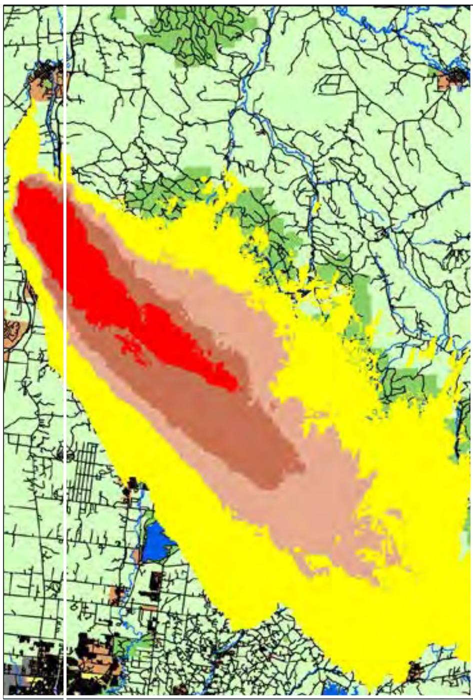

# FIRE IMPACT AND RISK EVALUATION DECISION SUPPORT TOOL (FIREDST)

## FINAL PROJECT REPORT


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Cover: At left, an ensemble view using the Fire Impact and Risk Evaluation Decision Support Tool of the Kilmore East, Victoria, bushfire on 7 February 2009.
At right, the Grampians, Victoria, bushfire in January 2014. Photo by Wayne Rigg, CFA.

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# Executive Summary

The Fire Impact and Risk Evaluation Decision Support Tool (FireDST) project has developed a simulation system that demonstrates it is possible to provide critical fire-planning information to emergency services, government and the public in an integrated system. FireDST is the proof of concept for a software suite that could assist fire managers to make quick decisions in extremely complex situations. In time, a system such as FireDST can help fire managers and incident management teams decide where to direct firefighting resources by simulating the potential impacts a bushfire may have on community assets, infrastructure and people.

To the knowledge of the combined authors and their organisations, the FireDST prototype is the world's first short term (1-2 day) ensemble fire spread and impact system. FireDST simulates multiple individual instances of a fire, each with different variations in the input conditions (such as a slight temperature change). Collectively, the simulations form a so-called ensemble. The individual simulations can be summarised into a single ensemble view of the bushfire event based on their percentage overlap.

FireDST achieves this by processing known information about ignition location, weather (humidity, temperature, wind speed/direction) and vegetation as well as the uncertainties associated with these data. FireDST can be run under predicted weather conditions, and be modified for different scenarios, such as changes to wind strength and direction, ignition location and time, and fuel load and type. In addition, for each scenario in the ensemble, FireDST can predict the likelihood of neighbourhood and house loss, as well as the potential health impacts of bushfire smoke.

The FireDST project has provided fire agencies with a preview of decision support information that could be common practice in future, and has highlighted the development priorities for realising such a capability.

### Translating uncertainty into probability

When the FireDST project started in 2011, fire spread simulation (single scenario) was being trialled for operational application with fire agencies. The science of fire behaviour modelling was empirical and had only been validated on a few case studies. It needed to be rigorously evaluated over a range of event types and severities.

This project has integrated fire spread modelling with three-dimensional, high-resolution fire weather modelling, to strengthen the fire impact assessment. The project approach was to develop a risk-assessment framework where the uncertainty was addressed and captured by presenting the outputs as an ensemble of multiple scenarios. In its current form, FireDST produces a ‘pseudo-probabilistic’ ensemble, because FireDST does not yet specify the likelihood of the occurrence of different scenarios and each simulation is given equal weighting within the ensemble.

Applying an ensemble approach in this way is novel for fire spread modelling but it is accepted practice in the insurance industry in dealing with natural hazard events. Insurance agencies regard the impact of all natural hazards as quantifiable, using actuarial, empirical and stochastic modelling approaches. The FireDST simulation system implemented this industry approach by applying quantity surveying and economic relationships to quantify in dollar terms the impacts from discrete events. FireDST can also estimate the financial impact based on the building loss across a range of simulations based on possible scenarios.

**Advancing the research**

Over a 30-month period, the researchers designed a computational framework and populated databases relating to people, housing and housing vulnerability. This allowed the calculation of event-based statistics on the number of people affected, houses in the impact zone, houses damaged/destroyed, and the potential for the impact of smoke on people.

At the FireDST project's outset, no impact/risk assessment framework and supporting computational platform of this type was known to exist. These are pioneering innovations in fire spread and impact modelling.

All of the computational platform elements (weather, fuel, exposure and vulnerability) were addressed in separate projects within the first seven-year round of the Bushfire CRC (2002-09). This project brought together these elements for the first time – a significant achievement in technical integration. It united researchers from four agencies (Geoscience Australia, Bureau of Meteorology, University of Melbourne and CSIRO). These teams worked across four modelling sub-projects in fire weather, fire behaviour and smoke dispersion, as well as system integration.

The proof of concept for FireDST was based on three case studies that were selected by the FireDST end-user advisory committee and covered a range of terrain, topography and fire severity. The case studies were: Kilmore East bushfire, (Black Saturday) Victoria, 7 February 2009, Wangary bushfire, (Eyre Peninsula) South Australia, 10 January 2005; and Mt Hall bushfire, (Blue Mountains) New South Wales, 24 December 2001. Other bushfires and prescribed burns were modelled in the numerical weather prediction system (ACCESS) and for smoke propagation and have been documented here.

**Pushing forecasting limits**

At the start of the project, the remarkable skill improvements in numerical weather prediction in the past decade had not yet delivered an operational forecast system that could help predict fire behaviour.

The fire weather research challenge was to push the 2010 12 km resolution limits of the Australian operational forecast system, called ACCESS (Australian Community Climate and Earth-System Simulator) to a finer gradation. The project team also sought to analyse and verify the fine-scale wind structures that were important to fire behaviour. This involved building capacity within the Centre for Australian Weather and Climate Research to do very high-resolution (grid spacing < 1 km) historical forecasts (termed hindcasts) of the meteorology of recent, significant fire weather events.

ACCESS has now been run at horizontal resolutions down to 440 metres and temporal resolution information up to every five minutes. It includes the vertical atmosphere at 4 kilometre resolution and 15-minute time steps. This magnified perspective reveals fine details of many small-scale, atmospheric structures that are likely to have an impact on fire spread and intensity. It is important to emphasise, however, that this research model uses computational capacity which is more than 10 times faster than is currently used operationally.

The meteorological information has been modified to produce a more realistic understanding of the local wind affecting the fire spread, using a simplified model that accounted for the effects of terrain and topography. The simplified model reveals the impact these interactions may have on a forest or building – information not previously available.

### Fire Behaviour Modelling Validating PHOENIX RapidFire

The FireDST project utilised the dynamic fire behaviour modelling from PHOENIX RapidFire as it is the only known bushfire simulator that incorporates the fire spotting process as a fundamental component of fire behaviour. FireDST introduced a convection driven spotting process which has been a great leap forward. However, with appropriate programming, any fire behaviour modelling could be integrated into a system such as this. In this project, researchers validated and assessed the simulations from PHOENIX RapidFire.

PHOENIX RapidFire had been developed as part of the original Bushfire CRC research program as a research tool, and it had been applied operationally.

The researchers developed practical mathematical methods to objectively assess the accuracy of fire spread predictions against known outcomes. They used a range of spatial and temporal resolution weather data in PHOENIX RapidFire and quantified the effect on fire spread prediction. They also modified PHOENIX RapidFire to incorporate upper level winds in the ember transport and spotting process.

The research has reinforced the importance of spotting in fire behaviour and its inclusion in the fire spread modelling process. The lack of validation data with regards to the ember transport process has forced a flexible approach within PHOENIX RapidFire where spotting can be dealt with using either surface and/or upper winds in the transport process. The uncertainty in the spotting modelling can be considered explicitly through a multi-scenario approach.

It is now possible to objectively quantify the accuracy of a fire spread prediction and identify and objectively quantify aspects of the prediction that are most in error, such as orientation or extent. New metrics for predictive performance have been developed and published; these will aid future model development and intercomparison efforts.

### Smoke risks to health

Before the FireDST project, research on smoke health impacts addressed only the occupational and health risks to fire fighters and other agency professionals from smoke exposure on the fire ground. The findings are summarised in the Reference Guide published by the bushfire CRC (Reisen & Meyer 2009). There was little information about the risk to regional an urban populations from the transport of smoke from prescribed fires and bushfires or how this impact compared with other risks to health from bushfires.

By analysing three contrasting fire scenarios, the researchers identified the major factors that determined region health risk from smoke exposure. The smoke modelling study established that the impact on rural and urban population health from bushfires can be extreme, but in most cases is manageable. Smoke from protracted and extensive fire events such as the 2006/7 Alpine fires impacted most of the Victoria and SE NSW; 30% percent of the region experienced average concentrations of particulates that exceeded the air quality threshold. Because a large population was exposed for a long period, the mortality risk was high; at a very conservative estimate 84 additional deaths occurred due to smoke exposure, making the smoke impact the major health risk for the event and rivalling the most extreme event on record, the black Saturday fires. In contrast, short lived events, such as the Kilmore East fire on Black Saturday and the autumn regeneration burns in the

Huon Valley, both of which caused substantial public alarm, actually posed negligible health risk from smoke due to rapid dispersion of the smoke plume across regions of low population. The current prescribed burning targets assigned to fire agencies carry the potential for major smoke exposure and health risk for peri-urban and rural populations; however the risk is manageable by careful planning and timing of prescribed burning events.

By developing the modelling frameworks to undertake these analyses the team has put in place reliable methods for (1) predicting emissions, transport, surface concentrations and impact from smoke on rural and urban populations from which (2) new methods for determining the relative significance of potential emission source regions for specified towns, buildings (e.g. hospitals) or horticultural cropping areas (e.g. vineyards) were developed. These techniques allow the development of risk climatologies for defined regions using modelling tools that are currently available to regional managers and planners. (3) The study has also developed methods for addressing uncertainties in smoke transport due to uncertainties in input parameters, particularly the timing an location of the emission sources. This is required for ensemble analysis of risk scenarios.

**FireDST drives broader applications**

Proposed additional applications for FireDST have been suggested during the project including for land use management/planning, determining community vulnerability and education.

It has also driven other potential applications, including advances in fire weather modelling. For example, ACCESS is now being applied to other types of severe weather, such as dust storms and tropical cyclones. The knowledge gained will also guide future operational development of high resolution forecast modelling within the Bureau of Meteorology, including the development of an on-demand, relocatable very high-resolution system to be applied to any impending high impact weather event.

**Where to from here?**

FireDST's proof of concept has been evaluated and its utility as a fire spread and impact simulation system successfully demonstrated.

The researchers have suggested some key steps to implementing an operational system, (i.e. software, underpinning datasets, governance, etc.).

The next challenge is the operational implementation of this new technology. More work is needed with the fire agencies to define a business case for predictive models such as FireDST and a sustainable implementation plan that includes further research, training and field trial validation. A national collaborative effort among Australian fire agencies is clearly required.

Fire weather modelling's next challenges include developing small-scale weather identification tools or techniques into operational forecast products.

For PHOENIX RapidFire, further work is needed in areas such as a more comprehensive fire suppression model to link with the fire propagation model, more well-documented case studies, and further testing and validation of fire behaviour models.

For emissions dispersion, the remaining issues include the need for accurate models and verification of plume rise, and improved emissions models that accurately account for coarse woody debris. The measurement and validation of emissions from bushfires are also priorities.

As a prototype, FireDST has already revolutionised fire simulation modelling. The methodologies developed in the project promise to be an invaluable asset to fire managers working under pressure to make quick decisions that affect lives and infrastructure. Operational fire decision support models could conceivably produce continually updated simulations of severe fire events which address the uncertainty in the input parameters (including the assimilation of fire ground intelligence and real-time performance statistics relating to the fire weather predictions). These simulations, developing products relating to fire spread and impacts, could provide valuable decision support for emergency management.

FireDST, through its case studies, has demonstrated significant gains in providing information for fire event decision support. But fire agencies face a steep learning curve in dealing with ensemble information which attempts to capture the outcome sensitivity by considering the uncertainty in model inputs. The development of a national approach to fire spread and impacts, as well as standardisation and consistency with the underpinning datasets, would help enable all fire managers to become accustomed to 'what if' scenarios that are expressed in ensemble terms, and to allow transparency in utilisation, validation and learning’s across state boundaries.

# End-user Summary

The FireDST ‘proof of concept’ has enabled fire agencies to begin considering the uncertainty associated with modelling wildfires and their impacts. The capability of scenario modelling with ensemble outcomes for fire spread and smoke, as well as their impacts on people and the built environment, clearly signifies a paradigm shift within the emergency management (EM) sector, which currently employs deterministic (single-scenario) hazard modelling approaches that do not consider potential impacts. This project makes a major contribution to fire agency ‘community safety' objectives; the outcomes support the preservation of life and the reduction of impacts on buildings and infrastructure threatened by bushfires.

The FireDST research team has had significant impact and influence in the EM sector both nationally and internationally. The project has gained international recognition for its development of an ensemble simulation system focusing on the spread and impact of extreme fires. Across all collaborators, the project produced over 25 peer-reviewed papers, over 35 reports, six magazine articles, and two videos, as well as being showcased at major EM and fire science conferences, with posters, presentations and information booths reaching many thousands of people. The FireDST team has demonstrated innovative products and services that we hope EM stakeholders will consider routine in 5-10 years.

The FireDST ‘proof of concept’ builds on the significant advancements in each of the key areas investigated (fire weather, fuels, building vulnerability, exposure databases) indicating a robust future for this research. The inclusion of this research into operational systems is a priority as end-users need to have a reliable simulation system and an operational understanding of uncertainty. Critically, support for FireDST, or similar simulation systems, is needed on a national level to be sustainable. This support should address further development, training, data standards and validation, as well as comprehensive documentation.

David Youssef and Ralph Smith

Lead end-users, FireDST end-user advisory committee

The Fire Impact & Risk Evaluation Decision Support Tool (FireDST) project was advised by an eight-member advisory committee that met eleven times during the course of the project. The advisory committee members were:

*Lead End users:*

| | |
|---|---|
| David Youssef | Deputy Chief Fire Officer, Regional Director South East Metro Region<br>Metropolitan Fire and Emergency Services Board (MFB), Melbourne, Victoria |
| Ralph Smith | Manager, Environmental Protection Branch<br>Department of Fire and Emergency Services (DFES), Western Australia |

*End-User members of advisory committee*

| | |
|---|---|
| Liam Fogarty | Department of Environment & Primary Industry, Victoria |
| Dr Simon Heemstra | New South Wales Rural Fire Service |
| Mark Chladil | Tasmanian Fire Service |
| Fergus Adrian | Queensland Rural Fire Service |
| Mike Wouters | Department of Environment and Natural Resources, South Australia |
| Lyndsey Wright | Research Manager, Bushfire CRC |

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# Research Questions

The fundamental question that the project sought to address is: ‘What are the impacts and risks of extreme fire events on regional populations and infrastructure in Australia?’ This project aimed to produce a decision support system that will enhance evidence-based decision making. Research questions were:

(1) What is the sensitivity of extreme fire behaviour to particular atmospheric conditions or states, specifically fine-scale three-dimensional wind flows over complex terrain? How are local weather conditions influenced by topography during extreme fire events?

(2) What is the sensitivity of the PHOENIX RapidFire fire characterisation model to detailed meteorology, and can uncertainties in its model predictions be quantified and communicated?

(3) What are the sensitivities of the current fire-hazard and fire-impact models to current fuel classifications? Are the current fuel definitions appropriate for accurate fire characterisation; are current spatial databases of biomass fuels and fuel properties adequate and what are the options for improving them? What is the potential in the near-term for application of remote sensing technology to spatial mapping of fuels?

(4) Can urban interface design be described at a neighbourhood level, so that potential house loss during a given scenario can be adequately predicted? Can urban interfaces be usefully mapped by remote sensing or otherwise so that the fuel levels and proximity can be used in both fire behaviour and house loss modelling?

(5) What are the requirements of a comprehensive and up-to-date spatial database of values and assets to be accessed prior, during and after bushfire events?

(6) What are the impacts on air quality from smoke emitted from extreme fires? How does this compare with the impacts from prescribed burning? What are the risks to population health from exposure to smoke from both sources? How effective and accurate are current models of smoke emission and dispersion in describing the vertical and horizontal distribution and concentration of smoke? What are the options and requirements for developing them into operational tools for planning and incident control?

(7) How do we integrate the research components that address the questions above to produce a tool that assesses the potential impact of fire on specific community values and assets (specifically life, human health, and housing) in relation to fire weather, fuel conditions and fire characteristics?

(8) How will the tool address the needs of end-users and fellow researchers? How will their input improve the development of the tool, e.g., through continuous development addressing several ‘what if’ case study scenarios?

## Table of 'Outcomes vs. Aims'

| AIM | OUTCOME (1) | OUTCOME (2) |
|---|---|---|
| (1a) Determine the sensitivity of extreme fire behaviour to particular atmospheric conditions. | The sensitivity of PHOENIX RapidFire predictions to varying nine weather, terrain and fire ignition inputs and parameterisations was evaluated and reported. Specific simulation configurations of high sensitivity, including the interaction of wind direction and slope and ignition time and location were highlighted for further investigation. | PHOENIX RapidFire was modified to include a 'transport layer' wind as well as a new 'bubble' convection column and ember transport mechanism. This new version was more accurate in reproducing all the case study fires. |
| (1b) Include detailed topography in local weather conditions. | The hindcasts of the meteorology of the case studies have included topography appropriate to the various grid spacings, particularly at very high resolution, with consequent large increases in the extent of the small-scale atmospheric detail resolved in the simulations. | The Wind Ninja and Geoscience Australia's Wind Multiplier methods (down to 100m horizontal resolution) were applied to the wind strength files in ACCESS. Simulations produced using these multipliers were more accurate in both shape and direction than for simulations utilising the raw ACCESS weather forecasts. |
| (2a) Define the sensitivity of the PHOENIX RapidFire to detailed meteorology. | The surface wind strength forecast in the ACCESS model were lower than field observations and were unsuitable for reproducing fire spread comparable to observations. | There is an improved evidence base to understand the sensitivity of PHOENIX RapidFire to meteorology modelled at various resolutions and with different approaches, including bias correction and Wind Multiplier modification. |
| (2b) Identify, quantity and communicate uncertainties in model predictions. | FireDST demonstrates a graphical display of the ensemble fire spread and impact based on underlying fire scenarios that have been established sampling uncertainties in the information available about the fire. | Three case studies have demonstrated examples of potential value of the FireDST ensemble output in conveying information on the robustness and sensitivity of model predictions. |
| (3a) Identify the sensitivities of the current fire hazard and fire impact models to fuel classifications. | PHOENIX RapidFire prediction results were insensitive to changes in grass fuel load and varied in direct proportion to changes in forest fuel load. | PHOENIX RapidFire sensitivity studies were conducted on fuel classification and fuel properties, demonstrating a useful methodology for considering the role of fuel within fire spread. |

| AIM | OUTCOME (1) | OUTCOME (2) |
|---|---|---|
| (3b) Explore whether the current fuel definitions are appropriate for accurate fire characterisation. | PHOENIX RapidFire achieved realistic results (fire spread) for the case studies evaluated. Further evaluation is needed on the adequacy of fuel classifications. | |
| (3c) Determine whether current spatial databases of biomass fuels and fuel properties are adequate (options for improving them?) | Fuels were evaluated for the case study areas only. The quality of mapped fuels is the subject of further research. | |
| (4a) Determine whether urban interface design can be described at a neighbourhood level, so that potential house loss during a given scenario can be adequately predicted. | A strong correlation was found between potential house loss and the 'power' of the fire, particularly in areas subjected to the fire's convective footprint. | Implementation of the Building Fire Impact Model (BFIM) demonstrated the potential of an integrated methodology that extends impact modelling to account for sub-grid scale processes determining building loss. |
| (5) Determine the requirements of a comprehensive and up-to-date spatial database of values and assets which can be accessed prior, during and after bushfire events. | The project developed a database of population and building assets and values. The database relied on information sourced from the Geoscience Australia NEXIS building database and population information at the mesh block level from the 2006 Census. The database was essential in deriving statistics of exposure as well as simulated impact. | Understanding of the limitations of existing data sources, for example highlighting the need for the asset database to include correct building locations, and also outbuildings (such as garages, water tanks and sheds) so that correct shielding factors could be generated for wind damage and house to house fire spread (in the BFIM). |
| (6a) Determine and map the impacts on air quality from smoke emitted from extreme fires. | Emissions from the three scenarios were modelled and mapped. The 2006 NE Victoria fire event had a major urban and rural impact, in contrast to the Kilmore East fire where the smoke plume mostly dispersed in the troposphere with little surface impact. | |
| (6b) Determine and quantify how bushfire smoke impacts compare with prescribed burning impacts. | High intensity prescribed burning and intense wildfires have similar impacts. Most smoke is injected into troposphere and doesn't impact the surface. Most impacts occur at night (mixing depth diminishes) and previous emissions in plumes are mixed to the surface; new emissions are retained at surface. | Significant population impacts occur only when plume strike occurs on regional centres. This is uncommon, and hence health risks are relatively low. |

| AIM | OUTCOME (1) | OUTCOME (2) |
|---|---|---|
| (6c) What are the risks to population health from exposure to smoke from both sources? | Large forest fires of long duration have the potential to pose major risks to urban and region populations. | Risk associated with large fires can be mapped considering a multi-scenario (ensemble) approach to smoke production and human health impacts. |
| (6d) How effective and accurate are current models of smoke emission and dispersion in describing the vertical and horizontal distribution and concentration of smoke? | The current models available in Australia and internationally were reviewed. The Australian models CCAM, TAPM and CTM were found to be appropriate. These models provided excellent agreement between predicted and observed surface concentrations of PM2.5 and other air pollutants. | LiDAR observations, and sensitivity analysis of prescribed plume rise scenarios indicated that for most occasions, setting plume rise to the current atmospheric mixing depth provided the best agreement between observed and predicted surface concentrations of PM2.5 . |
| (6e) What are the options and requirements for developing them into operational tools for planning and incident control? | Chapter 4 discusses the potential to apply the modelling tools applied in the F.I.R.E-D.S.T. project for operational purposes. | A technical report describing how to configure and run the CSIRO dispersion model TAPM for several practical applications has been prepared by Meyer and Cope (2013) |
| (7) Integrate the research components that are being provided by the collaborators within FireDST to produce a tool that assesses the potential impact of fire on specific community values and assets (specifically life, human health, and housing) - in relation to fire weather, fuel conditions and fire characteristics | FireDST provides the proof –of-concept for a tool that can compute exposure and impact statistics for buildings and residents. FireDST derives the exposure and simulated impact buildings and people from a simulated fire spread. | The FireDST system provides the proof of concept for integration of fire spread, smoke and health impact modelling by producing smoke concentration contours that FireDST can overlay on the population to determine the smokes effect on human health. |

| AIM | OUTCOME (1) | OUTCOME (2) |
|---|---|---|
| (8a) Determine how FireDST will address the needs of end-users and fellow researchers. | FireDST has been used at the direction of our end-user advisory committee to produce outputs for:<br>• active fire management and risk assessment<br>• land management and<br>• land planning<br>FireDST end-users have indicated several other areas where FireDST could be used :<br>• exposure and impact prediction,<br>• human factor research (eg go/stay scenarios),<br>• building standards (eg revising for Embers),<br>• bushfire simulation model effectiveness<br>• cost benefit analysis<br>• education | |
| (8b) Document how collaborator input has improved the development of FireDST, e.g., through continuous development addressing several 'what if' case study scenarios. | There has been close contact with the End User Group to provide feedback on the development of FireDST.<br>Several workshops on FireDST have been held during the development with operational staff from Queensland, New South Wales, Victoria and Western Australia. Feedback from these workshops has been incorporated at all stages of the FireDST development. | The FireDST team has improved the development of FireDST by close collaboration in:<br>• improving PHOENIX RapidFire fire spread simulator (e.g., input ACCESS weather & extra model outputs & vertical plume modelling)<br>• vulnerability curves<br>• interaction between PHOENIX RapidFire and BFIM.<br>• integration of the individual research areas into a working proof-of –concept system.<br>• Refining smoke dispersion models and to display results as an ensemble |

# Glossary

**area difference index** – a 'critical failure' ratio, indicating the amount of area incorrectly predicted as a proportion of that correctly predicted.

