model parameterisation. By visualising the variability in model inputs as an ensemble fire spread, the system allows exploring the impact of model parameters and assumptions that interact as part of the modelling of a highly complex physical process.

6.4.1 Future Work

Further work is required to validate and improve the parameterisation of convection and ember transport in PHOENIX RapidFire. The 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 fuel load and fire history. The scope of the vegetation component of the research included varying two PHOENIX Rapidfire parameters that vary fuel load:

- the fuel regeneration curves, and
- 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.

7.2.3 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. 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 10 January 2005, 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

Figure 7.1 shows the fire spread from two simulations where the *r* values (surface only) for temperate grassland, the dominant fuel in the region, were increased by 0.1 and 0.5 to values of 1.3 and 1.7, respectively. The simulated fire shapes that resulted were more extensive than those based on the standard curve (*r* value 1.2). This was because the model assumed higher regeneration, which led to a higher fuel load that produced more radiation, which in turn spread the fire further and faster.

The increased fuel curves resulted in a more accurate fire spread simulation than that based on the best estimate of the historical conditions. This particular sensitivity suggests that fuel could be a significant source of error for the Wangary event. This could be caused by mechanisms such as the following.

- The Wangary fire occurred in a landscape with relatively uniform fuel types. In landscapes with a larger mix in fuel types, bias in particular fuel regeneration curves or the modelled fire spread based on those fuels would be less dominant.
- The dominant fuel types in the Wangary fire are temperate grassland and low crops. The parameterisation of the fuel load does not account for the stage in the growing cycle, where fuel load will vary through the season. For these fuel types, this error is more significant than for, say, forest (Tolhurst et.al 2008b).

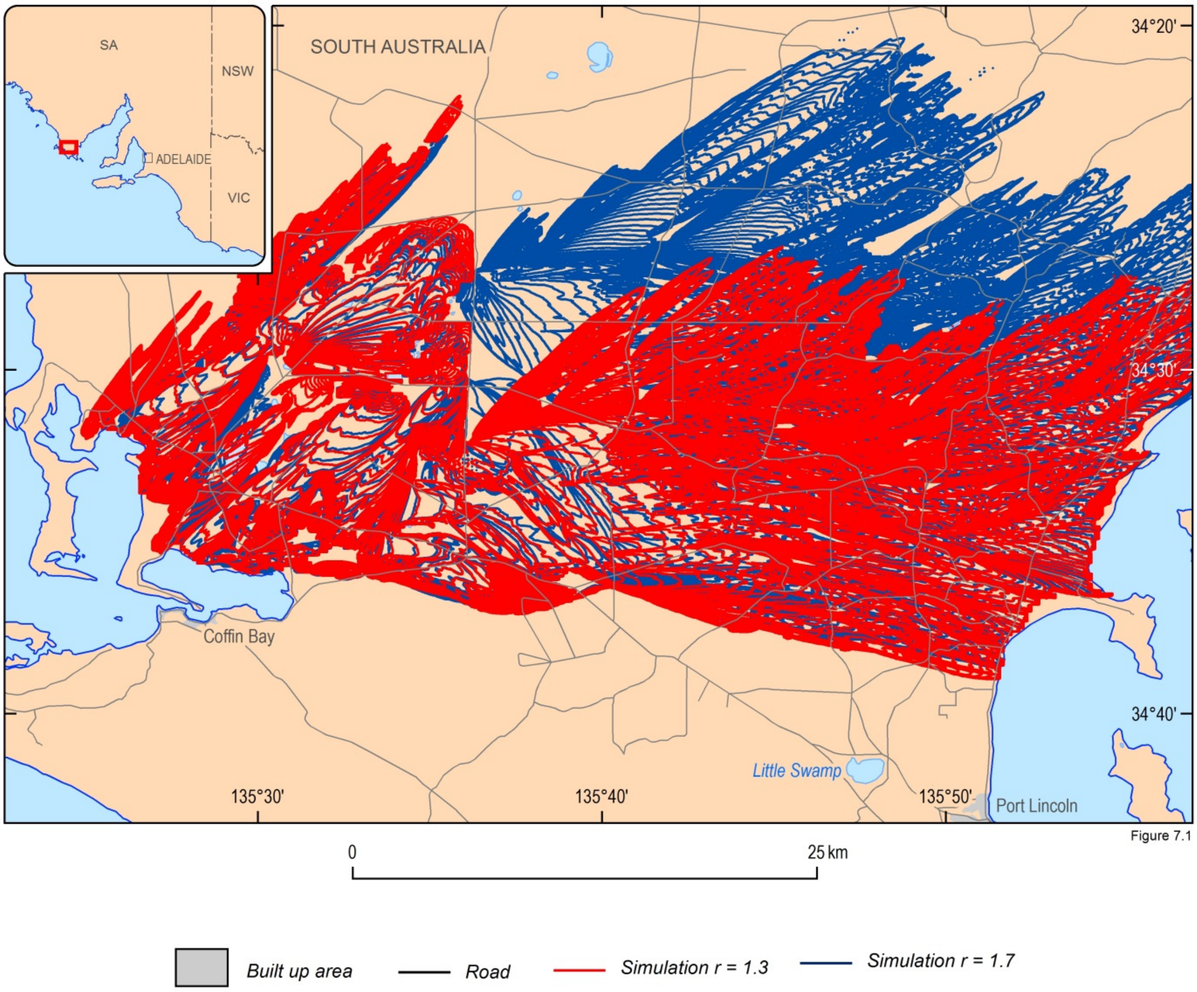

Figure 7.1 The effect of increasing the fuel regeneration curves for the temperate-grassland type to surface r = 1.3 (red) and 1.7 (blue).

7.3.2 Sensitivity to Fire History

Figure 7.2 shows a simulation without including the fuel history. When compared to a simulation using an actual fuel history, this simulation shows a larger burnt area. 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 whole landscape. This translates into a larger fire spread, as shown in the result.