**automatic weather station (AWS)** – a set of meteorological technologies for the automated real-time monitoring of surface meteorological conditions, including but not limited to dry-bulb air temperature, wet-bulb air temperature, atmospheric pressure, and wind speed and direction.

**building vulnerability** – see 'vulnerability'.

**bushfire** – an established fire in landscapes with a combination of forest, scrub country and grass vegetation, the fuel therefore being woody for a significant area in the fire impact zone.

**Bushfire CRC –** Bushfire Cooperative Research Centre. See www.bushfirecrc.com.au.

**ensemble** - a set of simulated scenarios of a bushfire event, each describing a slightly different realisation of the event.

**exposure** – elements within the landscape (people and buildings) that are open to damage and danger, and risk suffering loss in a natural hazard event (bushfire considered here).

**fire behaviour modelling –** modelling of the physical processes involved in a bushfire, such as the McArthur Grassland Fire Spread Model.

**fire hazard** – the state of combustion in which inflammable material burns, producing heat, flames, and often smoke (burning may occur through direct flame, radiant heat and/or ember attack).

**fire relative risk** – fire relative risk is defined within this report for a single event, scenario simulation or ensemble scenario simulation, as the relative risk at one location relative to another location (used to describe geospatial plots of fire risk [to people and buildings] across the landscape).

**fire risk** – risk is generically defined as the uncertainty of loss. Fire loss is usually measured as number of deaths and injuries or dollars of property damage, but includes significant intangible losses such as business interruption, mission failure, degradation of the environment, and destruction of irreplaceable cultural artefacts.

**fire weather** – weather conditions (wind, temperature, humidity, rainfall and lightning) that influence fire ignition, behaviour and suppression.

**forecast** – in NWP, an atmospheric prediction covering a temporal period which is partially or entirely in the future at the time at which the prediction is made.

**forecast skill** – in NWP, an objective measure or metric of how good a forecast (or set of forecasts) is. Forecast skill is often described in relation to 'reference' or 'base-line' forecasts (e.g., 'unskilled' and 'perfect' forecasts).

**forest fire danger index** – an index proportional to the modelled rate of spread of an established forest fire, scaled with respect to an estimate of 'the near worst possible fire weather conditions that are likely to be experienced in Australia' (Luke and McArthur, 1977), those conditions giving an index value of 100. It takes in estimates of present or future weather (air temperature, wind speed, relative humidity) and fuel dryness (via the drought factor). It gives guidance on the difficulty of suppressing established forecast fires under prevailing weather conditions.

**grassfire** – a fire in open country where grass is the predominant fuel.

**hindcast** – in NWP, an atmospheric prediction covering a temporal period which is entirely in the past at the time at which the prediction is made.

**numerical weather prediction (NWP)** – the prediction of future atmospheric states by means of comprehensive modelling of the fluid flow of the atmosphere.

**scenario** – a single instance (or simulation) of the fire that uses a specific set of input conditions such as weather or fuel state.

**short-term –** duration of one to two days.

**simulation –** using a computer to simulate the fire spread using a fire behaviour model.

**verification** – in NWP, the comparison of a forecast or hindcast against observational data which are not used in the preparation of the initial state from which the forecast is derived.

**vulnerability** – in the context of this project, vulnerability was defined as the susceptibility of a structure or person to the impact of fire as a consequence of the physical and environmental factors or processes (e.g. direct flame, radiant heat and/or ember attack). Throughout this report the term 'vulnerability' is used rather than 'susceptibility'.

**wildfire** – a bushfire or grassfire, especially one which is out of control.

**wind change** – in meteorology, a temporary or enduring change in the direction of the wind, either at the surface or aloft. Wind changes can have significant impacts on fire behaviour, can change narrow-fronted fires into broad-fronted fires, and can represent a significant source of risk for fire-fighters.

The reader is referred to the following sites for more extensive glossaries relating to fire terms:

U.S. National Fire Protection Association - Glossary
http://www.nfpa.org/press-room/reporters-guide-to-fire-and-nfpa/glossary

WIKIPEDIA - Glossary of wildfire terms
http://en.wikipedia.org/wiki/Glossary_of_wildfire_terms

WIKIPEDIA - Glossary of firefighting
http://en.wikipedia.org/wiki/Glossary_of_firefighting

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# 1. Introduction

This **F**ire **I**mpact and **R**isk **E**valuation **D**ecision **S**upport **T**ool (**FireDST**) project final report is a high-level overview document, which provides a summary of activities and outcomes from the project. In addition, it also provides a roadmap which links the many project deliverables with the overall project goals. This will allow readers to understand the links between a wide range of project milestones across the sub-teams and disciplines. This report details those links and also the major outcomes from each deliverable, while omitting many details contained within the original material.

The FireDST project was envisaged as a demonstration of how uncertainty could be expressed within fire spread modelling whilst also considering the consequences (impacts) of a range of scenarios associated with any particular event. At the commencement of this project, fire spread modelling was being trialled for operational application with some fire agencies. Fire spread modelling was based on empirical science, and had been validated on relatively few case studies in Australia. While it was evident that fire spread modelling can deliver great benefits to underpin decisions in an operational context, it was less clear how the uncertainties inherent in such model outputs should be treated.

The aim of the FireDST project was to explore whether fire spread scenarios based on uncertainty can convey information that is not given by 'best estimate' deterministic model outputs. Probabilistic multi-scenario information is successfully used in weather forecasts, and the FireDST team aimed to assess whether this approach might similarly deliver valuable information in the fire response context. The project used case studies to demonstrate a 'proof of concept' for a range of information generated by this approach. By using an integrated approach to visualise both the uncertainty in the fire spread as well as in the consequences of a fire, the outputs of the FireDST project allow stakeholders to scope a next generation in decision support tools.

The FireDST project was composed of five sub-projects (listed below) undertaken by different organisations:

- Risk Assessment Decision Toolbox (Geoscience Australia),
- Enhancement of fire behaviour models (University of Melbourne),
- Enhancement of weather predictions under extreme conditions (Bureau of Meteorology),
- Regional and local impacts from bushfire smoke dispersion (CSIRO Marine and Atmospheric Research),
- Enhancement of local impacts – Vulnerability parameterisation (CSIRO Ecosystem Science).

This report details the research questions addressed by the research team and their status at the end of the three-year project. The research plan for the project is detailed in the FireDST Science Plan (delivered October 2011). This document was one of the first outputs from the project and it outlines the roles and scientific material being examined by the different parts of the project. It also briefly examines the scope of work and its importance to the 'big picture' with regards to understanding uncertainty and developing a simulation system that provides both event and ensemble information on fire spread, exposure and impact to inform incident decision support. In summary, these are the main areas of research that were addressed by the five sub-projects:

- University of Melbourne
    1. Enhancement of PHOENIX RapidFire to consider the three-dimensional meteorology,
    2. Enhanced fire suppression within PHOENIX RapidFire,
    3. Vegetation mapping and properties.
- Bureau of Meteorology
    1. Development of a high-resolution numerical weather prediction (NWP) capability,
    2. Examination of how sub-scale phenomena can be parameterised (for NWP),
    3. Sensitivity of extreme fire behaviour to weather.
- CSIRO Marine and Atmospheric Research
    1. Development of a high-resolution smoke dispersion model,
    2. Examine health impacts of bushfire smoke.
- CSIRO Ecosystem Science
    1. Examination of the impact of the local environment on house survivability,
    2. Vulnerability parameterisation relating hazard (radiation, ember-attack) to house loss.
- Geoscience Australia
    1. Computational risk assessment framework,
    2. Simulation system (linking outputs from the other four sub-projects as well as databases with building and socio-economic information),
    3. Spatial mapping of fire weather from observations as well as reanalysis output.

The project was managed by Geoscience Australia.

Work undertaken on the 'Enhancement of local impacts – Vulnerability parameterisation' by CSIRO Ecosystem Science is not included in this final report.

FireDST has been developed and validated using data of the conditions experienced in three significant bushfires.

1. the Kilmore East bushfire in Victoria on Black Saturday (7 February 2009);
2. the Wangary bushfire in South Australia (Eyre Peninsula) on 10 January 2005; and
3. the Warragamba/Mt Hall bushfire in New South Wales on Christmas Day 2001.

These fires were selected as case studies as they encompass a range of terrain and topography, fire severity and complexity of extreme fire weather. The Kilmore East 2009 fire event was a fast-moving forest fire, the Wangary/Eyre Peninsula 2005 fire event was a fast moving grass fire, and the Warragamba/Mt Hall 2001 fire event was a slow/moderate moving valley fire within complex topography that escalated as it was affected by 'out of valley' synoptic wind flows. 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 house loss and people likely to be affected by smoke inhalation).

The FireDST project, with the assistance of the Bushfire CRC, is making all material associated with the project (such as papers, reports, posters, videos and PPT presentations) discoverable via two different media:

(1) Bushfire CRC FireDST website http://www.bushfirecrc.com/projects/2-1/FireDST

(2) USB drive (a copy available on request; details inside front cover).

NOTE: FireDST is a ‘proof of concept’ simulation system, constructed for developing and validating outputs related to scenario and ensemble fire spread as well as the exposure and impact associated with the scenario/ensemble assessment of the fire spread. In its current form, FireDST is a research product and is not suitable for operational applications.

## 1.1 FireDST – Project Research Leaders

| | |
|---|---|
| Project Leader: | Bob Cechet (Geoscience Australia) |
| Technical integration: | Ian French (Geoscience Australia) |
| Fire Behaviour Modelling: | Dr Kevin Tolhurst (University of Melbourne) |
| Fire Weather: | Dr Jeff Kepert (Bureau of Meteorology) |
| Smoke Composition and Dispersion: | Dr Carl (Mick) Meyer<br>(CSIRO Marine and Atmospheric Research) |

## 1.2 FireDST – Overview (Geoscience Australia)

The Council of Australian Governments (COAG 2002) recognised that Australia needed to develop and use sophisticated fire modelling techniques as an aid in the prevention and mitigation of bushfires. The last few decades has seen the development of computerised wildfire spread models. Models such as PHOENIX RapidFire (Tolhurst *et al.,* 2008) in Australia, FireSite (Finney, 1998), FlamMap (Finney, 2006), WFDSS (Wildland Fire Decision Support System) - FSPro (Fire Spread Probability Model) (McDaniel, 2007) in the USA, and Prometheus, the Canadian wildland fire growth simulation model (Tymstra *et al.,* 2009) are all able to assimilate information on the terrain, vegetation load and type, built features and weather predictions to produce a single graphical output of the progress of the fire. These models, which are calibrated against how past fires have typically progressed, consider: vegetation type; terrain and topography; a fire's perimeter; and air temperature, wind, and humidity. They then model where a fire will go, and when it will arrive at a certain location.

While the science underpinning these models continues to advance, the nature of fire processes is inherently complex. Besides limitations in our understanding of the fire process and our ability to capture this in a computer model, the input data in such models will always contain error. As a result, outputs from fire spread models contain uncertainty, as is the case for all complex numerical models. It can be very difficult for users of such models to gauge the uncertainty of the model output. Yet users have to understand how robust the output is. Would the predicted fire spread be significantly different if the input parameters were changed within the margin of known error? This could significantly influence decision making based on model outputs.

One of the main aims of the project was to develop a 'proof of concept' system that produces an ensemble fire spread that could visualise this uncertainty and thereby provide essential information to fire managers. The system was designed to allow users to project uncertainties in the input data in the form of an ensemble fire spread. Additionally, the system would go beyond fire spread modelling, and estimate the potential impacts of the fire. Part of the project involved developing a framework for such a system that conforms to internationally and nationally recognised impact modelling standards. The 'Quantitative Bushfire Risk Assessment Framework for severe and extreme fires' (Jones *et al.,* 2012) was then implemented to enable computational evaluation of bushfire impact and risk.

FireDST is a bushfire impact and risk simulator that aims to support an understanding of the risk to people and infrastructure, with the ultimate aim of providing information which enables decision makers to prioritize emergency management resources. The FireDST system is built from modules that each apply significant research undertaken as part of this project. The key results of this work are described in the subsequent chapters in this report. This section gives an overview of the FireDST system and in doing so illustrates how the work described in the respective chapters in this report links together to achieve the objectives of this project. Figure 1.1 displays the information flow to produce a FireDST simulation.

The core of the FireDST functionality is built around its ability to model a fire spread and estimate the fire's impact. Weather information is a major driver for the fire spread modelling. The Bureau of Meteorology's ACCESS (Australian Community Climate and Earth-System Simulator) (Puri *et al.,* 2011) numerical weather prediction (NWP) simulation outputs specify temperature, relative humidity, wind speed and wind direction at 10 m height, and at 4000 metre, 1200 metre, and 440 metre grid spacing and five-minute time steps[1]. For this project, the Bureau of Meteorology also supplied a simulated vertical atmosphere profile at the 4.0 kilometre grid spacing and 15-minute time steps which included the horizontal wind speed/direction and vertical wind speed at 50 levels.

The FireDST system uses PHOENIX RapidFire (developed by the University of Melbourne) to run simulations of the fire based on the weather. PHOENIX RapidFire modifies the wind speed to account for the local terrain/topography using the Wind Ninja system (Forthofer *et al.,* 2009) or wind multipliers (Yang *et al.,* 2014). The vegetation used in FireDST as fuel input for the fire spread modelling is the standard vegetation model used by PHOENIX RapidFire, specified at 25 m to 100 m resolution depending on the Australian peri-urban location. The Digital Elevation Model data used in this project were generally between 5 and 30 m horizontal resolution.

One of the key differences between FireDST and many other fire spread simulation systems is its ability to create multiple scenarios of possible fire spread. FireDST creates 'ensembles' of fire spread scenarios by applying variations to the modelling input parameters or modelling assumptions. For example, the Fire DST Weather Ensemble Generator produces different scenarios of weather that are variations on the 'best estimate' provided by the ACCESS model. The fire spread and impacts are then modelled for each scenario. Similarly, the Ensemble Fire Generator generates scenarios with modifications to the specified ignition points, fuel type, load or curing, or building characteristics.

Considering how the modelled fire spread changes when the input weather, fuel load or ignition point is modified across the ensemble gives clear insights in the sensitivity of the fire forecast to uncertainties in the atmospheric modelling or ignition location. The user can set up and modify one or a number of 'rule-sets' to represent some of these uncertainties. For example, scenarios could explore the impact of different timing of a predicted cool change or a shift in the wind direction or variations in wind strength. Relatively small variations could lead to vastly different fire spread outcomes. This information indicates the 'robustness' or sensitivity of the modelled fire spread. Divergence in the

[1] The grid resolutions quoted for the ACCESS NWP simulations are indicative only. In reality, ACCESS grid resolutions were 0.036°, 0.012° and 0.004° latitude/longitude. This equates to approximately 4000 metre, 1.200 metre and 440 metre in the north-south direction. Grid resolution in the east-west direction is obtained by multiplying by the cosine of the latitude, and in consequence the spacings are smaller than those in the north-south direction.

ensemble may suggest a particular resource allocation to pre-empt certain scenarios from occurring or escalating.

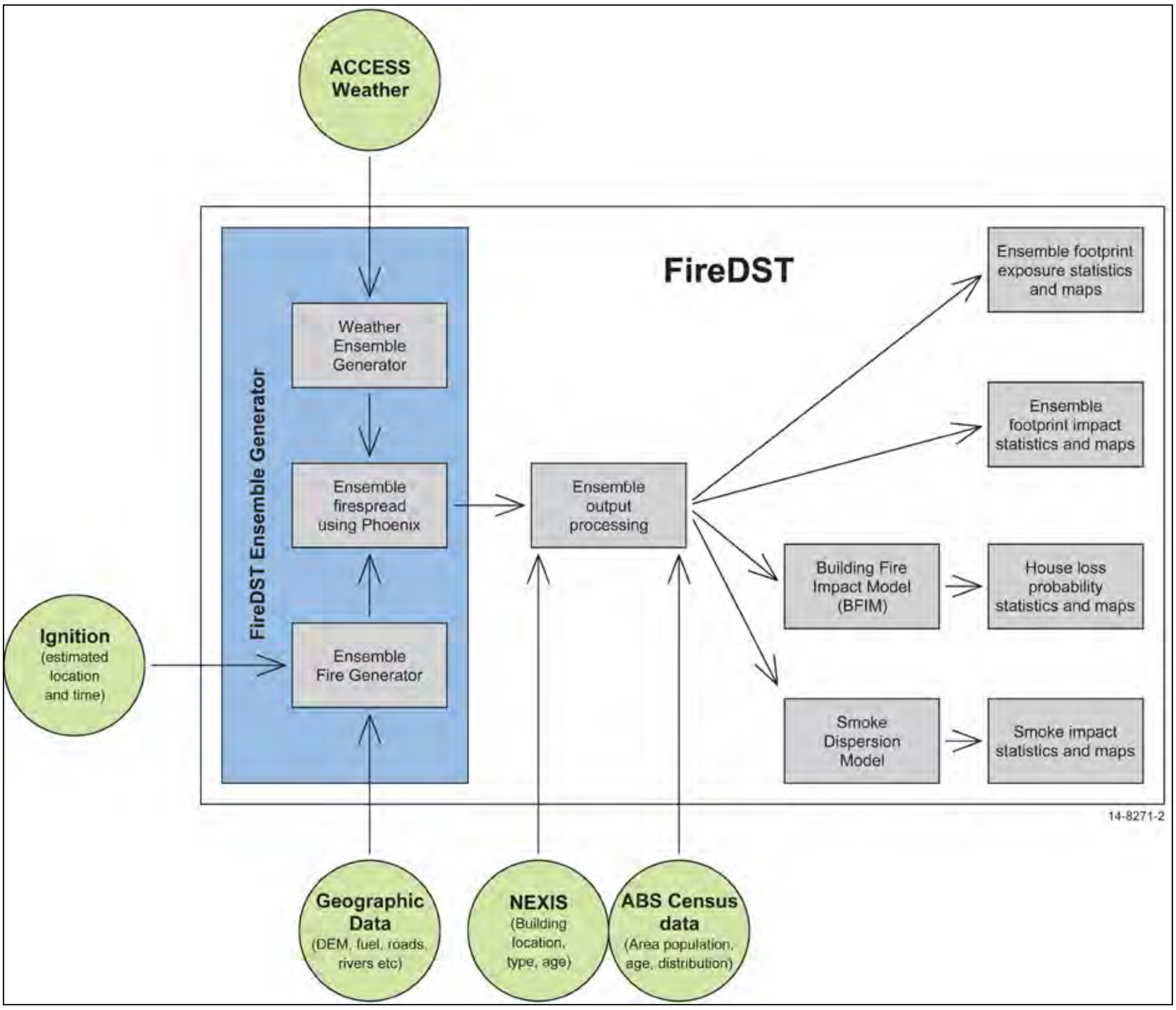



***Figure 1.1*** *Information flow within FireDST*

The FireDST system combines the different fire spread scenarios from the ensemble members into an ensemble fire shape. An ensemble fire shape is produced by overlaying each fire spread simulation shape. An example of how this is undertaken is shown in Figure 1.2. The percentage overlap in the final shape is displayed in discrete intervals. The FireDST system can display the ensemble scenarios at various time steps through the simulated timeframe. Typically, either half-hourly or hourly time increments are used to understand the progression of the fire.

The FireDST system analyses the people and structures exposed to and likely to be impacted by the fire spread. House location data were based from Geoscience Australia's built environment database NEXIS (National EXposure Information System; Nadimpalli, 2009; Canterford, 2011). Statistical information on residents was extracted by Geoscience Australia from the 2006 Australian Bureau of Statistics Census. Data of people and assets exposed to the fire are extracted based on the overlap of the single or ensemble fire spread shapes with the geo-located houses and people in the database.

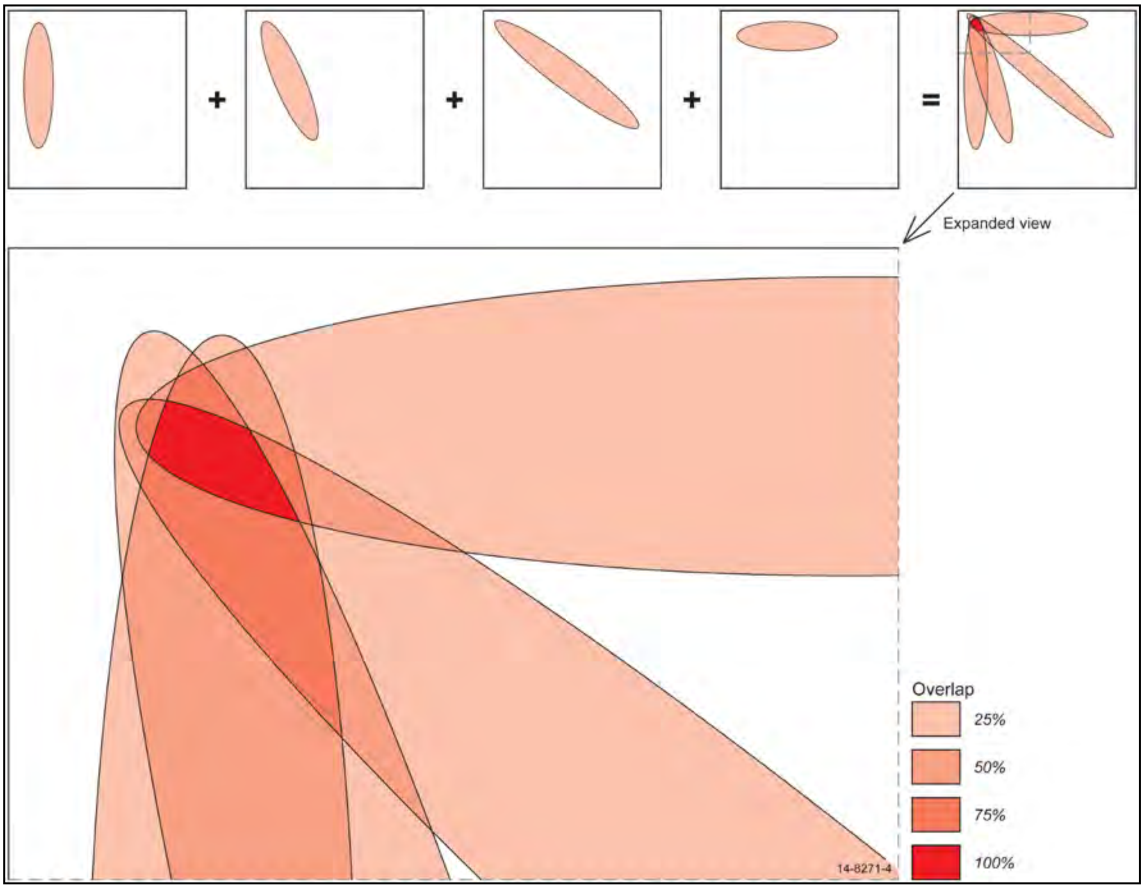



***Figure 1.2*** *Example of how an ensemble likelihood shape is produced. The fire scars of the four different notional fire simulations are combined to compute the likelihood that a particular location will burn.*

The FireDST system models the probability of house loss due to ember ignition or radiation. In a refinement of the basic house loss model, FireDST can use the Building Fire Impact Model (BFIM) to adjust modelled building losses to account for the impacts of house-to-house fire spread, as well as the presence of people able to defend a building against the fire. The information produced by the house loss modelling can be visualised alongside the ensemble fire spread modelling results, as well as being summarised in tabular form.

Finally, CSIRO Atmospheric and Marine Research developed a numerical model for smoke dispersion which accepts the simulated fire spread shapes and burn characteristics supplied by the fire spread model in FireDST to produce surface and atmospheric concentrations of a range of gases and particles (smoke constituents). The individual smoke simulations from several simulated fires were used to generate an ensemble view of the smoke spread.

# 2. Applications of very high resolution atmospheric modelling for bushfires (Bureau of Meteorology)

The Bureau of Meteorology's contribution to the FireDST project has been principally to prepare high-resolution and very-high-resolution hindcasts (both spatially and temporally) of the meteorology of significant fire events, using a state-of-the-art numerical weather prediction (NWP) system. This NWP system (ACCESS) is currently being used at the Bureau of Meteorology for operational weather prediction, although for the purposes of this project it was used in research mode at resolutions far higher than those currently used operationally. The meteorological outputs, after validation against available observational (weather station, radar, satellite, radiosonde) data, were supplied to the project partners for use in downstream modelling and applications.

There have been significant improvements in operational NWP at the Bureau of Meteorology since the three events chosen for principal study (2001, 2005, 2009). Indeed, the hindcasts have revealed at the higher resolutions details of the atmospheric flow (of apparent importance to fire-meteorology) which are either simply not present or else only very weakly resolved in the operational forecasts of the time. It is anticipated that, in time, the addition of ensemble weather forecasting techniques to operational practice will be able to identify the level of uncertainty attached to aspects of the weather forecasts.

Research questions (RQ) in the FireDST science plan being addressed by this component:

RQ(1a) What is the sensitivity of extreme fire behaviour to particular atmospheric conditions or states, specifically fine-scale three-dimensional wind flows over complex terrain?

## 2.1 RQ(1a) What is the sensitivity of extreme fire behaviour to weather?

Bushfire behaviour is well known to be sensitive to the weather, and a thorough appreciation of this fact is implicit in the pioneering work of McArthur and Luke (see for example, Luke and McArthur 1977). What is perhaps less well appreciated is that the behaviour is affected by all scales of atmospheric behaviour, from the large-scale and long-term (drought), through the medium-scale (weather systems such as fronts and wind changes) to the small-scale (short-term fluctuations in humidity and wind). Ongoing improvements in numerical weather prediction (NWP) have given us the ability to resolve features as small as a few hundred metres, and provide an unprecedented window into atmospheric structures that may affect a bushfire.

Here, we summarise the past three years of research by our group into fine-scale modelling of severe fire weather. In that time, we have modelled and verified the meteorology of various events including Melbourne's notorious dust storm (1983), the Blue Mountains fires (2001), the Eyre Peninsula fire (2005), Black Saturday (2009), the Margaret River fires (2011), and the recent Coonabarabran and Forcett/Dunalley fires (2013). These are listed below in Section 2.2. We have identified several medium to small-scale meteorological phenomena that have the potential to significantly escalate a fire, and in the case of the Margaret River fire have good evidence that the small-scale meteorology was *the* major contributor to the fire intensity and spread at a critical point in its history. We summarise some of these phenomena, and indicate the prospects for future prediction, thereby improving fire-fighter effectiveness and safety.

This chapter is a necessarily brief summary of our research. Readers interested in more detail should refer to the more detailed reports cited herein. This research forms one section of the Fire Impact and Risk Evaluation Decision Support Tool (FireDST) project, and has been funded by the Bushfire CRC and the Australian Bureau of Meteorology. The results of our meteorological modelling have also been a key input into fire modelling, smoke dispersion and risk-assessment research under that project.

### 2.1.1. Modelling approach

A numerical weather prediction (NWP) model is an application of relevant laws of physics to the problem of modelling atmospheric flow. Those laws include the equations of fluid flow, the laws of thermodynamics, the interaction between electromagnetic radiation and gasses, the physics of moisture including phase changes (e.g., evaporation and condensation), and an equation of state describing the relationship between atmospheric density, temperature, pressure and humidity. The atmosphere is approximately represented by a three-dimensional grid, and these laws are applied at each grid point to predict the state of the atmosphere a short time (typically seconds to minutes) into the future. Longer forecasts can be prepared by taking many such time steps.

This process has been developed to a high level of sophistication over the past few decades, and such forecasts now exhibit useful skill out to a week or more. Running such a forecast requires two types of information: an initial condition, and boundary conditions. The initial condition, or analysis, is an estimate of the three-dimensional atmospheric state at the forecast start time, and is usually prepared by blending a short-term forecast from a previous analysis with all available satellite and *in situ* observations. The boundary conditions include data on topography, sea-surface temperatures, vegetation type, soil moisture, and so forth.

Models may be run at a variety of resolutions, depending upon the spacing between grid cells[2]. Global models predict the weather for the entire atmosphere, but the large horizontal extent necessitates relatively coarse resolution. Finer resolution requires that the forecast be restricted to a limited area, and that the forecast be ‘nested’ within a larger-scale forecast to provide an estimate of how conditions vary along the boundaries of the finer resolution domain – this allows weather systems to migrate into

[2] The smallest feature that can be represented in a model is twice the grid spacing, but the evolution of such small features is not accurately modelled. The smallest feature for which the flow dynamics are well represented is somewhat larger – for example, Skamarock (2004) suggests that this length scale is about seven times the grid spacing in the WRF model. Hence a distinction is made between the grid spacing which is specified in advance and the resolution which is an emergent quantity of the model.

the limited-area domain. Very fine resolution can be achieved by successive nesting steps. In this project, grid spacings of down to about 440 metres were used, which required four levels of nesting from the global-domain model (and consequently five separate model runs in total). As an example, the domains for the three finest resolutions in our Black Saturday simulations are shown in Figure 2.1.

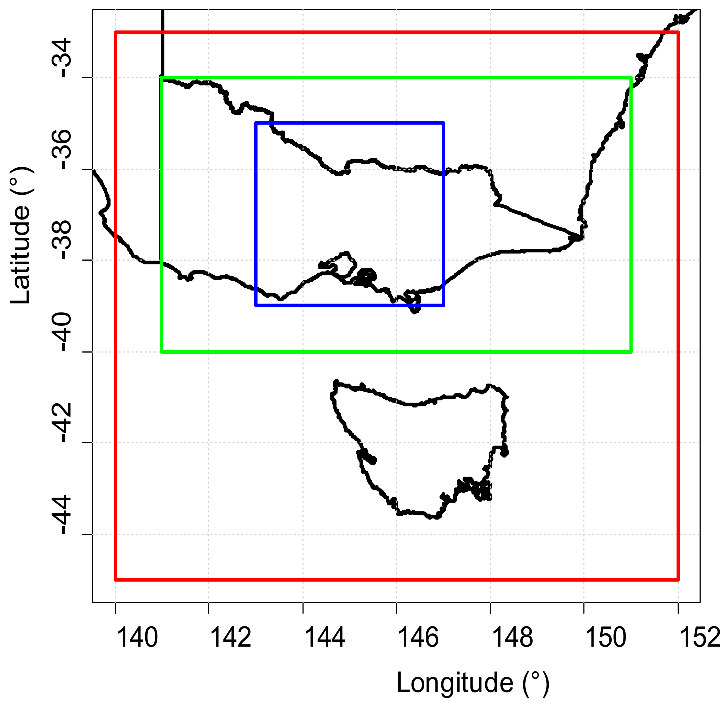



***Figure 2.1*** *Boundaries of the third (0.036° grid spacing, red), fourth (0.012° grid spacing, green) and fifth (0.004° grid spacing, blue) nesting levels for the Black Saturday model runs. Model boundaries are chosen, as far as is possible, to avoid areas of elevated topography. The 0.036°-grid-spacing model run is nested in a large regional model (0.11° grid spacing) comprising all of Australia and surrounding areas of the oceans.*

High-resolution modelling of this nature provides additional information for two main reasons. Firstly, the successively higher resolution nests can use more detailed topography and other boundary conditions, to which the simulated atmosphere can then respond. Secondly, the atmosphere can itself generate fine-scale structures such as the very strong temperature gradients across cold fronts. The higher-resolution simulations can more accurately depict the natural processes that cause these structures, and thereby better resolve them.

### 2.1.2 Verification

Weather forecasts continue to improve, but are not perfect. One source of error arises because the model itself is not exact: a finite grid spacing is used and some important physical processes, such as turbulence and convection, have to be approximated. Another source is that the initial condition and boundary conditions are not exact. A third source is that the atmosphere is chaotic, which means that small initial errors or uncertainties grow exponentially and eventually swamp useful information in the forecast. Therefore, it is necessary to verify NWP forecasts and hindcasts.

For this project, we used two main verification techniques. Where suitable meteorological features were present, we verified the location and/or timing of those features. An example of this objectoriented verification is our verification of the timing of the wind change on Black Saturday, in which Figure 2.2 shows the difference in timing of the wind change between the model and AWS sites having a measurement frequency of one minute in the available data, and Figure 2.3 compares the location of the wind change at four-hour intervals from two of the available resolutions, to that analysed by the Bureau of Meteorology (BoM 2009, VBRC 2010). The other technique was direct verification against observations. The simulated data were compared to all available AWS observations within the model domain, enabling a qualitative assessment to be made of the model accuracy. An example of this type of verification can be seen in Figure 2.4, which shows the observed one-minute-interval data at Eildon Fire Tower, together with the modelled five-minute-interval data at the nearest grid point. Full verification of the simulations, together with detailed discussion, can be found in our various project reports and other publications, including Fawcett *et al.* (2012a,b, 2013a,b,c,d,e,f,g), Kepert and Fawcett (2013a,b), and Kepert *et al.* (2012a,b, 2013).

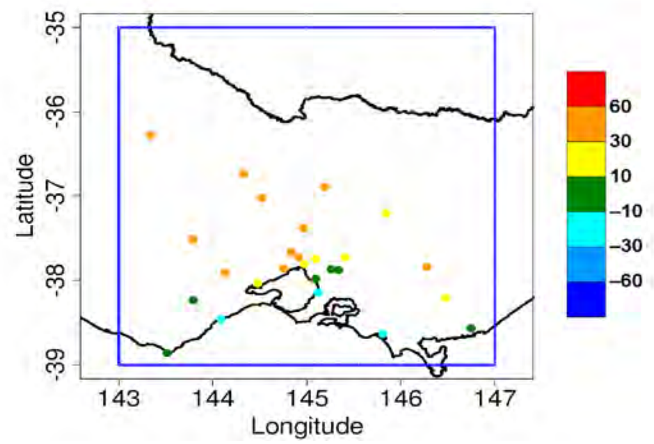



***Figure 2.2*** *Approximate timing errors in minutes for the location of the primary wind change on Black Saturday. Positive (negative) values imply that the primary wind change in the 0.004°-grid-spacing simulation is late (early) relative to the change at the indicated AWS locations. The blue box denotes the model domain boundary.*

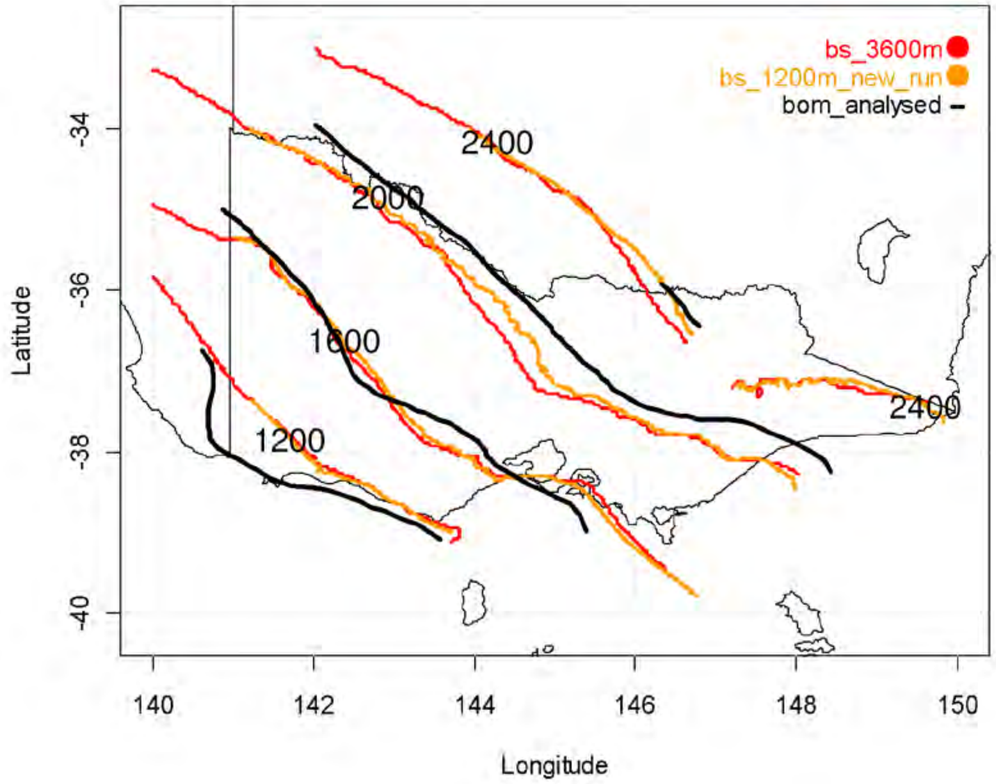



***Figure 2.3*** *Comparison of analysed primary wind-change positions (black lines) with model wind-change positions from the 0.036°-grid-spacing (red lines) and 0.012°-grid-spacing (orange lines) simulations, for 1200, 1600, 2000 and 2400 EDT on Black Saturday. Analysed wind-change positions are from BoM (2009) and VBRC (2010). Modelled wind-change positions are determined semi-objectively from the 10-metre wind-direction field.*

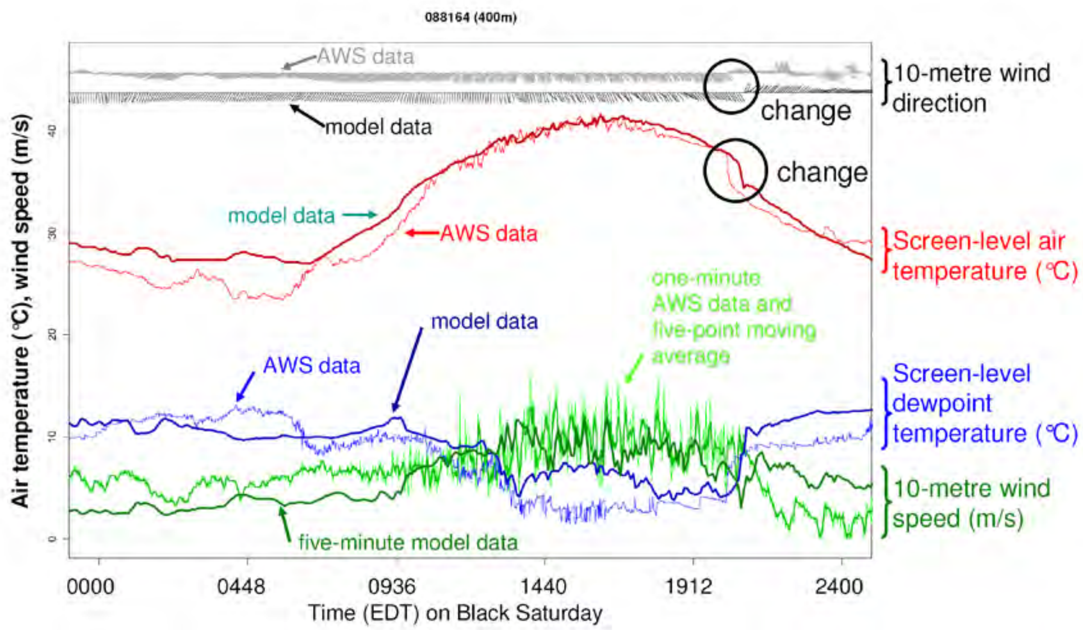



***Figure 2.4*** *Verification of the 0.004°- grid spacing simulation of Black Saturday against one-minute-interval observations from the Eildon Fire Tower. Model data are shown in thick lines and observations in thin lines. Meteorological variables are as annotated on the diagram. The timing of the change is indicated in the wind direction and temperature data.*

### 2.1.3 The meteorology of the Black Saturday fires, 7 February 2009.

Black Saturday (7 February 2009) was the worst fire disaster in Australia's recorded history, with 173 deaths, thousands of houses and other buildings were destroyed, as well as major environmental damage (VBRC 2010). The fires followed a decade-long drought and a severe heatwave in the preceding week, which combined to cause extremely dry fuels. The fires spread exceptionally quickly, both directly and due to spotting over distances exceeding 30 km, and were extremely intense. The weather on the day itself was broadly similar to earlier major disasters in southeast Australia such as Black Friday of 1939 and Ash Wednesday of 1983, with hot dry gusty northerly winds preceding a strong south-westerly change. As in the earlier events, the majority of the deaths occurred close to the change.

The quality of our simulations was high. Screen-level maximum temperatures were very accurately predicted, humidity somewhat less so, while the 10-metre wind speeds showed a consistent negative bias (in excess of 20% at times). The timing of the change was within an hour of that observed or analysed. The ACCESS NWP system is therefore substantially more accurate in this regard than the LAPS system, which was the operational limited-area model within the Bureau at the time. A small ensemble of ACCESS runs was made by running the model from initial conditions from two NWP centres and four different initialisation times. The spread of timing of the primary wind change from this ensemble is consistent with the actual timing error.

The simulations showed a wealth of fine-scale detail, including the complex time-varying structure of the wind changes, the development of boundary-layer rolls and their transition to cellular convection, and the development of fine-scale vortices on the wind changes. These features are briefly discussed below. Several of these features possessed significant updrafts, which we suggest may have interacted with the fire plume to facilitate long-range spotting. Research is continuing to confirm this hypothesis, and to eventually provide a means to forecast the processes.

The main wind change originated from a synoptic-scale trough reinforced by an overnight land-sea temperature contrast along the coast to the west of Cape Otway, which began to propagate to the north-east around dawn. There was a weaker, east-west oriented change over western Victoria, and several less extensive lines that originated at other coastal boundaries. This structure is apparent in the plot of surface wind and temperature at 0600 UTC (1700 EDT = UTC + 11 hours) shown in Figure 2.5. The main change moved a little slower than observed during the day, but sped up during the evening such that the timing error in northern Victoria was only 15 minutes. During the day, the change had the character of a density current, transitioning to a bore propagating on the nocturnal inversion as this formed later in the day (Figure 2.6). Radar data from Yarrawonga clearly showed the bore as it passed through, and also strongly suggested that it caused a significant intensification of the plume from the Beechworth-Mudgegonga fire at around midnight. The modelled change had an updraft in excess of 5 m $s^{-1}$ at 500 metres above the surface for much of the time, whether as a density current or as a bore, which is similar to the fall speed of embers and would have helped suspend and transport embers lofted to that level by the plume. We suggest that it thus contributed to the major outbreak of spotting at the Beechworth-Mudgegonga fire discussed in the 2009 Victorian Bushfires Royal Commission report (VBRC 2010).