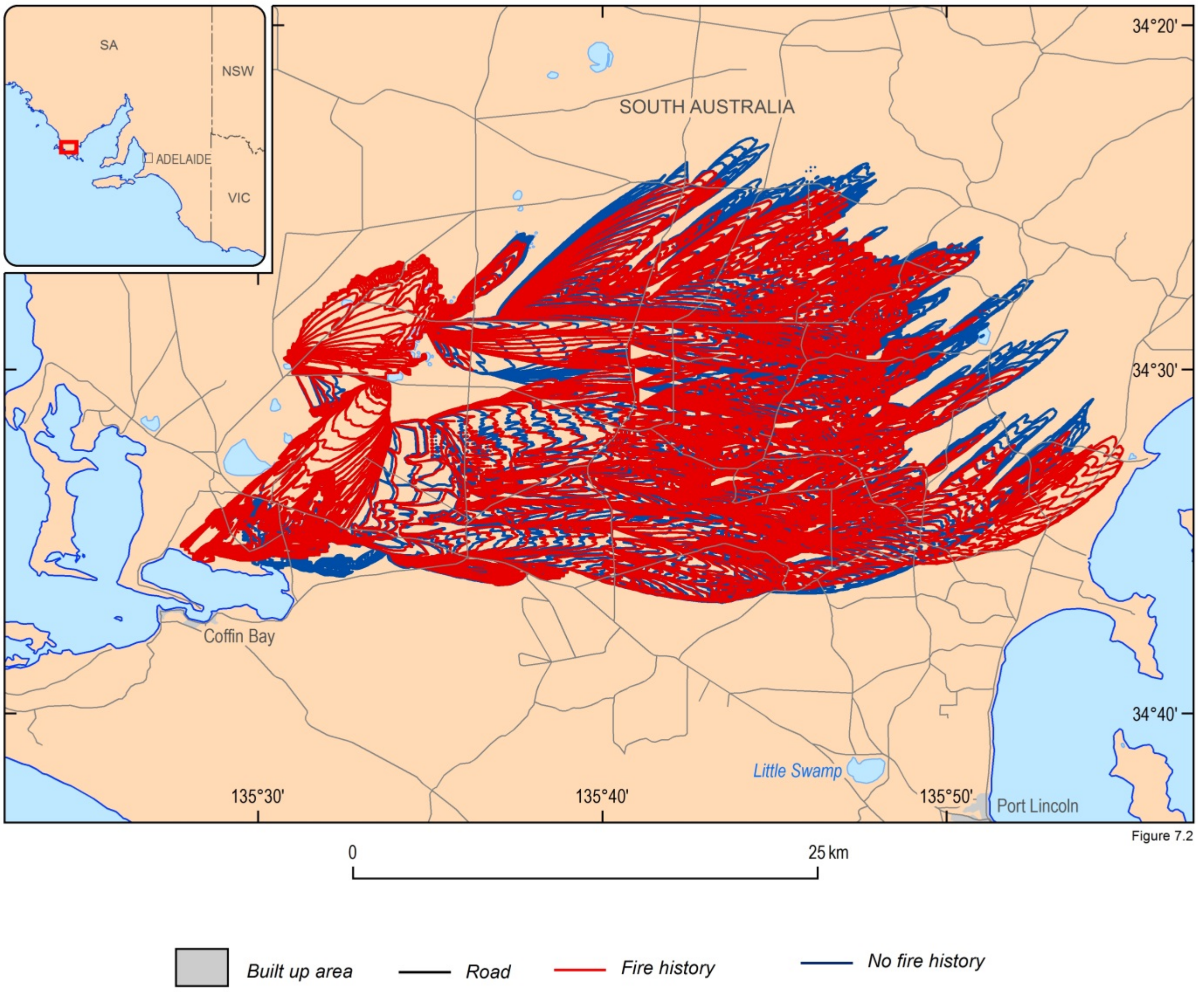

Figure 7.2 Sensitivity to fire history information.

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.

Increased fuel resulted in simulations that were closer to the reconstructed fire. The particular sensitivity to fuel load suggests that fuel-related parameterisation could be a source of error for the Wangary event modelling. The Wangary fire occurred in a landscape with a few dominant fuel types (grassland and crops). Moreover, the fuel load estimation did not account for seasonal effects, which can be significant for crops and grasslands (Tolhurst *et al*. 2008b). As a result, parameterisation errors in fuel load estimation or fire spread for those fuels would significantly affect model accuracy.

7.4.1 Future Work

- PHOENIX RapidFire includes a good method for parameterisation of the regeneration of each fuel type following bushfires. These curves apply globally to the individual vegetation type across the landscape. It is known that the same vegetation type will regrow at different rates based on location specific information (e.g shrubs in a wet gully versus shrubs growing on a dry plateau). Further work could indicate the benefit of including location specific factors that account for these conditions 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 includes:

- Examining the sensitivity to ignition location.
- 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 Wangary event. The ignition time for the historical Wangary event was not well specified (SA Coroner 2007) so 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 and time. 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 in different PHOENIX RapidFire grid cells (180 m).

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

Figure 8.1 shows a comparison of the 200 m north ignition and the 200 m south ignition. Even with only a 200 m variation from the actual ignition location, the two simulations presented variability in the fire spread. The differences could be attributed to the slight differences in the vegetation that each fire consumed.

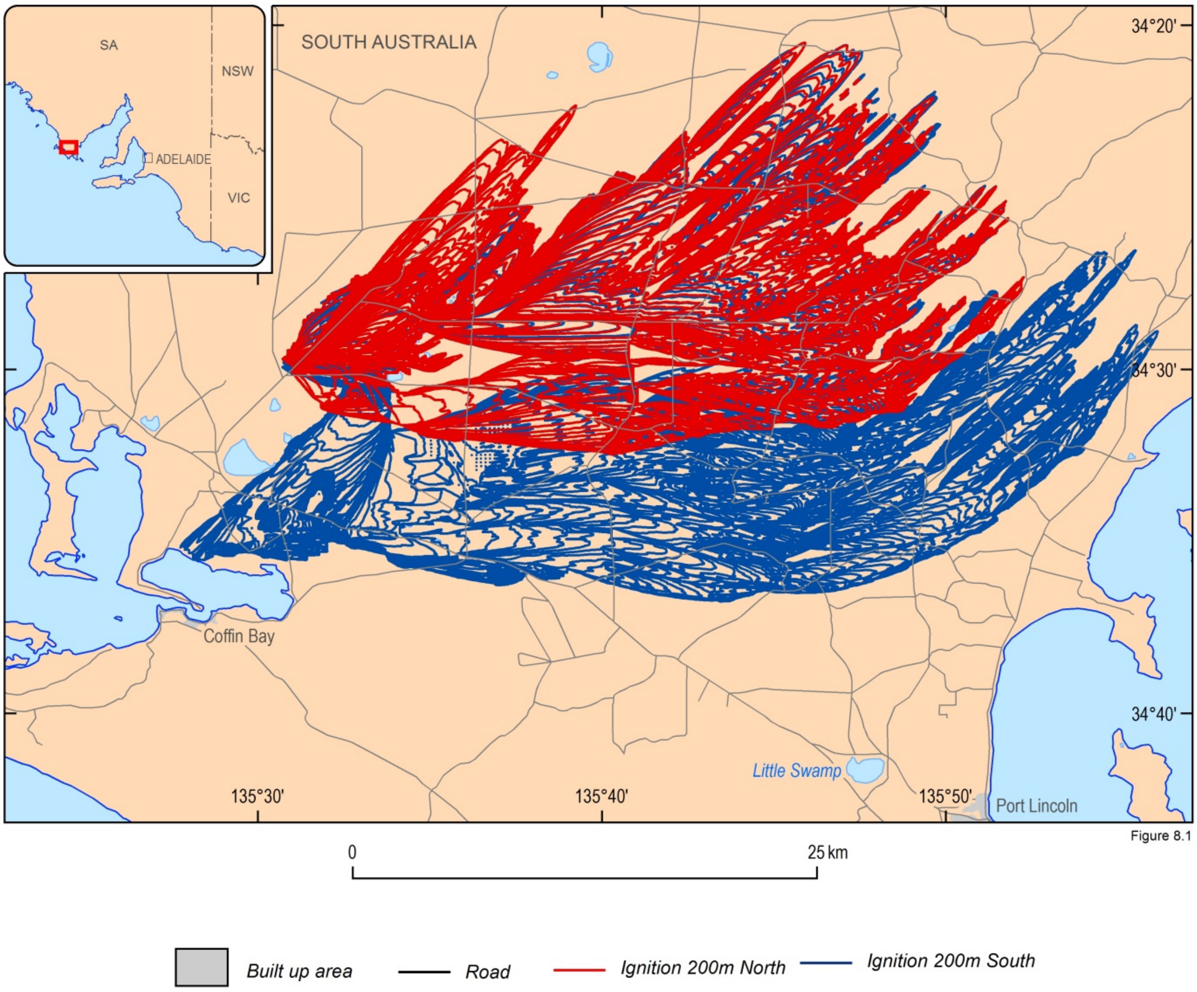

Figure 8.1 Fire spread simulation based on Ignition created 200 m to the south (blue) and 200 m to the north (red) of the Wangary Ignition (using 4000 m 5 minute bias corrected Wind Ninja modified ACCESS winds) to 19:15.

8.3.2 Sensitivity to ignition time

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

None of the simulations (4000 m 5 minute bias corrected, Wind Ninja simulations) showed much change in the simulation shapes when the ignition times for the Wangary case study were varied. Figure 8.2 shows the variation in the fire shape for +/-5 minutes. This lack of sensitivity is likely to be due to the uniformity of the weather over the day. The result also implies that the conditions of the fuel (fuel moisture and curing) were not sensitive to the variability in ignition time.

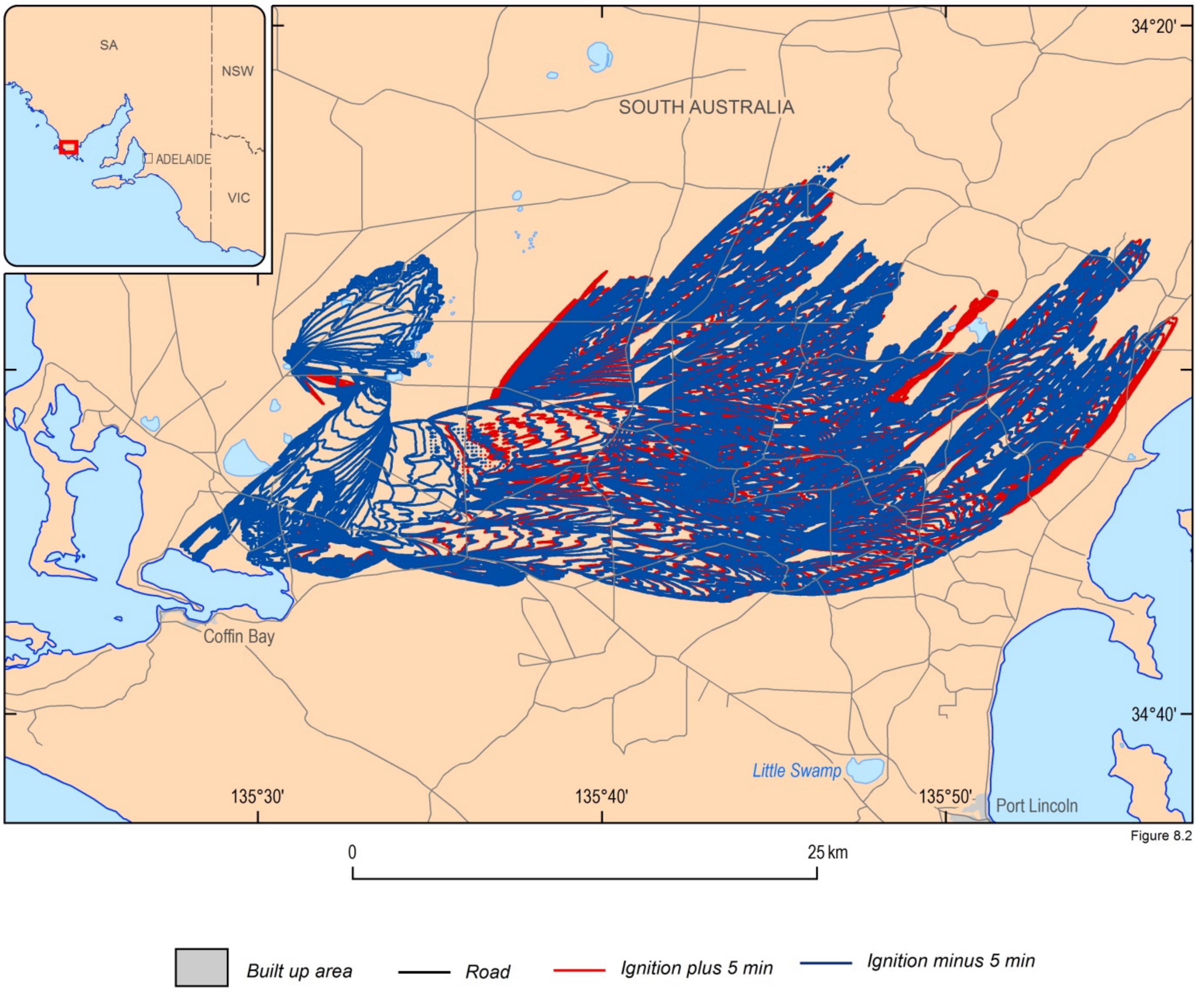

Figure 8.2 Simulated fire spread based on ignition time +/-5 minutes, using 4000 m, 5 minute, Bias Corrected, Wind Ninja ACCESS weather to 19:15.

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 Wangary fire spread was sensitive to a limited extent to variations in the ignition location. Sensitivity to ignition location would be mostly related to the change in the fuel conditions encountered by the fire. There was limited or no sensitivity to changes in ignition time, reflecting the uniform weather conditions during the day.

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

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 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 natural hazard 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 Wangary 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.

	RESIDENTIAL
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 NEXIS demographic/economic information is statistically derived from a variety of sources including the 2006 Census Collection District aggregate information. This means the demographic and economic results are accurate when aggregated, but only an average is available at the individual building level within each Collection District. The version of NEXIS (2011) used for the Wangary Case Study located the house location at the centre of the land parcel in the study area. For larger rural parcels, this is likely to be significantly different from the true location of the building, and could have caused issues with PHOENIX RapidFire not burning the cell around the house correctly because of the different conditions in each 180 m cell.

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 always as 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.

9.3 Results and Discussion

9.3.1 Ensemble fire spread – viewing exposure statistics

Figure 9.1 shows an ensemble fire spread overlaid with building locations. Table 9.1 contains the statistics for the population exposed to the full ensemble fire spread (Figure 4.3). The table shows that 22 people live in the area that is burnt in over 80% of the ensemble scenarios. Table 9.3 shows that there are 18 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.