The simulated change also featured a string of small-scale vortices along its length, associated with small patches of stronger winds and perturbations to the quasi-linear nature of the change (Figure 2.7). These features were small enough that they are not resolved by the observational network, so we do not have independent evidence of their existence, but would clearly warrant further investigation.

However, they would likely cause locally more intense fire behaviour, so confirmation of their occurrence would provide extra knowledge of the dangers of wind changes. From late morning, the flow ahead of the change developed an extensive area of boundary-layer rolls. This sequence of counter-rotating horizontal vortices aligned approximately with the mean wind direction had meandering quasi-linear updrafts in excess of 5 m $s^{-1}$. As with the updraft on the wind change, we suggest that these may have contributed to ember transport. They also led to significant fluctuations in near-surface wind speed and direction, temperature and humidity, on a time-scale of the order of 10 minutes, which would have likely influenced fire behaviour. The variation in wind direction is perhaps especially significant, since it would have helped the fire front to broaden, leading to a more intense and faster-moving fire. Figure 2.8 shows a plan view and cross-section of these rolls. The presence of the rolls is confirmed by radar and satellite data. As time progressed, daytime heating caused the boundary layer to deepen, and hence the rolls to deepen and broaden. The character of the rolls also changed, with them becoming less linear and eventually breaking up into cellular convection.

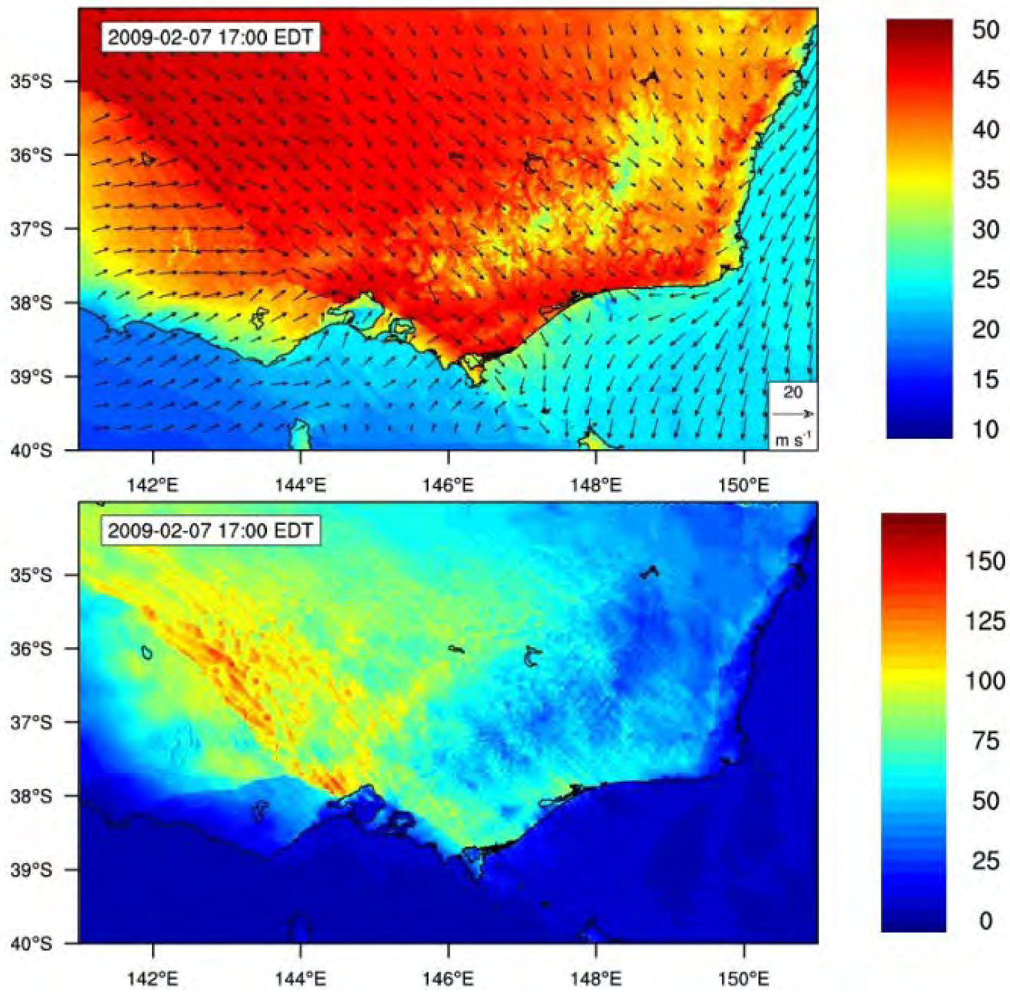



***Figure 2.5*** *Simulation of the surface meteorology over Victoria at 1700 EDT on 7 February 2009. Top: 2-metre air temperature (colour) and wind (vectors). Bottom: Notional instantaneous forest-fire danger index (FFDI). The dual structure of the wind change to the west is clearly apparent. The variations in wind direction ahead of the change, and the fine-scale structure in the FFDI field, are due to mesoscale convective features in the boundary layer following the breakdown of the rolls.*

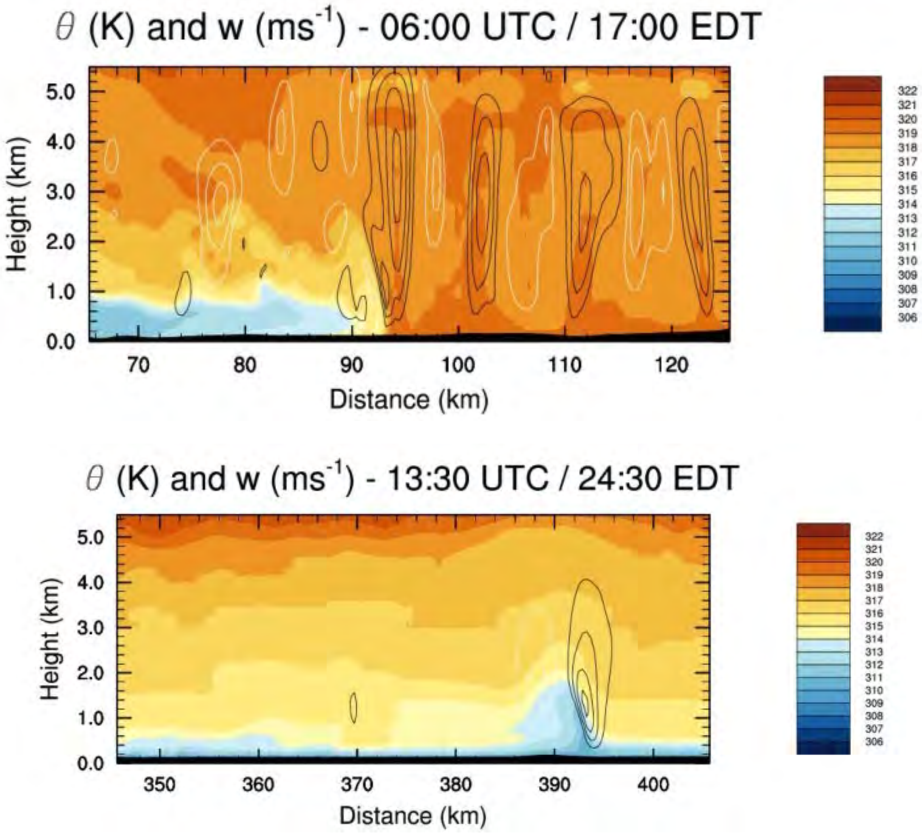



***Figure 2.6*** *Cross-sections of potential temperature (colour) and vertical velocity (contours, interval 1.5 m s$^{-1}$, black contours denote upward motion, white contours downward motion) through the wind change at 1700 EDT on 7 February 2009 (top) and 0030 EDT (bottom) on 8 February 2009. During the afternoon, the wind change has the structure of a density current propagating into the unstable boundary layer. By midnight, the change has transformed into a bore, propagating on the near-surface nocturnal stable layer.*

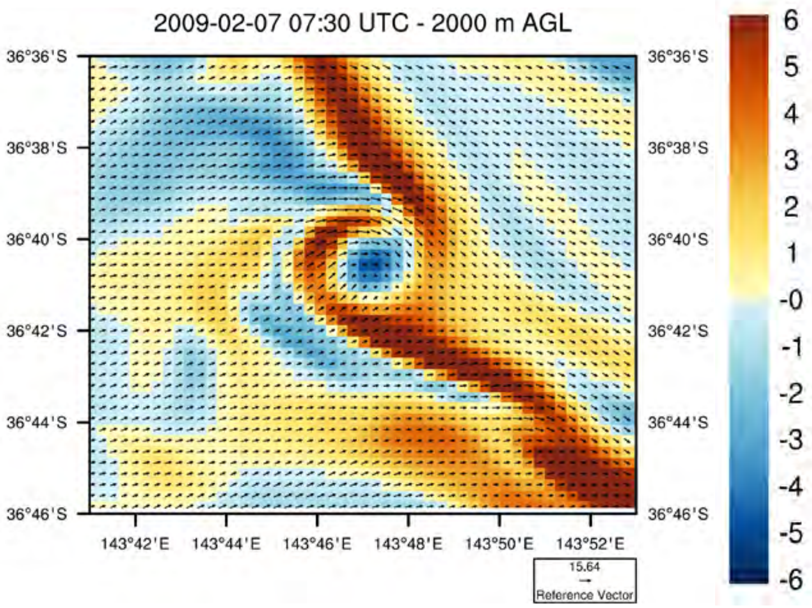



***Figure 2.7*** *Vertical velocity at 2000 m above ground level (shading, m s$^{-1}$) and horizontal wind at 10 m above ground level (vectors) in one of the vortices along the wind change at 0730 UTC (1830 EDT) on Black Saturday. The wind change is represented in the model, amongst other things, by a line of updrafts (brown shades), but the centre of the vortex is modelled as having a downdraft (blue shades).*

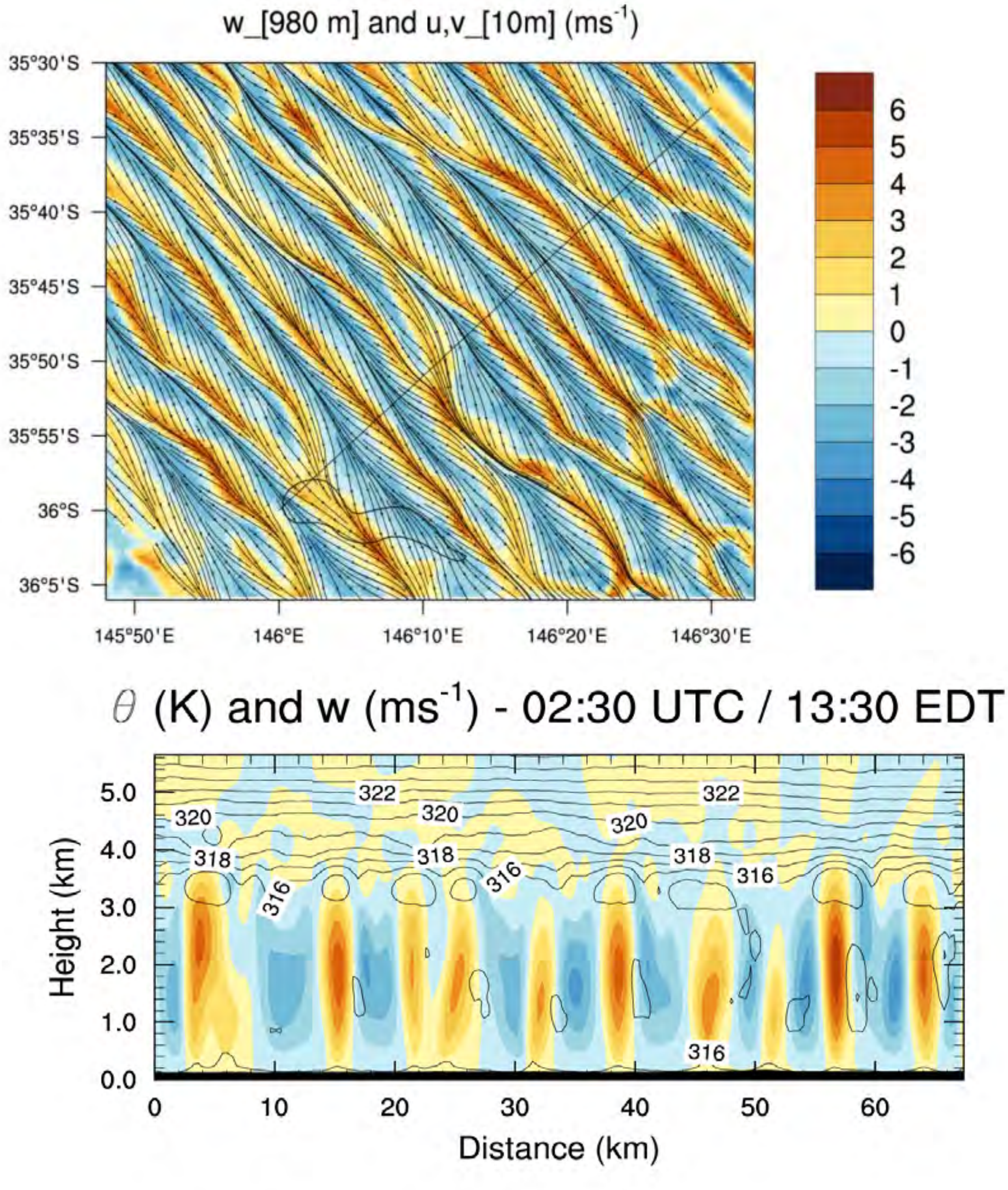



***Figure 2.8*** *Boundary-layer rolls at 0230 UTC (1330 EDT) on the afternoon of Black Saturday. Top: 10-m wind (streamlines) and vertical velocity at 980 m (shading). Bottom: Cross-section along the line indicated in the top panel, of vertical velocity (shading) and potential temperature (contours, K). The top of the boundary layer is where the significant potential temperature gradient begins, near 3-km height.*

Full details of the above research may be found in the major publications by Fawcett *et al.* (2013a) and Thurston *et al.* (2013a). Briefer accounts are contained in Fawcett *et al.* (2012a, 2013d).

### 2.1.4 The meteorology of the Wangary fire, 11 January 2005.

A significant bushfire broke out on the Lower Eyre Peninsula (LEP) in South Australia on 10 January 2005, not long after 1500 CDT (Central Daylight Time = UTC + 10.5 hours). Under favourable conditions for bushfire spread, it burnt some 1800 hectares of swamp, scrubland and pasture paddocks that day. The following morning strong northwesterly winds caused the fire to break out of containment lines established overnight. By 1300 CDT on the 11th, the fire had changed direction under the influence of south-westerly winds behind the wind change and reached North Shields, 35 km from the original fireground. The fire resulted in nine deaths and 115 injuries. 77,964 hectares of land were burnt, with 47,000 in stock losses and around $100 million in total property damage.

Similarly to our reconstruction of Black Saturday, the simulation of the wind change timing was very accurate, within 45 minutes and mostly within 30 minutes of the analysis, as shown by isochrones of frontal position (Figure 2.9). In contrast with the Black Saturday simulation, the model tended to be early, rather than late, with the timing. The change showed marked structural changes as it made landfall; over sea, the structure was that of an undular bore, propagating on the shallow stable marine boundary layer. As it made landfall, it moved into a deeper, well-mixed daytime continental boundary layer, and transformed into a structure similar to a density current. Prior to landfall, the change had a several parallel updrafts a few kilometres apart at its head, while afterwards, there was just a single updraft. The direction of this structural transition was opposite to that on Black Saturday, from a bore-like structure to a density current rather than the reverse. Another difference was that the updraft over the fire was weaker and possibly less able to support ember transport.

Another similarity to Black Saturday was the development of a region of boundary-layer rolls in the hot north-westerlies preceding the change. These were located well to the north of the fire ground and would not have affected this fire. However, they similarly caused significant fluctuations in the instantaneous values of fire danger indices, wind direction, and vertical motion, which we expect would have affected any fires in that region.

Previous work on this event demonstrated that a period of marked drying, lasting several hours, occurred prior to the change. This dry air would have contributed to the fire intensity through its effect on fine-fuel dryness, and was attributed to a narrow band of subsidence followed by strong vertical mixing within the boundary layer (Mills 2008). Additional shorter drying occurred following the change. Our simulation captures the timing of the first drying well, but at lower amplitude, while the second is not represented. A fuller account of this research is available in Fawcett *et al.* (2012b, 2013b).

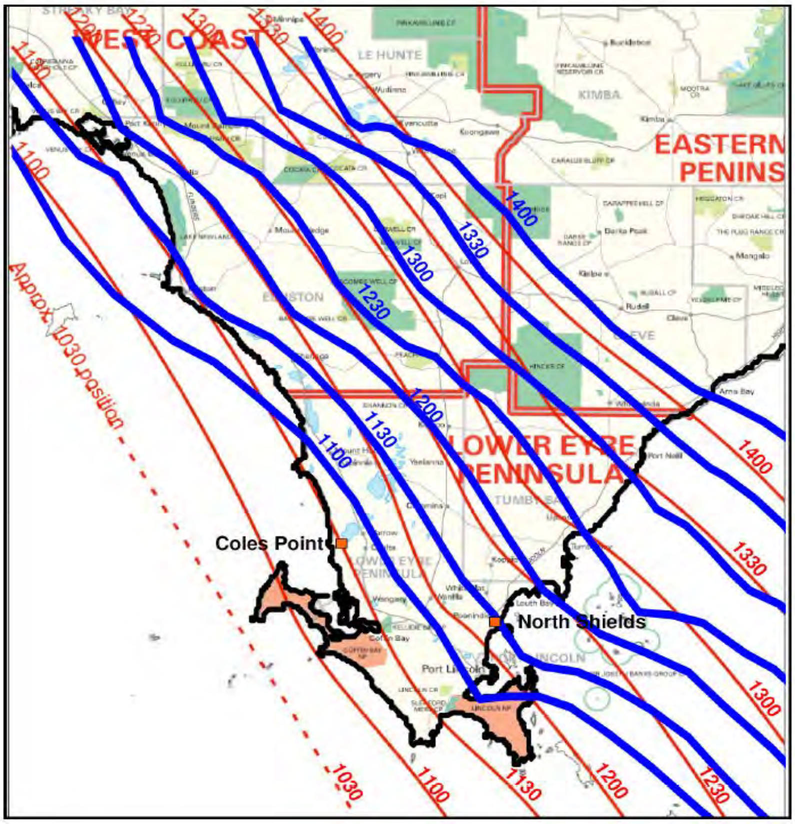



***Figure 2.9*** *Comparison of modelled (blue lines; 0.012°-grid-spacing model run) and analysed (red lines) wind-change isochrones at half-hour intervals across the Lower Eyre Peninsula (1100 to 1400 CDT on 11 January 2005). The locations of the two AWSs are indicated.*

## 2.1.5 The meteorology of the Warragamba/Mt Hall fire on 24 – 25 December 2001.

Of the three fire weather cases investigated specifically for the FireDST project (discussed here in Sections 2.1.3 – 2.1.5), this one is the earliest (December 2001), has the most orography, and is the least successful in terms of the three simulations. Significant aspects of the AWS observations (see below) are missed or otherwise inadequately represented. These include the nocturnal moistening at many sites (e.g., Sydney Airport) in the early hours of the morning of 25 December, the overnight cooling at some sites (e.g., Richmond RAAF), and the period of dry air during the afternoon of 24 December at some sites (e.g., Canterbury Racecourse).

The relatively poor simulation is possibly due to the quality of the ERA-Interim initial condition, although we tried initialising from several different times without significant improvement from our original simulation. We note that an ERA-Interim initial condition was also used in the later and more successful Eyre Peninsula simulation (January 2005) – see previous section. The complex topography may be another factor. A third may be that the synoptic forcing in this case was weaker than for the Black Saturday or Wangary simulations, although the Margaret River simulation was successful in the absence of such forcing, but with much simpler topography. Unfortunately, because the event occurs so far in the past, it was not possible to examine the sensitivity to initial conditions from other sources. While this simulation is probably of insufficient quality for research into the fire behaviour, it should not be concluded that all events of similar age will present such problems. [In support of this point, we note that the simulations of the 1983 Melbourne Dust Storm, also initialised from ERA-Interim initial conditions, appear to be more successful than these 2001 simulations, possibly because of the strong synoptic forcing.] Rather, it illustrates the importance of thorough verification before the fields are used for downstream applications.

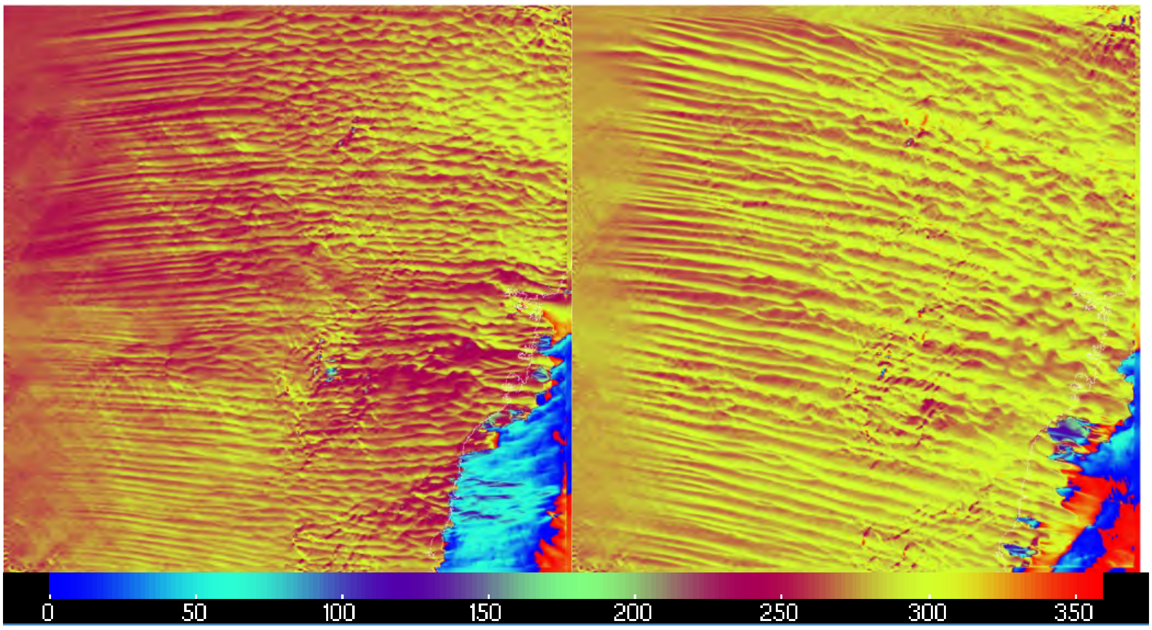



***Figure 2.10*** *Wind direction at 0300 UTC (1400 EDT) on 24 December (left) and 25 December (right), from the 0.004°- grid spacing simulations.*

On the afternoons of 24 and 25 December 2001, the 0.004°-grid-spacing simulation shows winds from the westerly quadrant crossing the simulation domain from west to east (see Figure 2.10). There is an impression of the orography of the Blue Mountains causing ‘streamers’ (coherent patterns of variation in the 10-metre wind direction) to trail across the domain, although with more downstream disturbance on the 25th. These look a little like the boundary-layer rolls seen in the Black Saturday simulations, but appear to be too fixed in their positions to be boundary-layer rolls, so instead are considered to be similar to the wakes apparent in the simulations of the Margaret River event. Further details of this simulation can be found in Fawcett *et al.* (2012c,d).