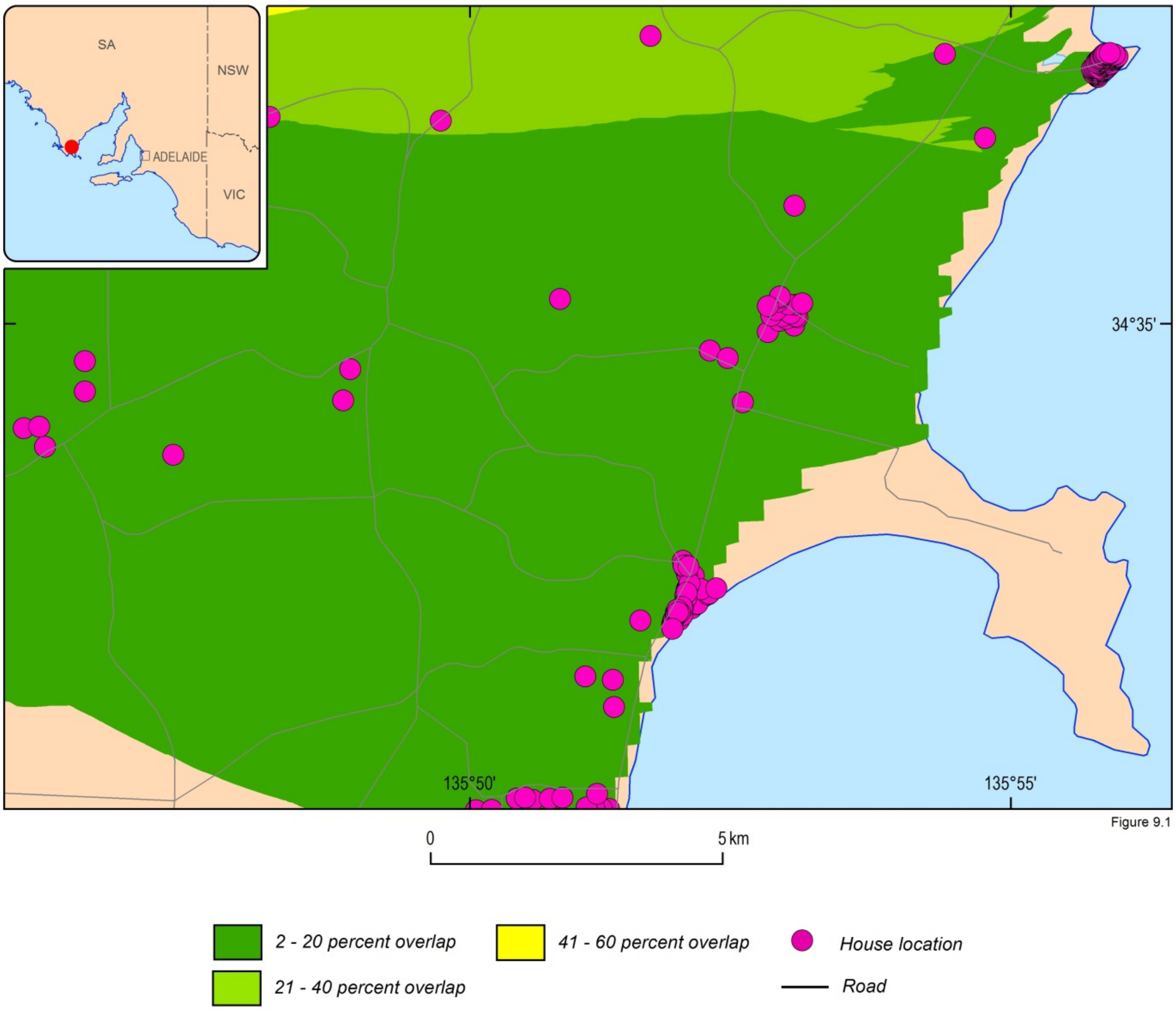

Figure 9.1 Part of the ensemble footprint shown in Figure 4.3 with house locations displayed.

Table 9.2 FireDST people related exposure statistics for the ensemble simulation shown in Figure 4.3.

Ensemble shape impact area likelihood	Number of people exposed	Number of people over the age of 65	Number of people under the age of five	Number of people who need assistance
81-100	22	1	1	0
61-80	2	0	0	0
41-60	7	0	0	0
21-40	4	0	0	0
5-20	21	3	1	1

Table 9.3 FireDST building related exposure statistics for the ensemble simulation shown in Figure 4.3.

Ensemble shape impact area likelihood	Number of houses exposed	Estimated house replacement cost $	Estimated house contents value $
81-100	18	2,968,980	1,121,750
61-80	10	451,473	183,983
41-60	9	1,373,163	553,690
21-40	8	906,081	663,503
<20	12	3,878,900	1,531,740

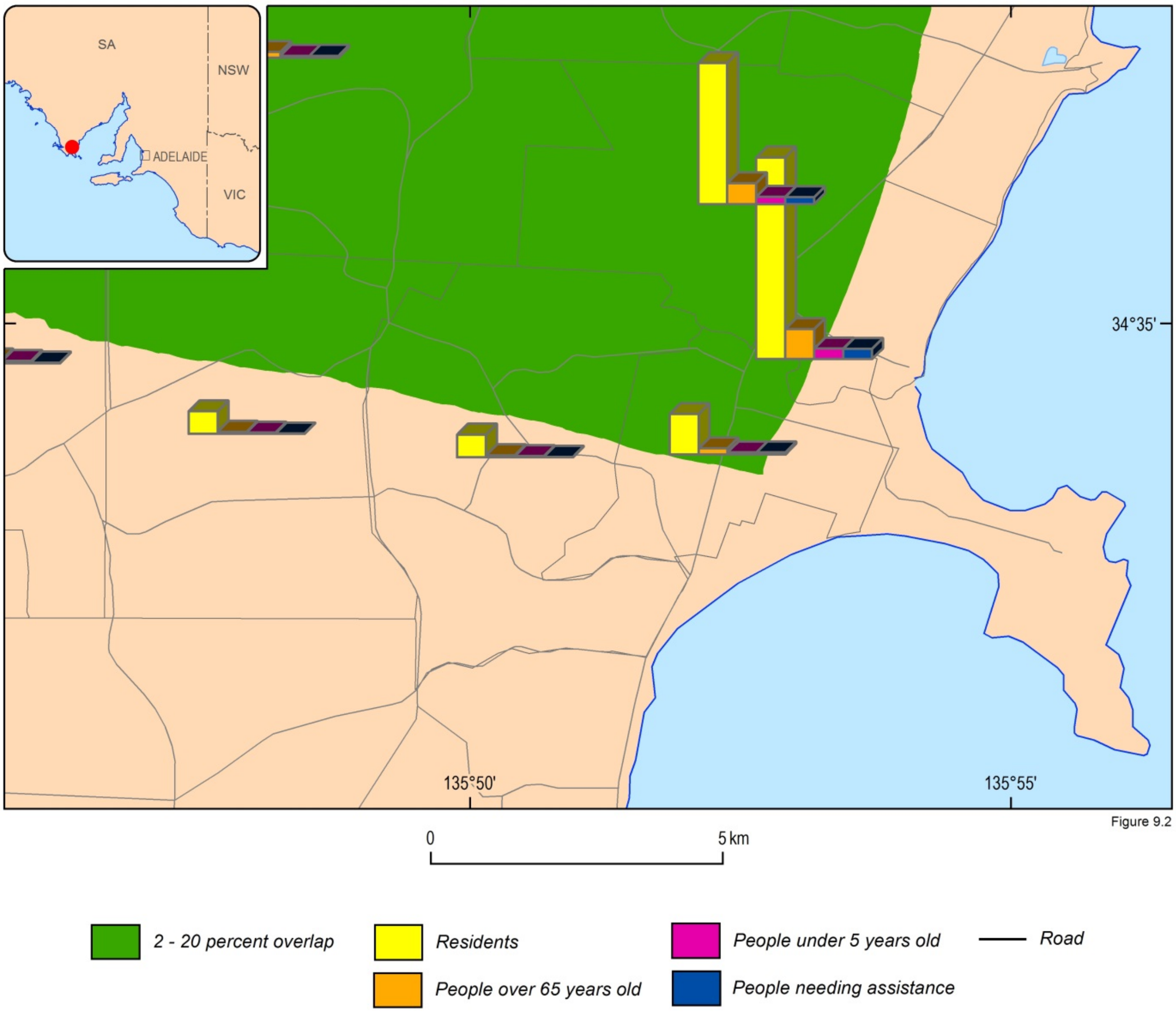

Figure 9.2 Ensemble spread with mesh block statistics displayed for the population in or just outside the ensemble fire spread envelope.

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 database of building and population statistics was developed based on existing information, mainly from Geoscience Australia and the Australian Bureau of Statistics data. 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.

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 red 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.

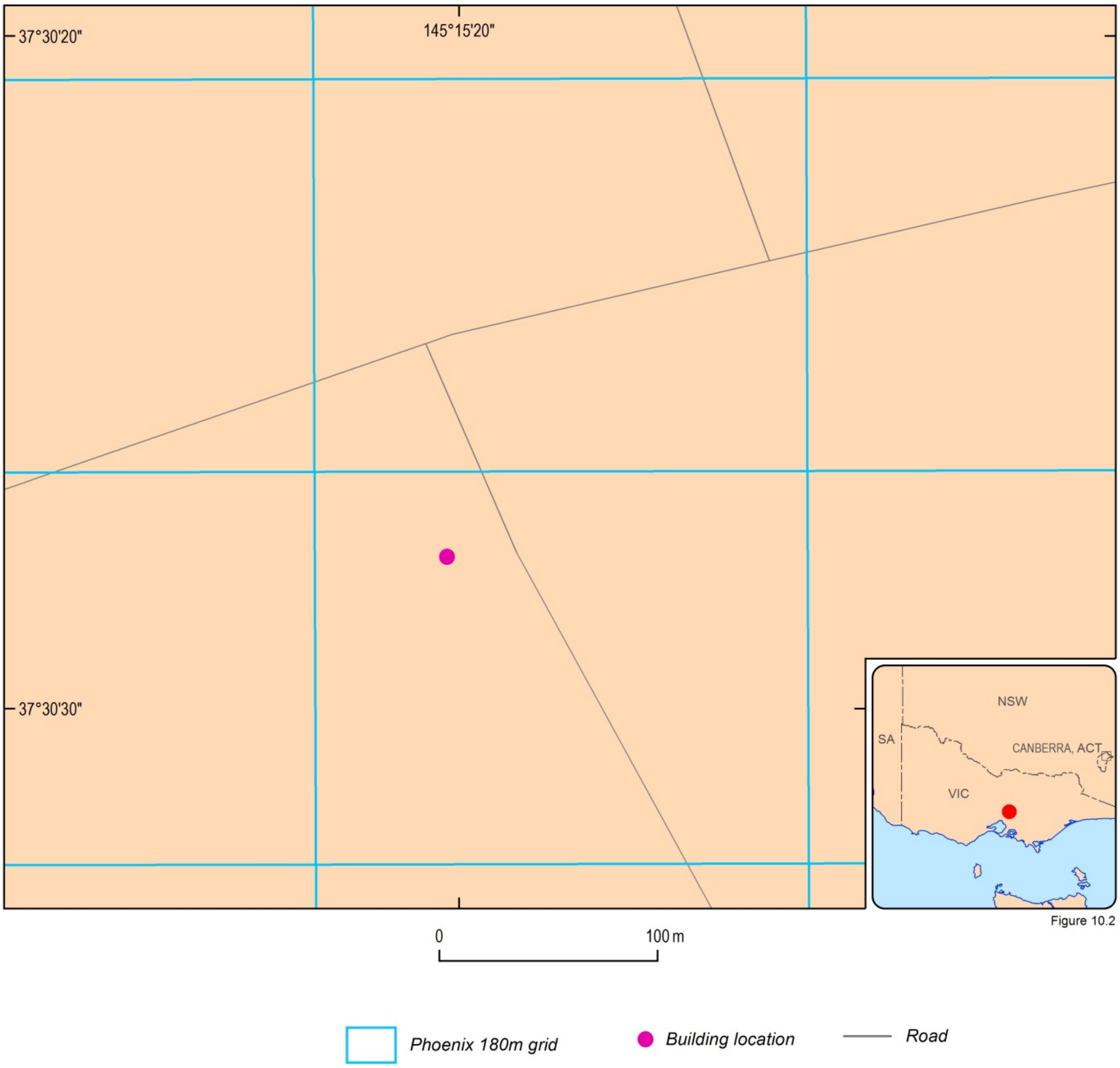

Figure 10.2 Contrast between the resolution of a single building location and a 180 m grid cell. The characteristics of the fire hazard need to be scaled down from the larger grid cell to the resolution of the individual building.

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/m) to the radiation experienced at various distances away from the house (in kW/m^2). 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.