## 2.2 Other events

In addition, simulations were prepared for the weather of a number of other severe fire danger days, for which the analysis is still in progress. Several of these were notable events that were simulated shortly after their occurrence. A brief description of each of these extra simulations follows. A discussion on our simulations for the Margaret River 2011 fire is given in Section 9. These additional events are listed alphabetically.

- *Boorabbin, 30 December 2007.* This fire occurred in the Western Australian goldfields region, near the main east-west road. Several trucks were engulfed in flames, resulting in three fatalities. The highway was closed to traffic for over a week. Analysis of this simulation is ongoing, initial results show that the wind change prior to the fatalities was well captured.

- *Canberra, 18 January 2003.* These fires resulted in several deaths, over 490 injuries, severe damage to the outskirts of Canberra, and the destruction of the Mt Stromlo observatory. They were notable for the formation of an intense tornado. (Analysis has not yet commenced.)
- *Coonabarabran, 13 January 2013.* This event occurred in the Warrambungle National Park in north-east NSW. The weather featured exceptionally strong temperature gradients associated with a strong wind change which moved through from the southwest. The pre-frontal winds and the change itself showed similar features to our Black Saturday simulations, including boundary-layer rolls and fine-scale vortices. The situation also featured sea-breeze penetration inland, and the formation of some marked deep convective cells. Further details can be found in Fawcett *et al.* (2013c).
- *Dereel, 27-28 March 2013.* Simulations were prepared at up to 1.3-km grid spacing for this fire event in central Victoria that destroyed at least 16 homes. Verification showed that the simulations were of good quality. Figure 2.11 shows a model verification plot for Ballarat Aerodrome in western Victoria from these simulations.

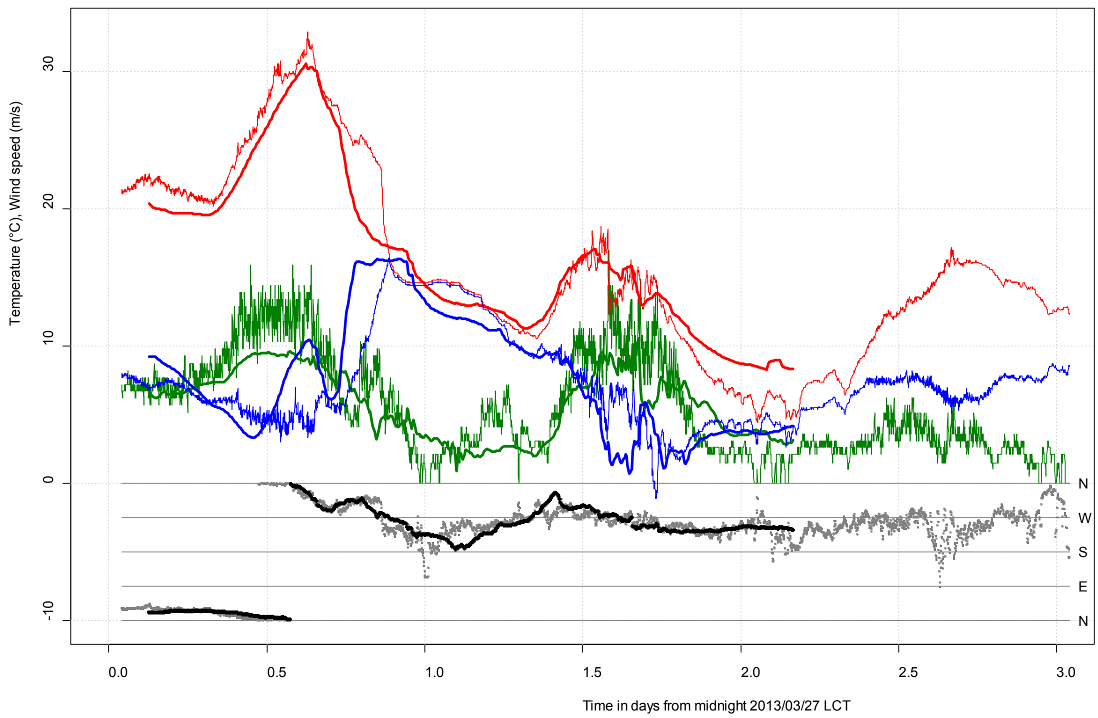



***Figure 2.11*** *Comparison of modelled (thick lines, black dots 0.012°-grid-spacing model run) and observed (thin lines, grey dots) air temperature (red lines), dewpoint temperature (blue lines), wind speed (green lines) and wind direction (dots) for Ballarat Aerodrome in the Dereel fire case study. At this site, wind directions are generally well modelled, although peak afternoon wind speeds are under-forecast.*

- *Forcett/Dunalley, 4 January 2013.* This fire occurred in south-eastern Tasmania on a day of record heat, and destroyed at least 100 properties and isolated 2700 people. The simulations showed that the heat was partly due to a Foehn effect in the north-westerlies off the Tasmanian central highlands. A wind change propagating from the southwest developed a complex structure as it encountered the numerous islands and peninsulas in that region. Verification was generally quite good on our initial analysis, with timing of wind changes and maximum temperatures being well captured. Further details can be found in Fawcett *et al.* (2013f,g).

- *Melbourne Dust Storm, 8 February 1983.* This day was not a severe fire event, although fires were present on the day and the overall synoptic situation features a strong wind change similar to those of severe fire days in south-eastern Australia (e.g., Ash Wednesday 1983, Black Saturday 2009). The simulation was performed partly to examine the utility of reanalysis data for studying old events, and partly to try to determine why this event was not a severe fire day. Further details can be found in Fawcett *et al.* (2013e).

## 2.3 Work on a parallel Bushfire CRC project (Dr. Will Thurston – summary)

A parallel project, *Understanding complex fire behaviour: modelling investigation of lofting phenomena*, has investigated meteorological contributions to complex fire behaviour, including contributions from wind direction variability (known to broaden fire fronts leading to more rapid fire propagation), and wind influence on fire plume structure (with emphasis on firebrand lofting potential).

The study initially focussed on boundary layer rolls (BLR) that were observed on Black Saturday and simulated in the high resolution ACCESS simulation. The following potentially important impacts of BLR on fire spread were identified:

(i) Wind direction variability. The lateral propagation of BLRs led to winds that backed and veered through 60 degrees with the passage of the up and down branches of the rolls overhead.

(ii) Firebrand lofting. Maximum updraft speeds exceeded 6 m $s^{-1}$, which could conceivably carry large firebrands lofted by the fire plume an additional few kilometres into the atmosphere.

(iii) Enhanced FFDI. The FFDI was found to be greatest in the descending branches of the BLRs, where the surface wind speeds were greatest.

The study then shifted to the investigation of fire plume behaviour in a Large Eddy Model (LEM). The model was tested and found to produce very realistic turbulence, which is particularly important for plume studies. An intense heat source was added to simulate the heat from a fire, and the model atmosphere responded by generating updraft plumes, with very realistic behaviour. Experiments included a simple idealized initial state (e.g., flat terrain, dry atmosphere, thermodynamically neutral boundary layer 3 km deep, circular heat source) in which the background wind was systematically varied from 2.5 to 15 m $s^{-1}$. The plumes that developed in the lower wind speed environments tended to be tall and nearly lamina throughout much of the plume, with turbulent characteristics only in the upper regions, whereas for the higher wind regimes the plumes were bent over and turbulent from close to the surface. Maximum updraft speeds were much higher in the laminar than turbulent parts of the plumes. Despite a wide variation in plume structure across the wind speed regimes, all plumes showed considerable potential for firebrand lofting.

Further information regarding this project can be found in Thurston (2012a) and Thurston *et al.* (2012b,c,d,e; 2013a,b,c,d,e,f).

## 2.4 WRF – Fire simulations (Mika Peace – PhD student)

Fires and the atmosphere are three-dimensional and feedback loops between the two can produce unexpected fire behaviour. Simulations undertaken using the coupled fire-atmosphere model WRF-fire have given new insights into fire-atmosphere interactions. The coupled modelling enables an understanding of how the heat and moisture released by a fire changes the surrounding atmosphere, and how that changed atmosphere subsequently impacts fire behaviour. Findings from the coupled simulations show that a fire can modify mesoscale features of the surrounding atmosphere; that is the fire-modified winds, not the environmental winds that propagate the fire front; and interactions between a fire and features of the surrounding atmosphere can cause surges and lulls in fire spread.

Further information about this project and be found in Peace *et al.* (2011; 2012a,b; 2013a,b,c).

## 2.5 Summary

Very-high-resolution simulations of the meteorology associated with nine significant fire events and the Melbourne dust storm have been made, using the Bureau of Meteorology's new ACCESS numerical weather prediction system. Validation of these simulations shows that, with the exception of the Warragamba/Mt. Hall fire, they are of high quality. Features important to fire behaviour such as the timing of wind changes and the maximum temperature are very well predicted. Humidity is not quite so good, consistent with extensive experience suggesting that this is a more difficult variable to forecast. Wind speed has a systematic low bias which can, however, be statistically corrected.

Detailed analyses have been carried out on two of the cases, Black Saturday and the Margaret River fires. Analysis of the remainder is ongoing. One important finding was the development of a range of small-scale phenomena that likely impacted the fire behaviour, including boundary-layer rolls, fine-scale vortices on wind changes, and strong downslope winds on relatively small hills. We presented strong evidence that the latter was the likely cause of the escape of the Margaret River fire. Another important finding was the variety of different forms that a wind change could take, which may mean that its impact on a fire is not always the same. A third was a range of processes that could cause significant near-surface updrafts in the absence of a fire, and in the presence of a strong fire plume could enhance the ember transport and spot-fire potential.

The ability to run both recent and historical events at high resolution is an important development for future research. As well as continuing to learn from major events of record, our research contributed to the rapid determination of 'lessons learned' from the Margaret River fire in particular.

We note, however, that the resolution used for these studies will not be available operationally for some years because of the very high computational cost, and even then will not be available for the whole of Australia. Hence there is a need to develop techniques to forecast the phenomena described herein from much coarser resolution NWP. We regard such work as an important avenue for future research.

# Bureau of Meteorology publications for this project

## Peer-reviewed publications


Fawcett, R.J.B., W. Thurston, J.D. Kepert and K.J. Tory (2012a) Modelling the fire weather of Black Saturday. Extended abstracts, Annual Conference of the Australasian Fire and Emergency Services Council and the Bushfire Cooperative Research Centre, Perth, 28 to 30 August 2012.

Fawcett, R.J.B., W. Thurston, J.D. Kepert and K.J. Tory (2013b) Modelling the fire weather of the Eyre Peninsula fire of January 2005. Extended abstracts, Annual Conference of the Australasian Fire and Emergency Services Council and the Bushfire Cooperative Research Centre, Melbourne, 2 to 5 September 2013 (*in review*).

Fawcett, R.J.B., A J Wain, W. Thurston, J.D. Kepert and K.J. Tory (2013e) The Melbourne dust storm revisited: an ACCESS case study. 20th International Congress on Modelling and Simulation, Adelaide, 1 to 6 December 2013.

Fawcett, R.J.B., M Webb, W. Thurston, J.D. Kepert and K.J. Tory (2013f) Modelling the fire weather of the Dunalley fire of January 2013. 20th International Congress on Modelling and Simulation, Adelaide, 1 to 6 December 2013.

Kepert, J.D. (2011) Weather Forecasting: A long way since Tropical Cyclone Tracy, Invited presentation. Extended Abstracts, Annual Conference of the Australasian Fire and Emergency Services Council and the Bushfire Cooperative Research Centre, Sydney, 29 to 31 August 2011.

Kepert, J.D., A. Wain and K.J. Tory (2012b) A comprehensive, nationally consistent climatology of fire weather parameters. Extended abstracts, Annual Conference of the Australasian Fire and Emergency Services Council and the Bushfire Cooperative Research Centre, Perth, 28 to 30 August 2012.

Kepert, J.D., R.J.B. Fawcett, W. Thurston and K.J. Tory (2013) Applications of very high resolution atmospheric modelling for bushfires. Extended abstracts, Annual Conference of the Australasian Fire and Emergency Services Council and the Bushfire Cooperative Research Centre, Melbourne, 2 to 5 September 2013 (*in preparation*).

Kepert, J.D. and R.J.B. Fawcett (2013a) Meteorological aspects of the Margaret River fires on November 2011. Extended abstracts, 20th International Congress on Modelling and Simulation, Adelaide, 1 to 6 December 2013.

Peace, M., T. Mattner and G. Mills (2011) The Kangaroo Island bushfires of 2007: A meteorological case study and WRF-fire simulation. 19th International Congress on Modelling and Simulation, Perth, 12 to 16 December 2011.

Peace, M., L. McCaw and G. Mills (2012a) Meteorological dynamics in a fire environment; a case study of the Layman prescribed burn in Western Australia. Australian Meteorological and Oceanographic Journal 62 127-142.

Peace, M., G. Mills and T. Mattner (2013c) Coupled numerical simulations show a fire changes the weather forecast, 20th International Congress on Modelling and Simulation, Adelaide, 1-6 December 2013.

Thurston, W., R.J.B. Fawcett, K.J. Tory and J.D. Kepert (2013a) Simulating boundary-layer rolls with a numerical weather prediction model. *For submission to Q. J. Royal Meteorol. Soc.*

Thurston, W., K.J. Tory, R.J.B. Fawcett and J.D. Kepert (2013b) Large-eddy simulations of bushfire plumes in the turbulent atmospheric boundary layer. 20th International Congress on Modelling and Simulation, Adelaide, 1 – 6 December 2013.

## Bushfire CRC/Internal-reviewed publications


Fawcett, R.J.B., W. Thurston, J.D. Kepert and K.J. Tory (2012b) Modelling the fire weather of the Eyre Peninsula fire of January 2005. Poster, Annual Conference of the Australasian Fire and Emergency Services Council and the Bushfire Cooperative Research Centre, Perth, 28 to 30 August 2012.

Fawcett, R.J.B., W. Thurston, J.D. Kepert and K.J. Tory (2012c) Blue Mountains case study – December 2001. Project report to the Bushfire CRC.

Fawcett, R.J.B., W. Thurston, J.D. Kepert and K.J. Tory (2012d) Blue Mountains case study – December 2001. Additional material. Project report to the Bushfire CRC.

Fawcett, R.J.B., W. Thurston, J.D. Kepert and K.J. Tory (2013a) The meteorology of Black Saturday: a high-resolution ACCESS modelling study. CAWCR Technical Reports (*in review*).

Fawcett, R.J.B., W. Thurston, J.D. Kepert and K.J. Tory (2013c) Modelling the fire weather of the Coonabarabran fire of 13 January 2013. Poster, Annual Conference of the Australasian Fire and Emergency Services Council and the Bushfire Cooperative Research Centre, Melbourne, 2 to 5 September 2013.

Fawcett, R.J.B., W. Thurston, J.D. Kepert and K.J. Tory (2013d) Modelling the Weather on Black Saturday. Poster, Annual Conference of the Australian Meteorological and Oceanographic Society, Melbourne, 11 to 13 February 2013.

Fawcett, R.J.B., M Webb, W. Thurston, J.D. Kepert and K.J. Tory (2013g) Modelling the fire weather of the Dunalley fire of January 2013. Paper presented at the Science to Services Workshop, Bureau of Meteorology, Melbourne, 15 to 16 August 2013 (*submitted*).

Kepert, J.D., L.W. Logan and K.J. Tory (2011a) Modelling the fire weather on Black Saturday, Poster, Annual Conference of the Australasian Fire and Emergency Services Council and the Bushfire Cooperative Research Centre, Sydney, 29 to 31 August 2011.

Kepert J.D., P.J. Steinle, C.I.W. Tingwell and K.J. Tory (2011b) Verification of High-Resolution Forecasts from ACCESS. Poster, Annual Conference of the Australasian Fire and Emergency Services Council and the Bushfire Cooperative Research Centre, Sydney, 29 to 31 August 2011.

Kepert, J.D. and K.J. Tory (2011c) Using Numerical Weather Prediction to Forecast Wind Direction Variability. Poster, Annual Conference of the Australasian Fire and Emergency Services Council and the Bushfire Cooperative Research Centre, Sydney, 29 to 31 August 2011.

Kepert, J.D., R.J.B. Fawcett and M. Peace (2012a) Meteorological Aspects of the Margaret River Fires on 23 November 2011. Poster, Annual Conference of the Australasian Fire and Emergency Services Council and the Bushfire Cooperative Research Centre, Perth, 28 to 30 August 2012.

Kepert, J.D. and R.J.B. Fawcett (2013b) Meteorological aspects of the Margaret River fires on November 2011. Poster, Annual Conference of the Australian Meteorological and Oceanographic Society, Melbourne, 11 to 13 February 2013.

Peace, M. and G. Mills (2012b) A case study of the 2007 Kangaroo Island bushfires. CAWCR Technical Report No. 53, The Centre for Australian Weather and Climate Research, Melbourne, Australia.

Peace, M., G. Mills, T. Mattner, L. McCaw and J.D. Kepert (2013a) Coupled numerical simulations show a fire changes the weather forecast (*in preparation*).

Peace, M., G. Mills, T. Mattner, L. McCaw and J.D. Kepert (2013b) Coupled WRF-fire simulations of the Rocky River fire (*in preparation*).

Thurston, W. (2012a) Updraft phenomena in wildfires: an annotated bibliography. Project report to the Bushfire CRC.

Thurston, W., R.J.B. Fawcett, J.D. Kepert and K.J. Tory (2012b) Forecasting wind direction variability using numerical weather prediction. Poster, Annual Conference of the Australasian Fire and Emergency Services Council and the Bushfire Cooperative Research Centre, Perth, 28 to 30 August 2012.

Thurston, W., R.J.B. Fawcett, J.D. Kepert and K.J. Tory (2012c) Idealised numerical modelling of bushfire plumes. Poster, Annual Conference of the Australasian Fire and Emergency Services Council and the Bushfire Cooperative Research Centre, Perth, 28 to 30 August 2012.

Thurston, W., J.D. Kepert, R.J.B. Fawcett and K.J. Tory (2012d) A note on the ACCESS configuration used to investigate wind variability and boundary-layer structure. Project report to the Bushfire CRC.

Thurston, W., K.J. Tory and J.D. Kepert (2012e) Briefing note: choice of updraft phenomena conducive to firebrand lofting. Project report to the Bushfire CRC.

Thurston, W., K.J. Tory, J.D. Kepert and R.J.B. Fawcett (2013c) Briefing note: model configuration for investigating updraft phenomenon number one. Project report to the Bushfire CRC.

Thurston, W., K.J. Tory, J.D. Kepert and R.J.B. Fawcett (2013d) Briefing note: model configuration for investigating updraft phenomenon number two. Project report to the Bushfire CRC.

Thurston W., K.J. Tory, R.J.B. Fawcett and J.D. Kepert J D (2013e) Idealised numerical modelling of bushfire plumes and their potential for firebrand lofting. Poster. Annual Conference of the Australasian Fire and Emergency Services Council and the Bushfire Cooperative Research Centre, Melbourne, 2 to 5 September 2013.

Thurston W., K.J. Tory, R.J.B. Fawcett and J.D. Kepert J D (2013f) Large-eddy simulations of bushfire plumes in the turbulent atmospheric boundary layer. Poster. Annual Conference of the Australasian Fire and Emergency Services Council and the Bushfire Cooperative Research Centre, Melbourne, 2 to 5 September 2013.

# 3. Enhancement of fire behaviour models (University of Melbourne)

PHOENIX RapidFire is a fire characterisation package developed by the University of Melbourne as part of Bushfire CRC research. The model dynamically integrates information on fuel, weather, topography, the fire itself and fire suppression to create predictions of fire spread perimeters, local fire intensities, spread rates and ember load. The model has now been implemented as a tool for operational fire planning in Victoria and it is being evaluated in New South Wales, South Australia and Tasmania. It is also being used in Victoria to simulate suites of hypothetical fire events to evaluate landscape risk and determine the relative costs and benefits of alternative management decisions. PHOENIX RapidFire is an integral component of FireDST and acts as the computation engine that provides predictions of fire impacts for each scenario evaluated. This project focused on the enhancement of PHOENIX RapidFire to better enable effective integration into FireDST and the improvement of model function to achieve more accurate and robust predictions. Specific outcomes of this research project include:

- the development of metrics for evaluating fire model predictive performance against observed fire perimeters;
- modification of PHOENIX RapidFire code to incorporate BoM ACCESS gridded weather forecasts and reconstructions.
- an enhanced convection based ember transport model for improved prediction of extreme fires;
- the parameterisation of a house-loss probability model;
- the development of a functional definition of the Wildfire Urban Interface Zone based on risk
- the development of a novel algorithm for improving the simulation of fire suppression by better estimating vehicular travel times and routes; and
- an assessment of the sensitivity of PHOENIX RapidFire predictions to inputs and simulation parameters;

Research questions that were established at the commencement of the project include:

RQ(2) What is the sensitivity of the PHOENIX RapidFire fire characterisation model to detailed meteorology, and can uncertainties in model predictions be quantified and communicated?