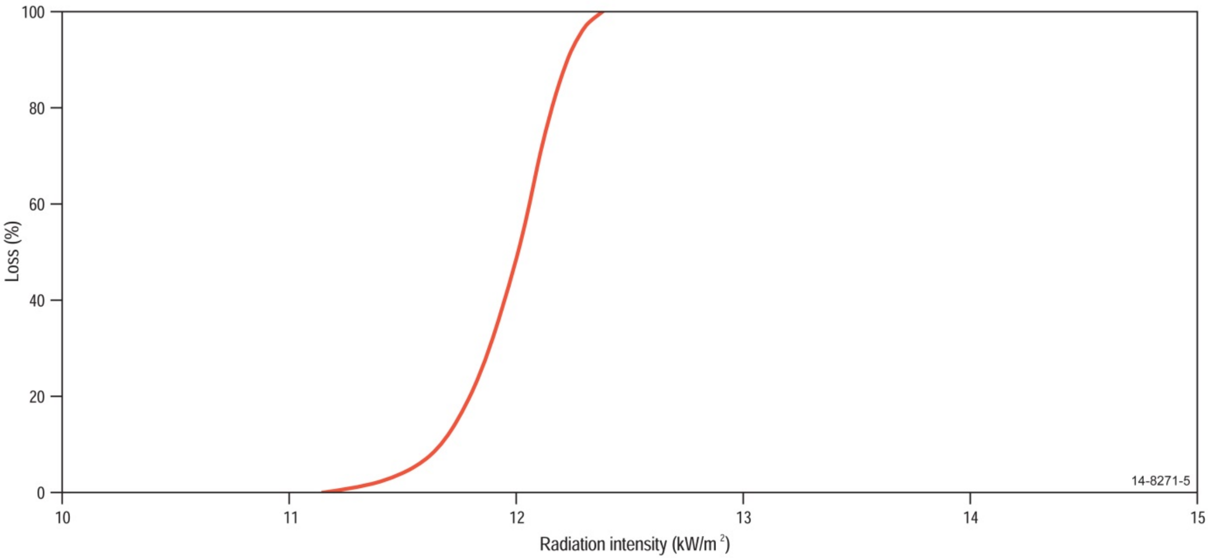

Figure 10.3 House loss as a function of radiation hazard, with total loss modelled at 12.5 KW/m2 of radiation.

The vulnerability curve for radiation hazard (Figure 10.3) reaches 100% loss occurs when the radiation reaches 12.5 KW/m^2, 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 10% (J. Leonard 2011 pers. comm.). Table 10.1 shows the relationship between fuel moisture and the respective vulnerability curves.

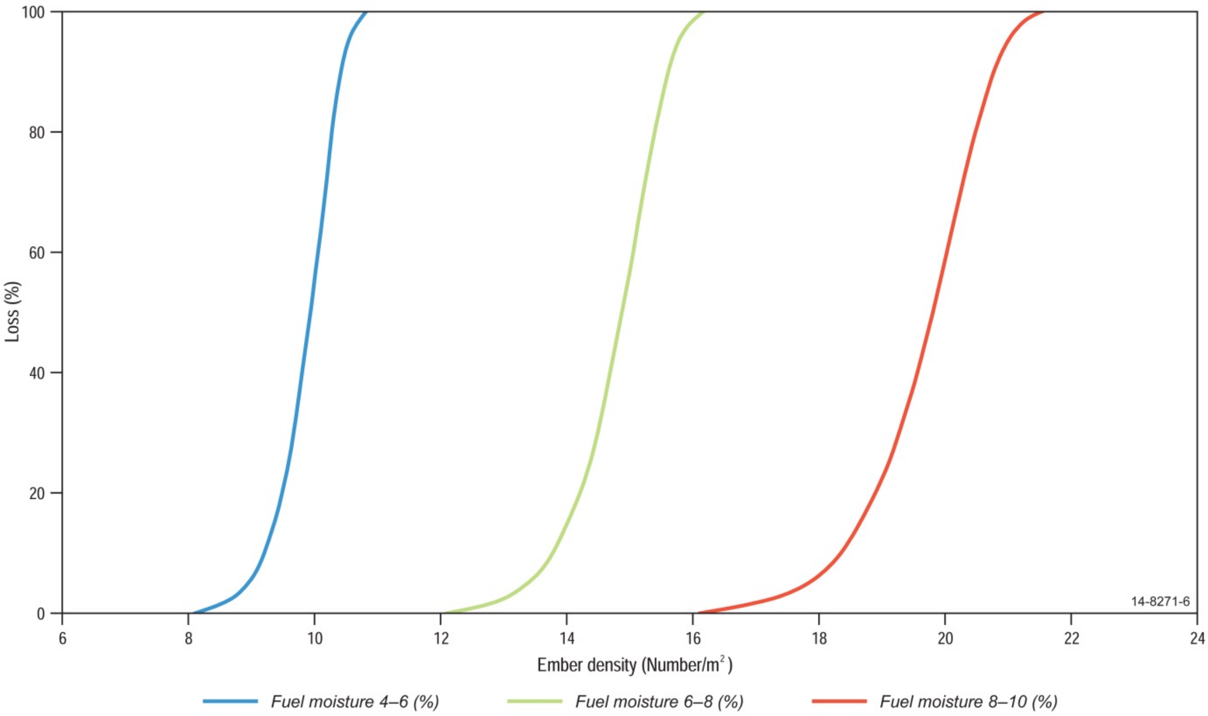

Figure 10.4 House loss as a function of ember density hazard (Number/sq.m.) for (a) 4 to 6% fuel moisture, (b) 6 to 8% fuel moisture and (c) 8 to 10% fuel moisture.

Table 10.1 Relationship between fuel moisture and the vulnerability curve.

Fuel Moisture	Vulnerability Curve
0-4%	House will be destroyed by ember attack, no curve required.
4-6%	4% curve
6-8%	6% curve
8-10%	8% curve
Greater than 10%	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^{o} 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 Wangary fire by comparing actual building damage against the modelled damage. For this experiment, the vulnerability curves specified above were used with 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/m2.

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 Damage 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 in the ensemble 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/m^2, 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% damage to 95% damage in steps of 5%. As the value increases, more buildings would be classed as damaged, rather than destroyed.

10.3 Results and Discussion

10.3.1 Damage Estimation

Table 10.3 shows the impact statistics for the 45 member ensemble simulation in Figure 4.3. The exposure analysis indicates there are 57 houses exposed to the ensemble fire spread envelope (Table 9.2), of which 57 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.

Table 10.3 FireDST Building related impact statistics for the ensemble simulation shown in Figure 4.3.

Ensemble shape impact area likelihood (%)	Number of houses impacted	Estimated house replacement cost $	Estimated house contents value $
81-100	18	2,968,980	1,121,750
61-80	10	451,473	183,983
41-60	9	1,373,163	553,690
21-40	8	906,081	663,503
5-20	12	3,878,900	1,531,740

Based on the ‘best fit’ fire spread scenario and the default vulnerability curves, FireDST achieved an accuracy of 100% for the modelled house loss in the Wangary event (Table 10.4(a)). This high accuracy is a promising result, but still raises potential issues. Only a single set of vulnerability curves was used to model house loss in this case study, which would not capture variability in the response of different house types to the same fire conditions. The Wangary exposure was relatively but not completely uniform. Furthermore, differences in maintenance and sub-grid scale conditions should introduce some variability in the actual fire impact. Variability of damage across neighbouring buildings is characteristic for many impact surveys (Blanchi *et.al* 2006). The 100% accuracy even when the radiation threshold was raised to 40KW/m^2 suggests that the vulnerability of buildings might be overestimated in the Wangary case study. Alternatively, the hazard conditions may have been overestimated.

Modelled impacts across all the simulations showed sensitivity to changes in the radiation vulnerability curve. Table 10.4(b) shows that the highest accuracy (57.5%) was achieved by using the 12.5 KW/sq m curve. The accuracy of houses destroyed against the actual destroyed decreases as the level of radiation resistance increases. These results reflect the interaction between various fire and vulnerability parameters. The fire spread parameters create a range of hazard characteristics, from low intensity fires to high radiation intensity fires, and the range of intensity triggers sensitivity to the radiation threshold in the vulnerability model.

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)	(a) Modelled Accuracy 'Best' Footprint	(b) Average Modelled Accuracy Ensemble
12.5	100	57.5
19	100	47.6
29	100	33.5
40	100	20.3

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 whether 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 sensitivity analysis of using the vulnerabilities in the Wangary fire showed two main results.

- Based on the fire spread that best matched the historical fire, there was an accuracy of 100% in the predicted house loss. Given the known limitations of the modelling approach, this apparently promising result suggests potential issues with overestimation of the vulnerability, or overestimation of the fire hazard in the Wangary fire.
- Ensemble results reflected the interaction between various fire and vulnerability parameters. The fire spread parameters create a range of hazard characteristics, from low intensity fires to high radiation intensity fires, and the range of intensity triggers sensitivity to the radiation threshold in the vulnerability model. Ultimately, the predicted house loss was limited by the accuracy of the fire spread modelling.

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 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.

11 Conclusions from the Wangary Case Study

The results discussed in this report demonstrate the potential of the FireDST methodology for assessing aspects of the sensitivity of modelled fire spread and impact for the Wangary 2005 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 Wangary 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.

Key findings of this work include:

- The modelled fire spread for the Wangary event based on the ACCESS simulations of the surface weather, ignition and fuel at the time did not compare well with the historical fire spread. Apart from the underestimated wind speeds, the parameterisation of fuel load was shown to be a potential source of error in the fire spread modelling.
- The FireDST ensemble approach did generate scenarios that compared favourably with the historical fire. The FireDST ensembles indicated a high likelihood that the fire would break the containment lines early on the 11/1/2005. This demonstrates that an ensemble fire spread can highlight potential scenarios that are realistic, but are not necessarily 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.
- 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.
- The sensitivity of fire spread modelling is not static, but changes between different events, and even within the lifetime of an event.
- As noted above, the scenarios in FireDST are not currently weighted by probability. However, FireDST provides the capability to ingest information on the uncertainty range of input parameters and generate probabilistic fire spread and impact estimates. This indicates the requirement for further work quantifying the uncertainty of input parameters. The benefit of probabilistic outputs over 'pseudo-probabilistic' results includes the ability to interpret the

ensemble in terms of the likely fire spread of an event, to assign a confidence range to the results, and to rank the parameter sensitivity of the model output.

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

The final report of the F.I.R.E-D.S.T. project (Cechet *et al.*, 2014) discusses the Wangary 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 Wangary weather bias correction calculation

Station name	Latitude	Longitude
Cape Borda	-35.755	136.596
Ceduna Airport	-32.13	133.698
Cleve Airport	-33.708	136.503
Coles Point	-34.375	135.374
Edithburgh	-35.112	137.74
Kingscote Airport	-35.711	137.523
Minlaton Airport	-34.748	137.528
Minnipa (PIRSA) Research	-32.843	135.152
Neptune Island	-35.336	136.117
North Shields (Port Lincoln)	-34.599	135.878
Port Augusta Airport	-32.509	137.714
Stenhouse Bay	-35.279	136.939
Wudinna Airport	-33.043	135.452
Whyalla Airport	-33.054	137.52

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.

- WA– Wangary fire
- 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^o Latitude
- GM – Grid minus 5^o 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.

These individual PHOENIX RapidFire simulations make up the ensemble shown in Figure 4.3. The meaning of the scenario labels is given in Appendix B.

Number	Indicator
1	WA_VN_W3600_T05_S0_MN_BC
2	WA_VN_W3600_T15_S0_MN_BC_RHM1
3	WA_VN_W3600_T15_S0_MN_BC_RHM2
4	WA_VN_W3600_T15_S0_MN_BC_RHM3
5	WA_VN_W3600_T15_S0_MN_BC_RHM4
6	WA_VN_W3600_T15_S0_MN_BC_RHM5
7	WA_VN_W3600_T15_S0_MN_BC_TEP1
8	WA_VN_W3600_T15_S0_MN_BC_TEP2
9	WA_VN_W3600_T15_S0_MN_BC_TEP3
10	WA_VN_W3600_T15_S0_MN_BC_TEP4
11	WA_VN_W3600_T15_S0_MN_BC_TEP5
12	WA_VN_W3600_T15_S0_MN_BC_TEP6
13	WA_VN_W3600_T15_S0_MN_BC_TEP7
14	WA_VN_W3600_T15_S0_MN_BC_TEP8
15	WA_VN_W3600_T15_S0_MN_BC_TEP9
16	WA_VN_W3600_T15_S0_MN_BC_TEP10
17	WA_VN_W3600_T15_S0_MN_BC_WDM1
18	WA_VN_W3600_T15_S0_MN_BC_WDM2
19	WA_VN_W3600_T15_S0_MN_BC_WDM3
20	WA_VN_W3600_T15_S0_MN_BC_WDM4
21	WA_VN_W3600_T15_S0_MN_BC_WDM5
22	WA_VN_W3600_T15_S0_MN_BC_WDP1
23	WA_VN_W3600_T15_S0_MN_BC_WDP2
24	WA_VN_W3600_T15_S0_MN_BC_WDP3
25	WA_VN_W3600_T15_S0_MN_BC_WDP4
26	WA_VN_W3600_T15_S0_MN_BC_WDP5
27	WA_VN_W3600_T15_S0_MN_BC_WSP1
28	WA_VN_W3600_T15_S0_MN_BC_WSP2
29	WA_VN_W3600_T15_S0_MN_BC_WSP3

Number	Indicator
30	WA_VN_W3600_T15_S0_MN_BC_WSP4
31	WA_VN_W3600_T15_S0_MN_BC_WSP5
32	WA_VN_W3600_T15_S0_MN_BC_WSP6
33	WA_VN_W3600_T15_S0_MN_BC_WSP7
34	WA_VN_W3600_T15_S0_MN_BC_WSP8
35	WA_VN_W3600_T15_S0_MN_BC_WSP9
36	WA_VN_W3600_T15_S0_MN_BC_WSP10
37	WA_VN_W3600_T15_S0_MN_BC_RHM1_TEP6_WDP3_WSP1
38	WA_VN_W3600_T15_S0_MN_BC_RHM2_TEP6_WDP3_WSP1
39	WA_VN_W3600_T15_S0_MN_BC_RHM2_TEP6_WDP5_WSP3
40	WA_VN_W3600_T15_S0_MN_BC_RHM2_TEP6_WDP7_WSP5
41	WA_VN_W3600_T15_S0_MN_BC_RHM2_TEP6_WDP9_WSP7
42	WA_VN_W3600_T15_S0_MN_BC_RHM2_TEP6_WDP10_WSP5
43	WA_VN_W3600_T15_S0_MN_BC_RHM2_TEP6_WDP15_WSP5
44	WA_VN_W3600_T15_S0_MN_BC_RHM2_TEP6_WDP20_WSP5
45	WA_VN_W3600_T15_S0_MN_BC_RHM2_TEP6_WDP25_WSP5

Appendix D 2006 Census Human Vulnerability Indicators

Table D.1. 2006 Census human vulnerability indicators used in FireDST.