RQ(3) What are the sensitivities of the current fire hazard and fire impact models to current fuel classifications? Are the current fuel definitions appropriate for accurate fire characterisation; are current spatial databases of biomass fuels and fuel properties adequate and what are the options for improving them? What is the potential in the near-term for application of remote sensing technology to spatial mapping of fuels?

RQ(4) Can urban interface design be described at a neighbourhood level, so that potential house loss during a given scenario can be adequately predicted? Can urban interfaces be usefully mapped by remote sensing or otherwise so that the fuel levels and proximity can be used in both fire behaviour and house loss modelling?

## 3.1 RQ(2) Sensitivity of PHOENIX RapidFire to weather inputs

The Bureau of Meteorology supplied ACCESS model runs for each study area at three spatial resolutions (grid spacings of 440 m, 1.3 km and 4.0 km) and at five-minute intervals for evaluation. Current weather forecasts are available on a 6-kilometre grid at hourly intervals. In time, computing power will enable finer spatial and temporal forecast weather to be produced operationally. This study was undertaken to understand what benefit finer-scaled data might be to fire spread prediction.

Raw ACCESS model runs exhibited a significant wind speed bias, underestimating 10-metre wind speed by up to a factor of 1.5 at all resolutions when compared with AWS observations recorded close to the case-study fires. When these values were used as inputs to PHOENIX RapidFire, the resultant predictions were substantial underestimates when compared to actual fire spread (Chong *et al.,* 2012). While the ACCESS model simulations produced detailed and realistic indications of weather conditions on the day, further research is necessary to improve estimates of surface winds if the results are to be used for fire spread prediction. A wind speed bias correction process was undertaken by Geoscience Australian to allow the ACCESS model runs to be evaluated with PHOENIX RapidFire and compared to the actual fire spread for the Kilmore case study.

PHOENIX RapidFire was used to model the 2009 Kilmore fire with different spatial and temporal weather inputs (Table 3.1). Because a fire of this size interacts with the local weather, it was found that courser level weather inputs performed better than very fine resolution data. Overall, weather forecasts at 30 minutes intervals and 1.3 km grid spacing provided the best inputs for matching the progression of the fire (Chong *et al.,* 2012; see Figure 3.1). Once the fire had reached about 100,000 ha, 60 minute, 4 km data gave the best predictions (Chong *et al.,* 2012).

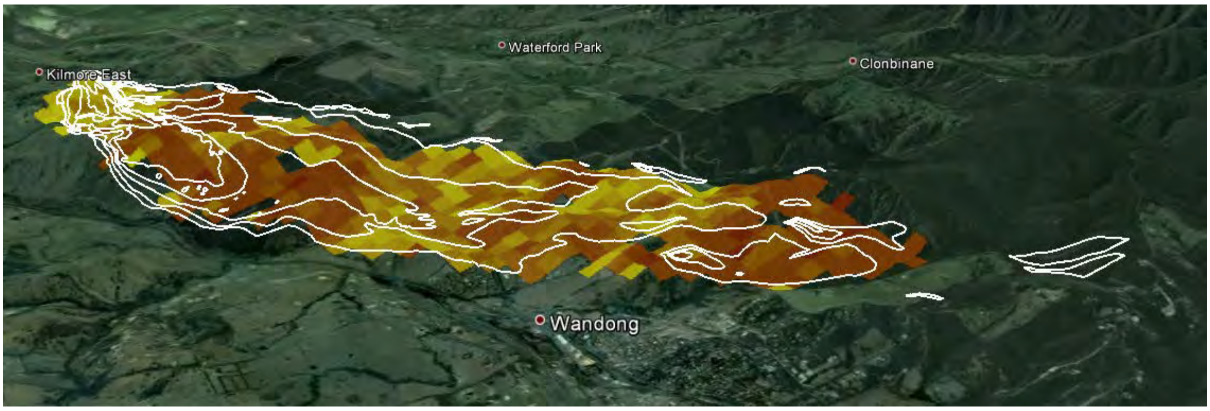



***Figure 3.1*** *Yellow to red pixels showing modelled flame height with the white polygons of the reconstructed fire progression as of 14:45 EDT.*

Modelling weather at 440-metre grid spacings and at five-minute intervals provides weather forecasters with good insights into the dynamics of the weather, but that additional detail is not temporally and spatially accurate enough to be of the same benefit to fire spread predictions. Large fires ‘smooth’ the weather, terrain and fuel in the landscape and so the coarser spatial and temporal weather forecasts resulted in better fire spread predictions under extreme fire weather conditions.

More case-studies need to be undertaken, including smaller fires burning under milder conditions to better understand the relationship between weather data scale and fire spread prediction.

***Table 3.1*** *Area-weighted-average ADI values for 11:45 EDT and 11:40 EDT ignitions modelled to 18:00 EDT (time steps = 18). (An ADI value of zero is an exact match so larger values are poorer fits; see Duff et al. (2013c) for an explanation of ADI.)*

| Input | ADI_1145 | ADI_1140 |
|---|---|---|
| 4000_T5 | 0.818 | 0.860 |
| 4000_T15 | 0.781 | 0.779 |
| 4000_T30 | 0.797 | 0.838 |
| 4000_T60 | 0.714 | 0.694 |
| 1200_T5 | 2.231 | 1.137 |
| 1200_T15 | 1.038 | 1.736 |
| 1200_T30 | 1.695 | 0.829 |
| 1200_T60 | 1.886 | 2.251 |
| 440_T5 | 2.083 | 2.082 |
| 440_T15 | 2.843 | 2.336 |
| 440_T30 | 2.325 | 1.583 |
| 440_T60 | 1.223 | 2.229 |

### 3.1.1 Introducing the third dimension into PHOENIX RapidFire

PHOENIX RapidFire is a dynamic fire behaviour simulator, but initial fire behaviour calculations are based on the Mk5 McArthur Forest Fire Danger meter and the CSIRO Grassland Fire Behaviour meter. These models were parameterised empirically using observations of experimental fires and were not designed for extreme fire events. A reconstruction of the pattern of spread of the Black Saturday Kilmore fire indicated that the ignition of new fires through ember transport was the predominant driver of fire propagation. Reconstruction evidence suggested that mass spotting events were preceded by extreme convective fire behaviour, commonly driven by topography. An ember transport mechanism to emulate this process was developed and calibrated using the Kilmore fire (Chong *et al.,* 2012c) and is one of the dynamic fire behaviour processes included in PHOENIX RapidFire.

This process was developed to emulate long-distance (>200 metres) spotting effects. Ember-driven fire behaviour at scales smaller than this was assumed to be captured in the spread models that underlie PHOENIX RapidFire. The conditions that facilitate convection driven spotting were determined by using a ‘heat segment’ approach, where areas of concentrated heat output on the fire perimeters were identified. The hottest 25% of the fire perimeters were assumed to be where convection-driven embers were assumed to occur.

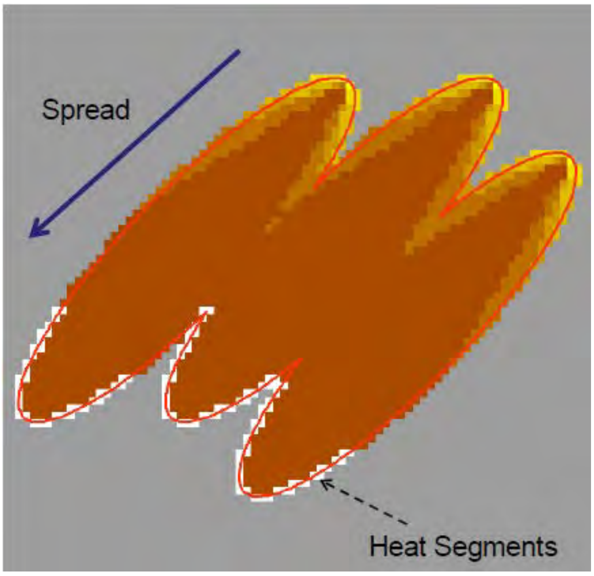



***Figure 3.2*** *Identification of the hottest 25% of the fire perimeter as sources for convection driven embers (Chong et al., 2012b).*

The amount of energy being generated by the fire within each heat segment was used as a proxy for convective uplift. Hotter heat segments were assumed to generate greater uplift and consequently loft embers higher. Convective-driven embers were modelled to travel in ambient winds before landing in a pattern based on a Weibull pattern. The number of embers launched was proportional to the amount of bark in the fuel cells burning within the footprint of the designated heat segments.

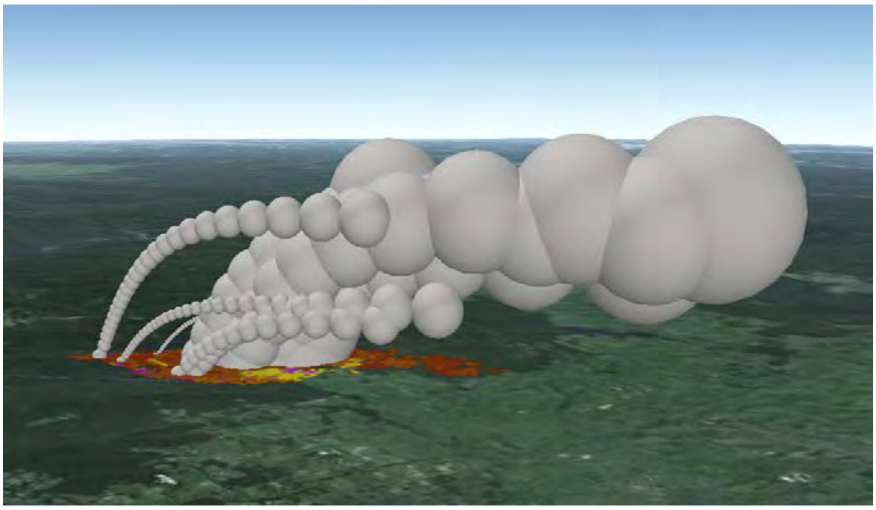


***Figure 3.3*** *Convection 'bubbles' used to scale ember transport based on surface heat concentration (Chong et al. 2012b)*

The ignition of new spotfires occurs when the number of viable embers entering an unburned cell reaches a particular threshold. Ignition thresholds are set based on the fuel conditions of the target cell. This process effectively emulates middle to long-distance spotting (1 to 30 km) based on the amount of bark material present, the convective strength in a cell from which the embers are launched, the wind speed and direction, and the fuel quantity and moisture content at the location of ember drop.

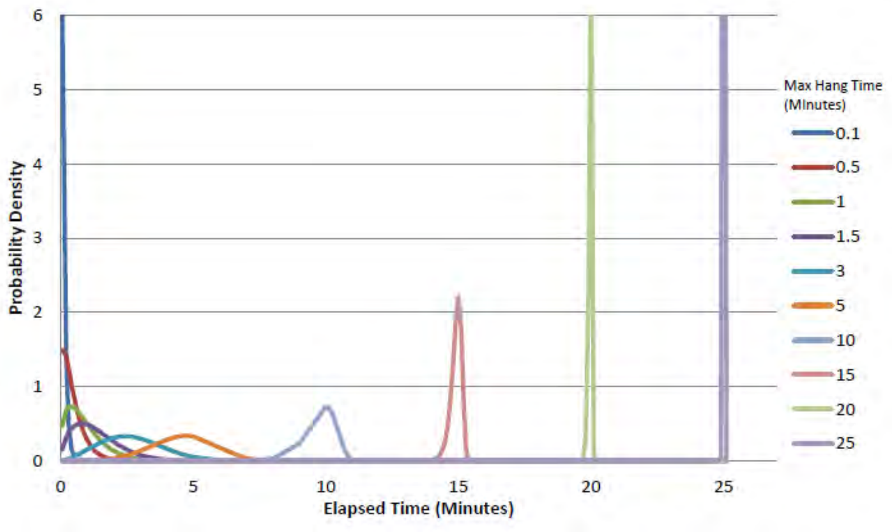



***Figure 3.4*** *Ember distribution pattern of the PHOENIX RapidFire convection lofted embers (Chong et al., 2012c)*

The ember transport model in PHOENIX RapidFire was empirically calibrated against spotfire ignitions observed at the Kilmore fire. There has been limited research that can verify whether the model as implemented is a realistic emulation of a physical process. Further study of real fires is required to evaluate how effective this model is in generalising ember driven propagation. In the case study fires, without the simulation of ember driven fire propagation, the model would substantially under predict fire spread.

#### *3.1.1.1 Use of ACCESS vertical wind information within PHOENIX RapidFire*

PHOENIX RapidFire was modified to be able to accept ACCESS weather forecasts and reconstructions as inputs. The modification allows spatially gridded weather to be processed at the resolution at which it is supplied. As a result, the current implementation is able to run simulations using point observations (such as AWS data), standard GFE forecasts or high resolution ACCESS simulations. A patch was developed to allow the use of upper level winds as a transport mechanism in the ember module for use in FireDST, however this feature is experimental only and has not been officially incorporated into a release of the PHOENIX RapidFire spread engine (Chong *et al.,* 2012a).

#### *3.1.1.2 Quantifying wind speed profiles within forest canopies*

A PhD student was engaged to investigate the link between the winds that drive forest fire spread and the open area wind forecast. When predicting forest fire spread, wind reduction factors are typically applied to reduce open area wind speeds to the more sheltered sub-canopy winds that drive fire spread. Winds were measured at different heights in a variety of vegetation types and compared to the open area (meteorological standard) wind speeds (Moon *et al.,* 2013).

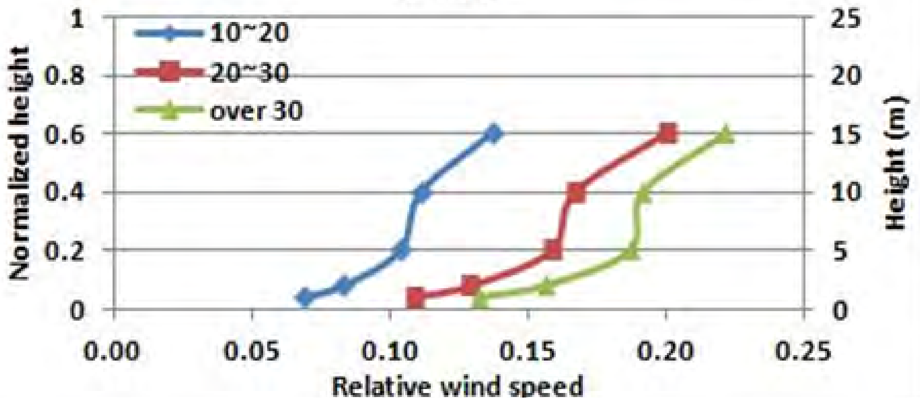
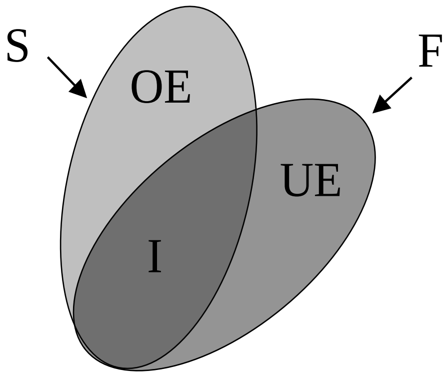



***Figure 3.5*** *Variation in relative wind reduction in open woodland categorised by open area wind speed (10-20, 20-30 and 30+ km $h^{-1}$).*

Our results indicate that the use of a single wind reduction factor is a gross over-simplification; horizontal wind speeds can vary by a factor of three depending of the height above ground. We have also found that even for a given height, the wind reduction factor can vary by a factor of two or more depending on the strength of the winds in the open. This is in addition to a factor of 10 or more variation in wind speed between different vegetation types. The magnitude of these effects is substantial and has not been reported elsewhere (Moon *et al.,* 2013). This is the topic of ongoing research.

## 3.1.2 Quantifying and communicating uncertainties in model predictions

This effective achievement of the goals of this project requires that the outputs of PHOENIX RapidFire simulations be compared to observations of fires or other fire spread simulations. To do this objectively, appropriate metrics for comparison were required. A substantial literature review was undertaken in order to source suitable comparison methodologies, however it became obvious that there were no suitable metrics in broad, regular use. As objective methods of evaluating fire spread models are critical for the validation, calibration and the systematic improvement of predictive performance, we developed a number of new methods for comparing fire shapes. An indication of overall area congruence was developed as the Area Difference Index. This is a 'critical failure' ratio, indicating the amount of area incorrectly predicted as a proportion of that correctly predicted (Duff *et al.,* 2013c). The ADI has been used for sensitivity analysis and for the calibration of model function.

A) 


B) $$ADI\ (t) = \frac{OE(t)+UE(t)}{I(t)}$$

***Figure 3.6*** *The Area Difference A) a spatial representation of the ADI, with S as the simulated fire and F as the reference fire, and B) the ADI equation (Duff et al., 2013c), where OE = Overprediciton Error, UE = Underprediction Error and I = area of Intersect at time (t) between the actual fire (F) and the simulated fire (S).*

A number of other metrics were developed for more precise assessment of model performance. In addition to the evaluation of area overlap, Procrustes shape configuration analysis was used as a model for evaluating differences in size, perimeter configuration and orientation.

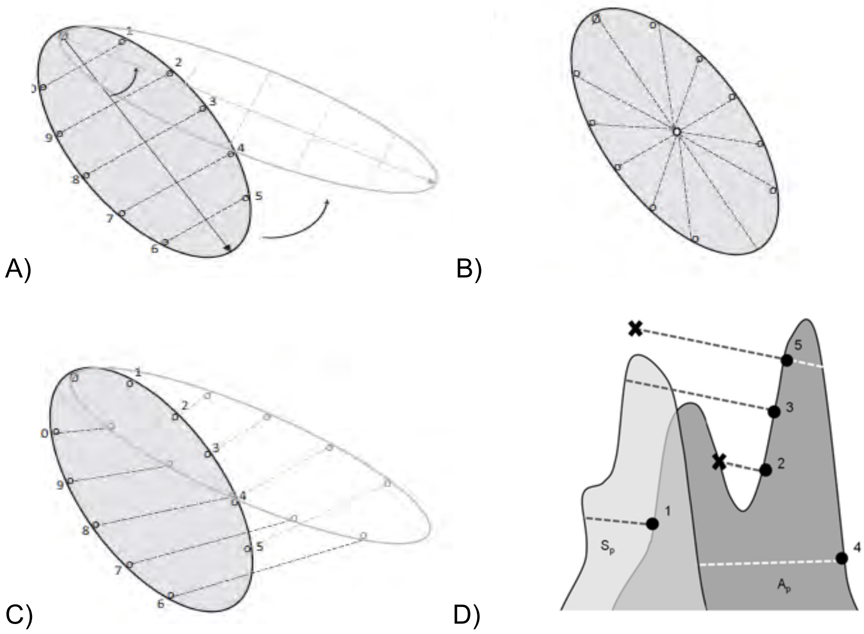



***Figure 3.7*** *Fire predictive performance shape comparators A) Orientation, B) Centroid size, C) Perimeter configuration (shape) and D) vector based spread difference.*

For highly congruent perimeters, a method of sampling presumed travel paths is demonstrated as a tool for evaluating spread differences in a spatially explicit manner. The metric design approach was to develop a toolbox of metrics to enable the systematic evaluation of all predictions (Duff *et al.,* 2012, Duff *et al.,* 2013a).

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### 3.1.3 Conclusions

The higher spatial and temporal resolution weather forecast data did not have the spatial and temporal accuracy needed to improve PHOENIX RapidFire simulations of large-scale fire events such as occurred on Black Saturday 2009. The optimum resolution for fire simulation of the Kilmore fire until it reached 100,000 ha was 1.3-km grid spacing and 30-minute time intervals. Beyond this size, 4.0-km grid spacing and 60-minute time intervals gave the best predictions of fire spread.

It is assumed that the reverse would also be true, i.e. that for smaller fires under milder conditions that higher spatial resolutions and shorter time interval data, e.g. 440 m grid spacing and 15 minutes, would be best, but we did not have appropriate fire spread observations to test this assumption.

From a weather forecasting perspective, the high resolution weather forecast data was very useful in detecting detailed weather phenomenon that was not apparent at larger scales.

## 3.2 RQ(3) Sensitivity of PHOENIX RapidFire to Fuel Inputs

The influence of fuel load on fire affected areas was evaluated by systematically varying the total fine fuel load under a consistent set of environmental conditions. The fire danger rating for the weather conditions was Severe.

Grass fuels were simulated as loads of 2, 4, 6, 8 and 10 tonnes per hectare. Forest fuels were simulated as loads of 10, 15, 20, 25 and 30 tonnes per hectare (t $ha^{-1}$). For forest fuel loads, the fine fuel load was distributed between surface, elevated fuel and bark using a ratio of 9:1:3. A wind reduction factor of 1.2 was used for grass fires and 3.5 for forest fires. Fires were assumed to ignite at 1300 h and burn for 4 hours.

### 3.2.1 Grass Fuel type

The CSIRO grassland model exhibited an almost linearly increasing area with increasing fuel load (Figure 3.8). This is in contrast to the PHOENIX RapidFire output which showed a positive, but diminishing effect with increasing fuel load. Observation of the PHOENIX RapidFire output indicated that lateral spread was lower than that predicted assuming zero wind in the direction of lateral spread, and is an indication that the fire shape assumptions (both of elliptical growth with the CSIRO model and the spread pattern of PHOENIX RapidFire) may need more consideration. As the CSIRO model fuel categories are intended to take into account fuel structure as well as load, the CSIRO model outputs are a combination of both properties, which may be contributing to the differences to in the model results. Above 6 t $ha^{-1}$ fuel load, the area burned in the PHOENIX RapidFire model was predicted to decline. This load is beyond the range for which the CSIRO model was developed. The effective range of the model for grass fuel loads has been extended to accept higher fuel accumulations in sedgelands and more productive grasses.