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

Table E.1 FIRE-DST scenarios used for the vulnerability sensitivity assessment.

Number	Indicator
1	WA_VN_W400_T05_S0_M0_BC
2	WA_VN_W400_T15_S0_M0_BC
3	WA_VN_W400_T30_S0_M0_BC
4	WA_VN_W400_T60_S0_M0_BC
56	WA_VN_W1200_T05_S0_M0_BC
6	WA_VN_W1200_T15_S0_M0_BC
7	WA_VN_W1200_T30_S0_M0_BC

Number	Indicator
8	WA_VN_W1200_T60_S0_M0_BC
9	WA_VN_W3600_T05_S0_M0_BC
10	WA_VN_W3600_T15_S0_M0_BC
11	WA_VN_W3600_T30_S0_M0_BC
12	WA_VN_W3600_T60_S0_M0_BC
13	WA_VN_W400_T05_S0_MN_BC
14	WA_VN_W400_T15_S0_MN_BC
15	WA_VN_W400_T30_S0_MN_BC
16	WA_VN_W400_T60_S0_MN_BC
17	WA_VN_W1200_T05_S0_MN_BC
18	WA_VN_W1200_T15_S0_MN_BC
19	WA_VN_W1200_T30_S0_MN_BC
20	WA_VN_W3600_T05_S0_MN_BC
21	WA_VN_W3600_T15_S0_MN_BC
22	WA_VN_W3600_T30_S0_MN_BC
23	WA_VN_W3600_T60_S0_MN_BC
24	WA_VN_W3600_T15_S0_M0_BC_RHM2
25	WA_VN_W3600_T15_S0_M0_BC_RHP5
26	WA_VN_W3600_T15_S0_M0_BC_TEM2
27	WA_VN_W3600_T15_S0_M0_BC_TEP5
28	WA_VN_W3600_T15_S0_M0_BC_WDM10
29	WA_VN_W3600_T15_S0_M0_BC_WDP10
30	WA_VN_W3600_T15_S0_M0_BC_WDP20
31	WA_VN_W3600_T15_S0_M0_BC_WSP5
32	WA_VN_W3600_T15_S0_M0_BC_WSP10
33	WA_VN_W3600_T15_S0_M0_BC_WSP15
34	WA_VN_W3600_T15_S0_M0_BC_WSP20
35	WA_VN_W3600_T15_S0_M0_BC_WSP25
36	WA_VN_W3600_T15_S0_M0_BC_WSP30
37	WA_VN_W3600_T15_S0_MN_BC_WDP15
38	WA_VN_W3600_T15_S0_M0_BC_WDP20
39	WA_VN_W3600_T15_S0_M0_BC_WDP25
40	WA_VN_W3600_T15_S0_M0_BC_WDP30
41	WA_VN_W3600_T15_S0_MN_BC_WDM10
42	WA_VN_W3600_T15_S0_MN_BC_WDP10
43	WA_VN_W3600_T15_S0_MN_BC_WSP5
44	WA_VN_W3600_T15_S0_MN_BC_WSP10

Number	Indicator
45	WA_VN_W3600_T15_S0_MN_BC_WSP15
46	WA_VN_W3600_T15_S0_M0_BC_RHM2_TEP5
47	WA_VN_W3600_T15_S0_M0_BC_RHM2_TEP5_WDM10
48	WA_VN_W3600_T15_S0_M0_BC_RHM2_TEP5_WDP10
49	WA_VN_W3600_T15_S0_M0_BC_RHP5_TEM2_WSP5
50	WA_VN_W3600_T15_S0_M0_BC_RHP5_TEP5
51	WA_VN_W3600_T15_S0_M0_BC_RHP5_TEP5_WDM10
52	WA_VN_W3600_T15_S0_M0_BC_RHP5_TEP5_WDP10
53	WA_VN_W3600_T15_S0_MN_BC_TEM2
54	WA_VN_W3600_T15_S0_MN_BC_RHP5
55	WA_VN_W3600_T15_S0_MN_BC_RHM2
56	WA_VN_W3600_T15_S0_MN_BC_RHM2_TEP5
57	WA_VN_W3600_T15_S0_MN_BC_RHM2_TEP5_WDM10
58	WA_VN_W3600_T15_S0_MN_BC_RHM2_TEP5_WDP10
59	WA_VN_W3600_T15_S0_MN_BC_RHP5_TEM2_WSP5
60	WA_VN_W3600_T15_S0_MN_BC_RHP5_TEP5
61	WA_VN_W3600_T15_S0_MN_BC_RHP5_TEP5_WDM10
62	WA_VN_W3600_T15_S0_MN_BC_RHP5_TEP5_WDP10
63	WA_VN_W400_T05_BC_S0_MN_IW200E
64	WA_VN_W400_T05_BC_S0_MN_IW200W
65	WA_VN_W400_T05_BC_S0_MN_IW200N
66	WA_VN_W400_T05_BC_S0_MN_IW200S
67	WA_VN_W3600_T15_BC_S0_M0_IW200E
68	WA_VN_W3600_T15_BC_S0_M0_IW200W
69	WA_VN_W3600_T15_BC_S0_M0_IW200N
70	WA_VN_W3600_T15_BC_S0_M0_IW200S
71	WA_VN_W3600_T15_BC_S0_MN_TEP5
72	WA_VN_W3600_T15_S0_MN_BC_WSP20
73	WA_VN_W3600_T15_S0_MN_BC_WSP25
74	WA_VN_W3600_T15_S0_MN_BC_WSP30
75	WA_VN_W3600_T15_S0_MN_BC_WDP15
76	WA_VN_W3600_T15_S0_MN_BC_WDP20
77	WA_VN_W3600_T15_S0_MN_BC_WDP25
78	WA_VN_W3600_T15_S0_MN_BC_WDP30

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 (generic set – applied to all houses).

Group	Definition	Comments
VGR	Generic Radiation curve (centred on 12.5 KW)	Uses 12.5 kW/m2 (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 6-8% 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 8-10% 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% in steps of 5%	%	Ember Destroyed Threshold = 50% Distance = 5 m	The Table E.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% in steps of 5%	%	Radiation Destroyed Threshold = 50% Distance = 5 m	The Table E.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 E.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.