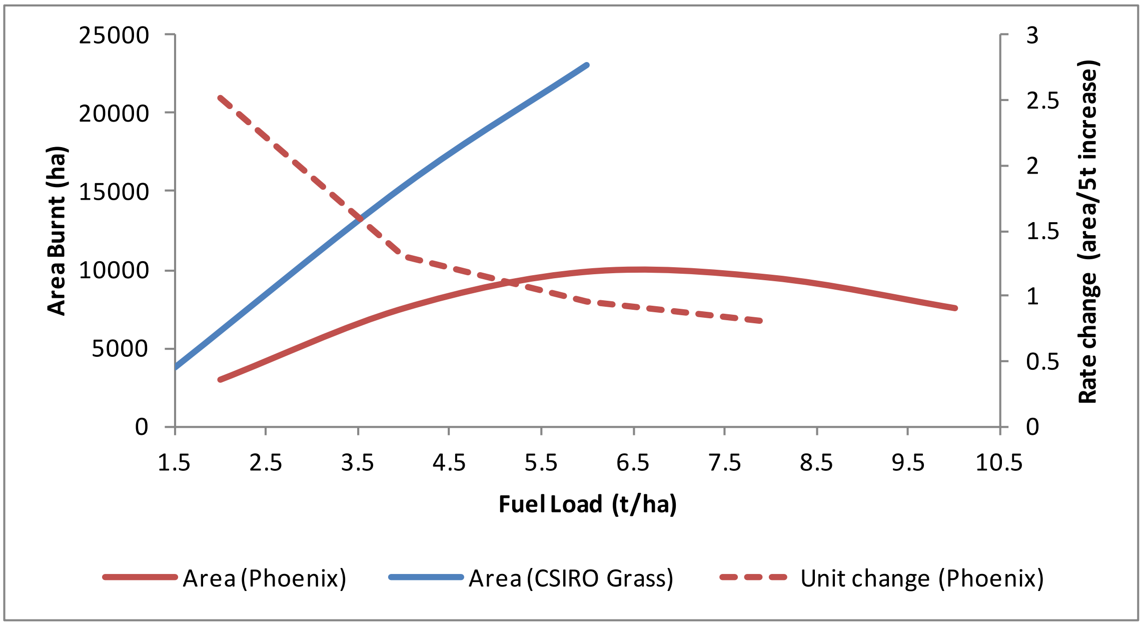


***Figure 3.8*** *Grass fuel type area burnt in response to systematically changing fuel load (Chong et al., 2012d).*

### 3.2.2 Forest Fuel type

In forest fuels, both the McArthur Mk5 model and PHOENIX RapidFire exhibited increasing burnt area in response to increasing fuel loads (Figure 3.9). At low fuel loads, the absolute predicted areas between the two models were similar, however PHOENIX RapidFire exhibited a greater rate of increase with increasing fuel load, resulting in approximately double the affected area at a fuel load of 30 t.ha$^{-1}$. An important feature of PHOENIX RapidFire is the ability to discriminate between different sources of fuel. At low calculated fire intensities (such as when fuel load is low), only the litter fuel will be consumed as a fire burns. As the intensity increases, the elevated and bark fuels will also be burned, accelerating spread rates. An important mechanism of fire spread at high intensities is the initiation of new fires through the transport of embers. PHOENIX RapidFire spreads fires spatially; this ember transfer can be simulated and can materially contribute to increasing fire affected area. It is likely that the increase in difference affected area above 25 t.ha$^{-1}$ is due to the simulation of spotting due to ember transport (Chong, 2013).

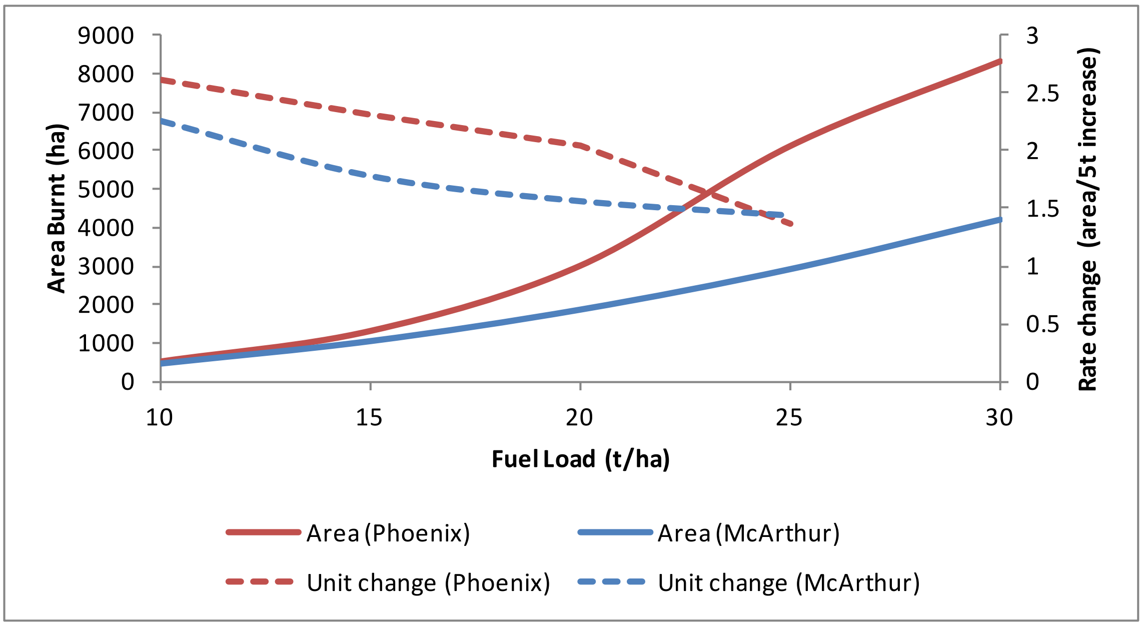


***Figure 3.9*** *Forest fuel type area burnt in response to systematically changing fuel load (Chong et al., 2012d).*

PHOENIX RapidFire therefore is quite sensitive to the arrangement of the fuel and the amount of spotting material (bark) present.

### 3.2.3 Conclusions

PHOENIX RapidFire is relatively insensitive to the mapping of grassland fuels. A ten-fold increase in fuel loads in grassland fuels only results in a change in spread area by a factor or two or three. Remote sensing could readily be used to map grassland fuels in sufficient detail for good simulation accuracy.

Forest, woodland and shrubland fuel arrangement and quantity are all important to fire simulations in PHOENIX RapidFire. The area burnt can be an order of magnitude greater for just a threefold increase in fine fuel loads. Whilst it is relatively easy to map the extent and coverage of the overstorey canopy, it is much more difficult to use remote sensing to map surface, elevated and bark fine fuels. These components of the fine fuel complex are important inputs to fire simulations in PHOENIX RapidFire.

## 3.3 RQ(4) Defining the Bushfire Interface

The interface zone in relation to wildfires has been defined in many ways.  Some definitions are tailored for a particular application. There is no consistent way of defining the interface or demarcating it on the ground. The reality is that the interface zone at a particular location will vary depending on the weather, fuel, scale of fire and terrain at any one time. Therefore, current definitions are based more on the ease of application rather than the likely extent of a wildfire into a residential area. There is a need to have a more consistent and relevant definition of the interface zone for planning, warnings and regulation.

The term ‘interface’ implies a zone where residential areas and fires will mix. The extent of the wildfire interface is therefore the extent to which a wildfire can penetrate a residential area before it either self-extinguishes or transitions into an urban fire, with the progression of a fire front via house-to-house ignition or structure-to-structure ignition rather than via wildland fuels. It therefore follows that the majority of house loss caused by wildfires should occur in the Wildfire Interface Zone.

The Wildfire Interface Zone has been referred to in several different ways.  It has been called the ‘I-Zone’, ‘Wildland-Urban Interface (WUI)’, ‘Rural-Urban Interface’, ‘Urban-Interface’, ‘Chaparral-Urban Interface’ (Radke 1983) and possibly others. These names themselves contribute to a level of confusion when talking about exposure to wildfire. Interestingly, all the names are euphemisms for what is really of interest - the interface with wildfire.

Dynamic wildfire characterization simulators such as PHOENIX RapidFire (Tolhurst *et al.,* 2008) have provided a means for defining the Wildfire Interface, taking into account potential fire size, intensity and ember density (Tolhurst *et al.,* 2013). PHOENIX RapidFire takes into account the spatial and temporal distribution of fuels, fire, weather, terrain, ignition time and location and modifications to fuels caused by recent fires or other fuel modification works and disruptions to fuels caused by roads, rivers, fuelbreaks, and other linear fuel-free areas (Chong *et al.,* 2012e). Figure 3.10 provides a comparison between a dynamically modelled wildland edge and a symmetrical zoning approach for defining the wildland edge.

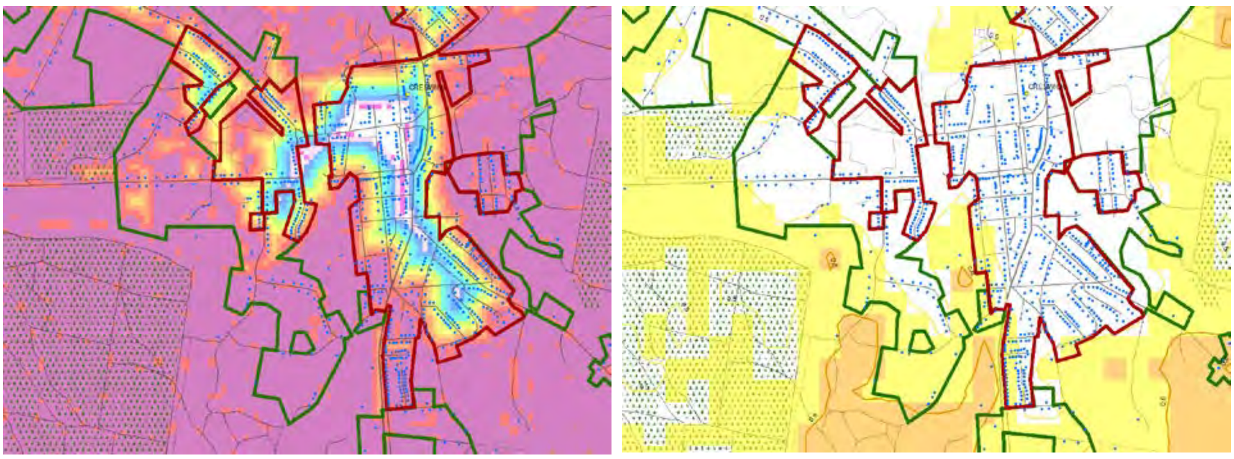

***Figure 3.10*** *A comparison with between a symmetrical zoning approach showing the distance from a defined "wildland" edge (left) and a dynamically modelled approach showing contours of house loss probability at a Forest Fire Danger Index of 100 (right) (Tolhurst et al., 2013).*

Some preliminary analyses have shown that it is not just the fuel within some set distance (e.g. 40m, 100m) of a residential area that affects the probability of house loss by wildfire, but all the factors that contribute to wildfire behaviour (Tolhurst *et al.,* 2013). PHOENIX RapidFire can be used to redefine the Wildfire Interface Zones based on local fuels, terrain and climate. We therefore propose a new definition of the Wildfire Interface Zone be adopted and defined as:

***"The area where dwellings, or flammable material in contact with dwellings, have the potential to be ignited by exposure to any combination of flame, radiation, embers, firebrands or hot gases from a wildfire. It does not include areas only exposed to smoke, ash or charred material from a wildfire.***

***The extent of the actual Wildfire Interface Zone will depend on the nature of the fuels, weather, topography, seasonal conditions and scale of wildfires in that geographic location at a given point in time, but for planning purposes the extent of the potential Wildfire Interface Zone can be determined for a stated set of conditions."***

### 3.3.1 Fire suppression

A key part of understanding fire behaviour in populated areas is understanding human responses. PHOENIX RapidFire includes a basic algorithm for emulating the effects of fire suppression, and as part of this project, methods of improving this were investigated. An exhaustive literature review was undertaken of existing fire suppression methodologies (Duff & Tolhurst 2012, 2013a,c,d), and this was used as a foundation for the improvement of the model module. As travel to fire is a key part of suppression, a novel algorithm was developed that could optimise and emulate emergency vehicle travel to fires. While network travel time algorithms are widely available, this method was unique as it allowed both on road and off road (cross country) travel to be evaluated. The method uses a cost-distance cellular automata to estimate the travel time from anywhere in the landscape to a reported fire location, route finding in complex terrain to determine the likely travel time and provide an indication of the optimal route (Duff *et al.,* 2013b).

The cellular automata is initiated at the target point of interest (for example a fire), and the algorithm then systematically spreads outwards, tallying the travel time back to the start point at each step. Figure 3.11 illustrates the process; the algorithm was initiated at the location of the black diamond, and the accumulated travel time (for programmatic efficiency, measured in millions of milliseconds) from the start point is indicated with colours grading from red (short travel time) to blue (long travel time). As it is unrealistic to search for cross-country routes long distances from the fire, after a specified accumulated travel time level, e.g. one hour, cross-country route finding is stopped only travel costs along preferred routes (roads or tracks) continue to be tallied. The travel cost takes the nature of the terrain and vegetation into account for cross-country travel and road quality is included in travel cost on roads. By analysing the lineage of the algorithm spread, the fastest route from any point in the landscape to the fire can be determined.

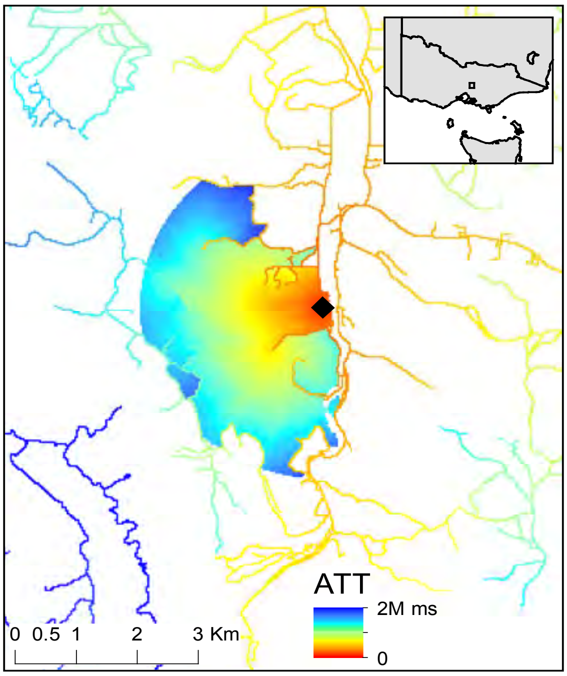


***Figure 3.11*** *An indication of on and off road travel time to reach a point of interest. Accumulated travel time (ATT) is in units of milliseconds.*

### 3.3.2 Conclusions

The travel cost method has been shown to be an effective and efficient way of determining the fastest route to a fire across trackless land combined with a road and track network of various travel speeds. This modelling could potentially be used to identify the optimal location for stationing fire suppression resources in preparation for fire suppression and for modelling the most efficient dispatch strategy for going fires. The travel time model builds on the data and methods used in PHOENIX RapidFire.

# University of Melbourne publications for this project

## Peer-reviewed publications

Duff, T.J., Chong, D.M., Taylor, P., and Tolhurst, K.G. (2012) Procrustes based metrics for spatial validation and calibration of two-dimensional perimeter spread models: A case study considering fire. Agricultural and Forest Meteorology, 160, 110-117.

Duff, T.J., Chong, D.M. and Tolhurst, K.G. (2013a) Quantifying spatio-temporal differences between fire shapes: estimating fire travel paths for the improvement of dynamic spread models. (submitted to Environmental Modelling and Software).

Duff, T.J., Chong, D.M. and Tolhurst, K.G. (2013b) Using discrete event simulation cellular automata models to determine multi-mode travel times and routes of terrestrial suppression resources to wildland fires. (submitted to the European Journal of Operational Research).

Duff, T.J., Chong, D.M., and Tolhurst, K.G. (2013c) The Area Difference Index (ADI), an improved index for the comparison of patterns of fire spread. (submitted to the Journal of Environmental Informatics).

Duff, T.J., and Tolhurst, K.G. (2013c) A review of approaches to modelling the suppression of wildland fires: 1. Preparedness (submitted to the Journal of Environmental Modelling and Software).

Duff, T.J., and Tolhurst, K.G. (2013d) A review of approaches to modelling the suppression of wildland fires: 2. Response (submitted to the Journal of Environmental Modelling and Software).

Moon, K., Duff, T.J. and Tolhurst, K.G. (2013) Characterising forest wind profiles for utilisation in fire spread models. 20$^{th}$ International Congress on Modelling and Simulation, Adelaide, 1$^{st}$ to 6$^{th}$ December .

Pugnet, L., Chong, D.M., Duff, T.J.,and Tolhurst, K.G. (2013) Wildland–urban interface (WUI) fire modelling using PHOENIX RapidFire: A case study in Cavaillon, France, 20$^{th}$ International Congress on Modelling and Simulation, Adelaide, 1$^{st}$ to 6$^{th}$ December .

Tolhurst, K.G. and Chong, D.M. (2011) Assessing potential house losses using PHOENIX RapidFire. In: R.P. Thornton (ed.) Proceedings of Bushfire CRC & AFAC 2011 Conference Science Day, 1 September 2011, Sydney Australia. Bushfire CRC. Pp. 74-86.

Tolhurst, K.G., Chong, D.M. and Duff, T.J. (2013) Redefining the Wildland-Urban Interface based on dynamic fire modelling. 20$^{th}$ International Congress on Modelling and Simulation, Adelaide, 1$^{st}$ to 6$^{th}$ December.

## Bushfire CRC/Internal-reviewed publications

Chong, D.M.and Tolhurst, K.G. ( 2012) PHOENIX -Under the Hood A technical guide to the PHOENIX bushfire characterisation model, Version 3.9. Technical Report, Bushfire CRC / University of Melbourne. 32pp.

Chong, D.M., Duff, T.J. and Tolhurst, K.G. (2012) Evaluation of weather data at different spatial and temporal scales on fire behaviour prediction using PHOENIX RapidFire 4.0 - Kilmore case study. Technical Report, Bushfire CRC / University of Melbourne. 19pp.

Chong, D.M., Tolhurst, K.G. and Duff, T.J. (2012a) Incorporating vertical winds into PHOENIX RapidFire's ember dispersal model. Technical Report, Bushfire CRC / University of Melbourne. 17pp.

Chong, D.M., Tolhurst, K.G. and Duff, T.J. (2012b) PHOENIX RapidFire 4.0's convective plume model. Technical Report, Bushfire CRC / University of Melbourne. 23pp.

Chong, D.M., Tolhurst, K.G. and Duff, T.J. (2012c) PHOENIX RapidFire 4.0's convective and ember dispersal model. Technical Report, Bushfire CRC / University of Melbourne. 22pp.

Chong, D.M., Tolhurst, K.G., Duff, T.J., Cirulis, B. (2012) Sensitivity Analysis of PHOENIX RapidFire. Technical Report, Bushfire CRC / University of Melbourne. 27pp.

Chong, D.M., Tolhurst, K.G., Duff, T.J., Ackland, A., Gretton, T. (2012) Interface Fuels for PHOENIX. Development Note, Bushfire CRC / University of Melbourne / Department of Environment and Primary Industries, Victoria. 9pp.

Duff, T.J. and Tolhurst, K.G. (2012a) Incorporating realistic suppression simulation into PHOENIX

RapidFire: Algorithm structure and description. Development Note, Bushfire CRC / University of Melbourne. 4pp.

Duff, T.J. and Tolhurst, K.G. (2012b) A review of approaches to the modelling of wildfire suppression for landscape management. Technical Report, Bushfire CRC / University of Melbourne. 50pp.

# 4 Regional and local impacts from bushfire smoke (CSIRO Marine and Atmospheric Research)

The team from CSIRO Marine and Atmospheric Research has developed the proof of concept for an operational smoke impact modelling framework.

The atmosphere is the medium transporting the impacts of fires from the fire ground to the wider region. It is becoming increasingly apparent that the health impacts can be significant. The challenge for a toolkit is to integrate smoke dispersions predictions, which typically require substantial computing resources into a short-term modelling framework. The aim of this project therefore was to identify the issues of smoke dispersion that are relevant to operational fire management and fire risk assessment.

This component of FireDST is addressing impacts from smoke dispersion. Research questions (RQ) in the FireDST science plan being addressed by this component are:

- RQ(6d) How effective and accurate are current models of smoke emission and dispersion in describing the vertical and horizontal distribution and concentration of smoke?
- RQ(6a) What are the impacts on air quality from smoke emitted from extreme fires?
- RQ(6b) How do these compare with the impacts from prescribed burning?
- RQ(6c) What are the risks to population health from exposure to smoke from both sources?
- RQ(6e) What are the options and requirements for developing them into operational tools for planning and incident control?

## 4.1 Introduction

Community concern about the impact of smoke on health arises because of two factors. The first is the direct impact of smoke from the event itself on the health of the population close to the event source and several hundred kilometres away from the source as smoke undergoes long range transport. The second arises from the management response to reduce risk of extreme fire events that has the potential to contribute to additional adverse health outcomes. Usually this management involves small prescribed fuel reduction burns designed to reduce the severity of extreme wildfires. However these fuel reduction burns produce smoke that impacts communities immediately surrounding the prescribed fires. And while the distance this smoke may be transported is low (10s of kilometres), many prescribed burns are conducted in or near the rural-urban interface where human population is significant.

## 4.2 Framework

To understand the impacts of smoke emitted from fires (extreme and prescribed burning fires) a smoke impact modelling framework has been developed.

The framework consists of:

1) Tools for developing a spatial emissions inventory suitable for input into chemical transport models (this provides information on the location and rate of smoke emissions);
2) A chemical transport model (CTM -this provides information on the dispersion of smoke and possible chemical transformations in the smoke plume);
3) Tools for verifying the performance of the two, particularly for predicting surface air quality (this provides information on how well the emission inventory/chemical transport model system is able to simulate smoke emission and dispersion);
4) Tools for determining population exposure (this provides information on the location of people and their proximity to smoke sources);
5) Knowledge of risk associated with smoke exposure (this provides information on how many people will experience a particular health outcome at specific particle loading).

### 4.2.1 Emission Model

Emission sub-models provide information on fuels, consumption and emission factors. They require a large amount of local information, although the general form of these sub-models are well established (Russell-Smith *et al.,* 2009). Information required to drive the model includes fuel loads, burning completeness, fire area, patchiness, and emission factors. Also required is information on the rate of fire spread in order to convert from the time frequency of fire area data (usually daily) to hourly emission rates required for smoke dispersion modelling. While much of this information exists (e.g. fuel load models and data bases for Victoria), it is currently not collated into a single data base. Additionally, emission factors are generally based on overseas data, and thus an important component of the current project has been the refinement of these factors based on local experimental work. This project has involved the collation of this information and the development of tools to convert the formats to those required for input to the CTM (below).

### 4.2.2 Chemical Transport Model (CTM)

Modelling fire is inherently difficult because it cannot be treated using the prescribed methods of managing emissions as either point or area sources. A fire cannot be treated as a point source because it can travel some distance on the ground; however area sources traditionally do not involve heat release and therefore cannot account for the vertical transport of smoke in buoyant plumes. Most plume rise calculations only work with point source emissions of hot plumes from chimney stacks. This then poses a problem for the dispersion modeller.

Fire modelling is also a complicated multi-scale process, from the flame reaction zone on millimetre scale to the synoptic weather scale of hundreds of kilometres (Mandel *et al.,* 2011). Weather has a major influence on wildfire behaviour; in particular, wind plays a dominant role in the fire spread. A forecast model for Australia may require an Australia wide grid in order to incorporate all influences on local meteorology.

This also poses a question of model scale. The model grid needs to be large enough to include large scale mixing features, yet small enough to depict valleys and local topographical features etc. Thus a model with a grid-nesting capability is required. After reviewing all available models and the costs of implementing them for southern Australia (Meyer, Emerson and Keywood, 2012) the modelling approach adopted in the Risk Tool Kit was

(1) The Cubic Conformal Atmospheric Model (CCAM) with the CTM for regional modelling

(2) The Air Pollution Model (TAPM) for local operational planning

### 4.2.3 Observational Data

Observational data available to assess the performance of the models included air quality data from Aspendale Victoria (Bayside Air Quality Station operated by CSIRO Marine and Atmospheric Research) from Ovens and Manjimup (collected as part of the Clean Air Research Program by CMAR; Meyer *et al.,* 2008; Reisen *et al.,* 2011), from the Huon Valley (collected as part of the Huon Valley Air Quality Study by CMAR; Meyer *et al.,* 2011) and air quality data collected by EPA Victoria and in the Victorian air quality monitoring networks. Also available was remotely sensed data products including aerosol data from CALIPSO (Cloud-Aerosol LiDAR Infrared Pathfinder Satellite Observations), aerosol optical depth (AOD) data from MODIS (Moderate Resolution Imaging Spectro-radiometer on the NASA Aqua and Terra satellites) .

### 4.2.4 Population Exposure

Population exposure to ground level PM2.5 can be estimated by combining the average hourly PM2.5 concentrations across the model grid for the duration of the event with the population distribution. The latter is sourced from the 2011 census at SA1 resolution which has a region size of approximately 300 people. This identifies the population centres at a finer resolution than the model grid, but tends to smooth the small rural population density across many model grid cells. For the most accurate assessment of impacts, the resolution of both the population distribution and the smoke dispersion should be matched to minimise the smoothing coincident peaks in population and PM concentration. The distribution of population density in Victoria and southern NSW is shown in Figure 4.1.

### 4.2.5 Health Risk

The impact of health outcomes resulting from exposure to PM2.5 – (atmospheric particles less than 2.5 μm in diameter) has been determined in numerous epidemiological studies involving cohorts of large groups over long time periods. In their comprehensive review of PM10 impacts on health, Pope and Dockery (2006) conclude that an impact of at least 1% increase in mortality per 10 μg $m^{-3}$ increase in PM10 concentration is consistently reported. Many individual studies, particularly those investigating both mortality and morbidity in susceptible population groups, report much higher sensitivities. Table 4.1 lists some of the studies conducted in the US, Europe and Melbourne.

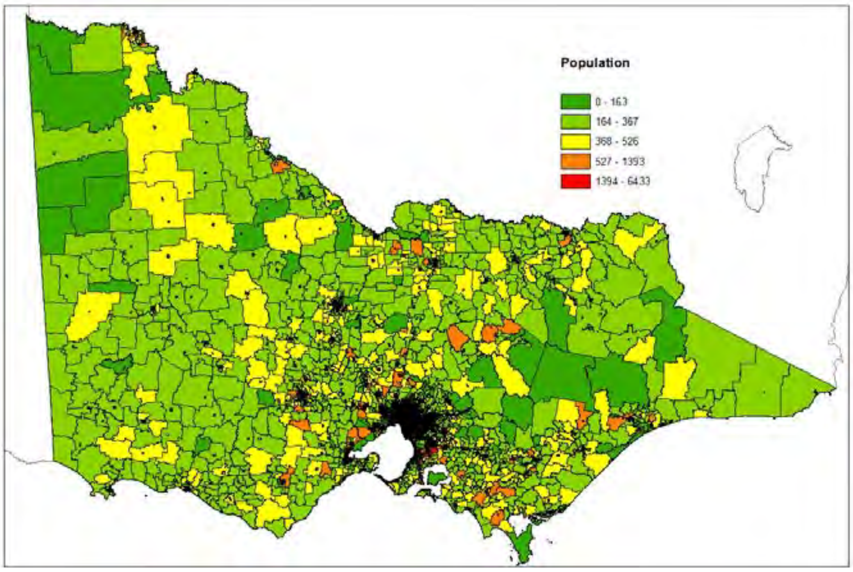


***Figure 4.1*** *Spatial distribution of population density in Victoria in 2011.*

### 4.2.5 Health Risk

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Health impact (I) is the combination of population exposure to the pollutant, and health risk, i.e.

$$I = C\ x\ P\ x\ D\ x\ R \qquad \textit{Equation 1}$$

Where:

I = health impact (deaths due to exposure to PM per unit area)

C = increase above ambient of mean 24h surface concentration of PM

P = population density.

D = death rate (deaths per 100,000 people per year)

R = risk (increase in death rate (increase in mean 24h PM concentration)

Integrating *Equation 1* across the smoke affected region yields the total health impact for an event.

*Table 4.1* *PM2.5 relative health risks for PM2.5 exposure*

| Location | Health Risk | Reference |
|---|---|---|
| Harvard Six Cities study (8096 white participants from various cities of the USA followed since the mid-1970 to 1998) | Increase of 10 μg $m^{-3}$ 16 % increase in mortality, 28% increase in cardiovascular disease, 8% increase in respiratory | Laden and Dockery 2006 |
| Women's Health Initiative cohort study, including 65,893 post-menopausal women | Increase of 10 μg $m^{-3}$ 76 % increase in cardiovascular mortality | Miller *et al.* 2007 |
| ACS-CPS-II study linked air pollution data with the individual data of approximately 500,000 adults from the USA, followed from 1982 to the end of 1998 | Increase of 10 μg $m^{-3}$ 6 % increase in all mortality, 12% increase in cardiovascular disease | Pope *et al.* 2002; Pope *et al.* 2004 |
| Los Angeles October 2003 wildfires | Increase of 10 μg $m^{-3}$ 3 % increase in respiratory hospital admissions, 5% increase in asthma hospital admissions, 4% increase in chronic obstructive pulmonary disease admissions | Delfino *et al.* 2009 |
| Madrid 2003-2005 | Increase of 25 μg $m^{-3}$ increase in hospital admissions of 7%, increase in cardiovascular admissions was 8%, increase for respiratory admissions was 7%. | Linares *et al.* 2010 |
| Melbourne, Alpine fires 2006/2007 | increase of PM2.5 of 6 μg $m^{-3}$ 4.52% increase in out of hospital cardiac arrest | Dennekamp *et al.* 2011 |

## 4.3 Performance of the model

Modelling smoke emission and dispersion from fires is an inherently difficult task due to the challenges of accurately representing plume rise and the variable spatial scale of the emissions fit the conventional definitions of neither point or area sources. Traditionally, point sources are associated with a heat flux which produces buoyancy and plume rise and are usually comparatively small in area while area sources are large, have no heat flux, and are released the surface layer of the model atmosphere. Chimney stacks are common point sources; soil and vegetation are area sources of NO and volatile organic compounds (VOCs) respectively. The methods used to introduce fire emissions estimates into the TAPM-CTM framework are described in the next section.

### 4.3.1 Modelling fire emissions in the TAPM-CTM framework

The plume rise behaviour of a vegetation fire is strongly dependent the fire heat flux, which in turn, is dependent on the fuel loading, the fuel moisture content, the slope of the terrain, and atmospheric drivers such as the air temperature, moisture and the wind speed. In TAPM-CTM fires can be treated as a matrix of point sources, providing a capability to inject the emissions into upper levels of the model thus representing plume rise due to the high temperatures of the fire plume. This is a critical consideration given that ground level concentrations may vary exponentially with the release height of the source.

For this assessment of the effect of plume rise, the transport and chemical transformation of emissions from the Victorian region during the 2006/2007 Victorian Alpine fires (both anthropogenic and fire-related) were modelled using the TAPM–CTM. Details of the model set up are given in Meyer, Cope and Young (2012). The results presented here were for a simulation of the period 2 December to 31 December 2006. Emissions from the Alpine fires were modelled as individual point sources, with hourly emission rates determined by scaling daily area-based emissions resolved to 1 km by the diurnal time-course of fire rate of spread.

The plume rise parameter in TAPM-CTM requires estimate of the fire buoyancy flux, which are represented in these model runs as a range of prescribed heights (1000, 2000, 3000 m), based on observations from the CALIPSO satellite. The CALIPSO overpass on 20 December 2006 (Figure 4.2) which captured the fire plume from the a day of extensive fire activity in the Alpine fire complex shows that the smoke was located between 1000 m and 4000 m above ground level.

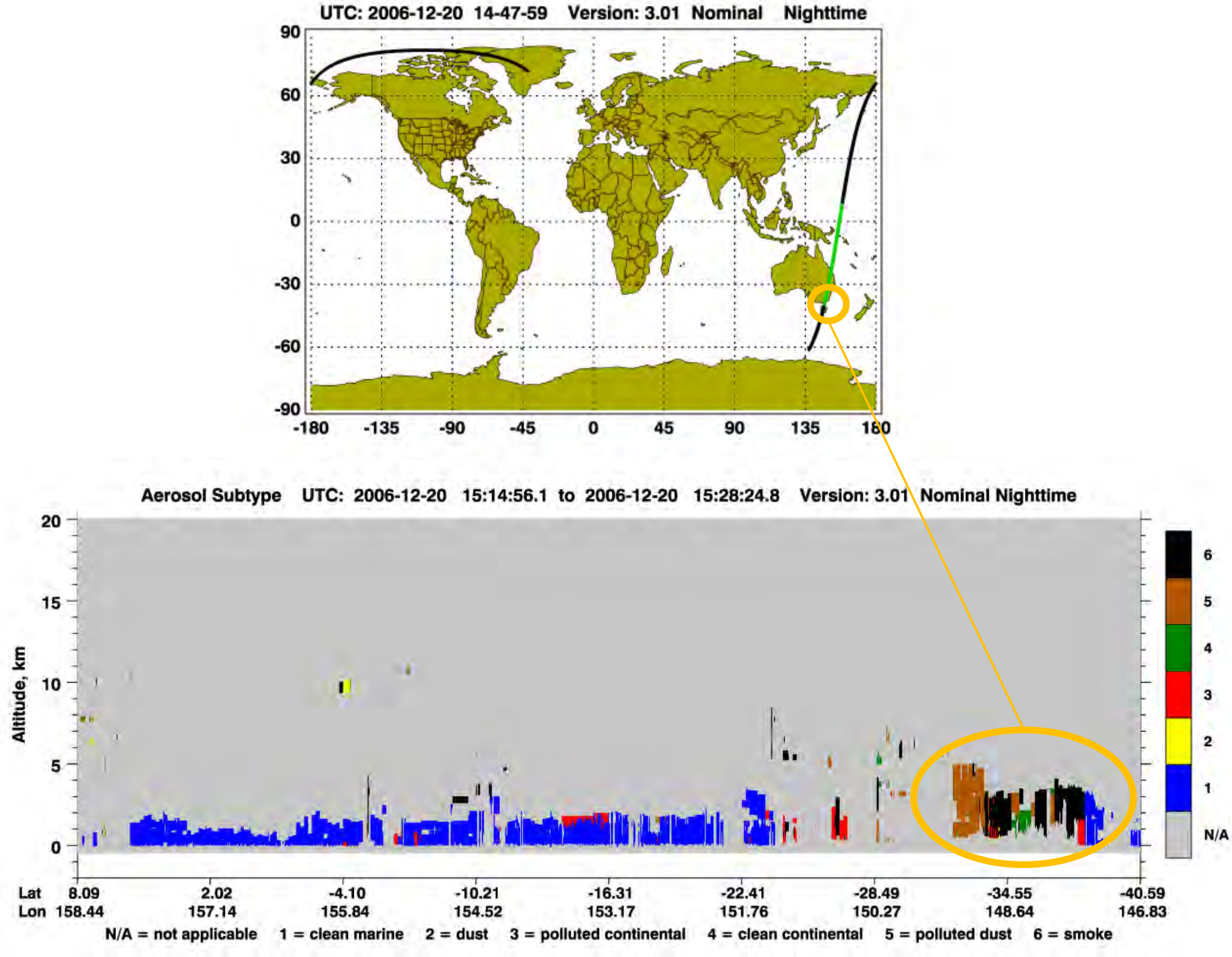


***Figure 4.2*** *Aerosol sub-type curtain plot (bottom) for the CALIPSO satellite trajectory (top) for 20th December 2006. The circled area (bottom) shows the diagnosed aerosol sub-type for the trajectory segment which passes through south eastern Australia. The smoke sub-type (black shade) corresponds to the Alpine fire.*

To determine the effective average plume rise height, four model scenarios were run. These were: scenario 0, the base case in which fires were absent but other sources of reactive pollutants were included; scenario 1 where the plume height was 1000 m; scenario 2 where plume height was 2000 m and scenario 3 where the plume height as 3000 m. The results of the model runs are presented as Taylor diagrams (Taylor, 2001), which graphically summarize how closely a pattern of model results matches the observations. The strength of the model/observation fit is quantified in terms of the correlation (the dotted radial lines labelled 0.1 to 0.99 on Figure 4.3 and Figure 4.4) and the ratio of modelled to observed variable (the concentric lines labelled 0 to 2).

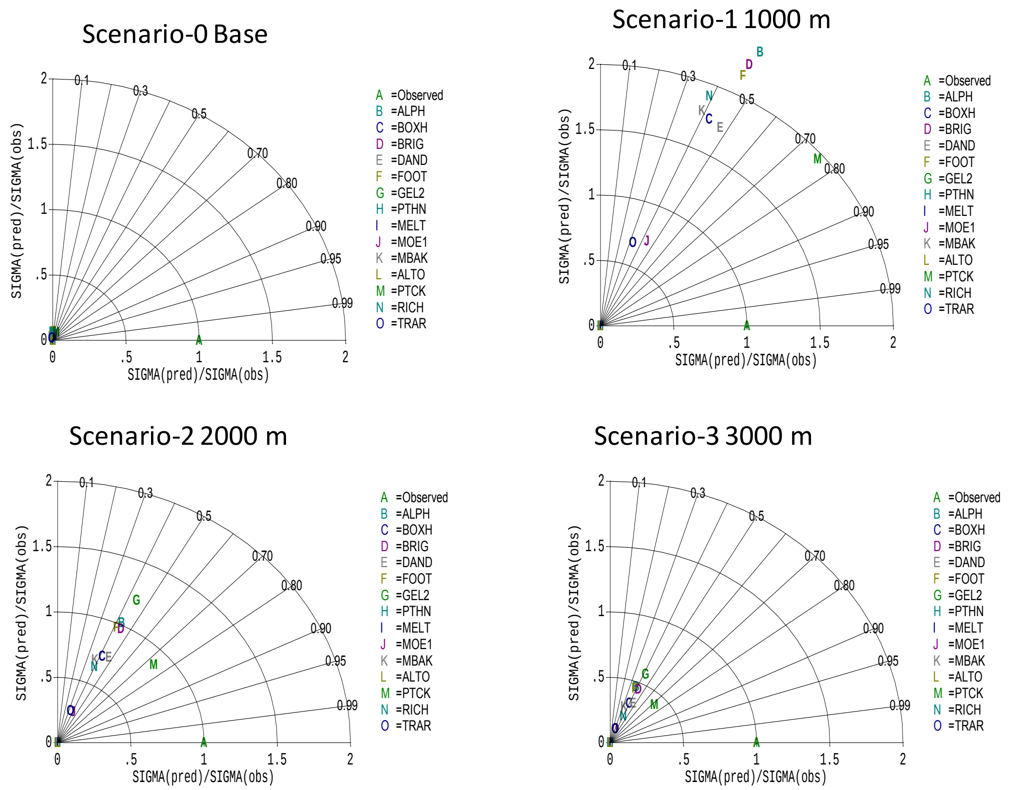


***Figure 4.3*** *Taylor diagrams of PM2.5 simulated during for four plume rise scenarios, using the 9 km grid, for December 2006*

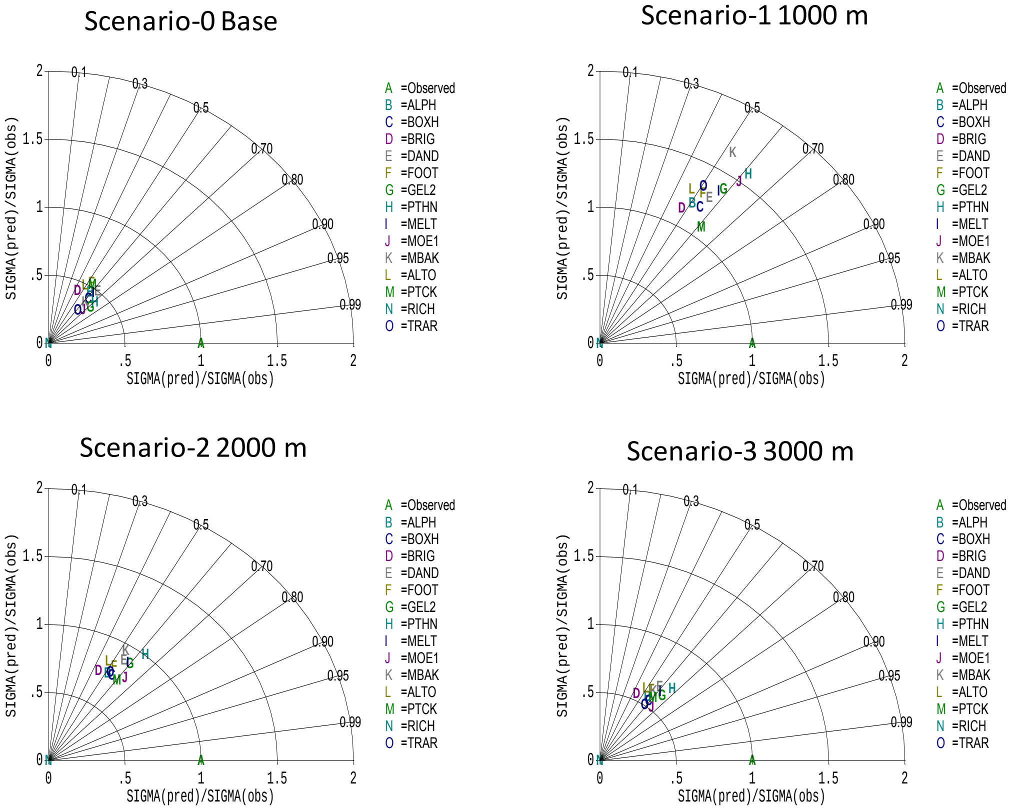


***Figure 4.4*** *Taylor diagrams of ozone simulated during for four plume rise scenarios, using the 9 km grid, for December 2006*

Figure 4.3 shows the Taylor diagram plots for PM2.5 simulated using the four plume rise scenarios. In the base case the data are crowded about the origin as is expected since this is the case were no fire emissions were included and all other sources of aerosol were small. In the other three plume rise scenarios the correlation between observations and predicted is around 0.4 for all the data points, however the ratio of predicted to observed for more of the data points is closest to 1 for the 2000 m plume rise scenario. In the case of the 1000 m scenario predictions are generally greater than observed (pred/obs >1.5), while for the 3000 m scenario the predictions are generally lower than observed (pred/obs < 0.5). The 2000 m plume rise scenario also does the best job of predicting ozone (Figure 4.4). The technique was also applied to a range of other pollutant species; for $NO_2$ all three plume rise scenarios produce similar results to the base case suggesting that $NO_2$ is more strongly influenced by non-fire sources, however for CO (for which fire is the largest source), the 1000 m plume rise scenario gives the best results. The difference in optimal plume rise heights with different smoke tracers arises from phochemisty which, because it is driven by UV radiation, proceeds at different rates across the plume's vertical profile.

## 4.3.2 Model Accuracy

Verification of model accuracy by comparing model predictions against surface observations is essential before modelled smoke dispersion can be used to assess population impact risks. The data summarised in the Taylor plots presents a good overall summary, and shows that model predictions across the Melbourne airshed are good, however it is also useful to compare the timeseries of modelled and observed concentrations at a selection of observing stations to confirm that the model dynamics. Figure 4.5 compares the observed and modelled concentration time series for 1-h ozone. Time series plots are given for Moe monitoring station in the Latrobe Valley, Brighton in Melbourne and Geelong South to the south-west of Melbourne. The modelled concentrations are plotted for a no–fire scenario, and three plume rise scenarios. The model is unable to reproduce the high observed ozone concentrations unless the Alpine fire is included in the simulation. When the fire is included, the modelling is able to predict the timing of the high ozone event periods for the majority of the event but (as shown above), the magnitude of the observed and modelled peaks are similar only for scenario 3 (plume rise of 2000 m).

Only two stations in the Melbourne network, Footscray and Alphington, recorded both PM2.5 concentration directly, however all stations recorded a backscattering coefficient (measured by nephelometer). Back scattering coefficient is highly correlated with PM2.5 concentration and this correlation can be applied reliably to estimate PM2.5 from backscattering for stations which do not record PM2. concentration directly. Figure 4.6 suggests that there were three significant fire plume impacts at Geelong South, 4–5 impacts at Brighton and 5 impacts at Moe. The modelling was able to predict the majority of these impacts within a window of ± 1 day. With the exception of Moe where the PM2.5 impacts of the fires are under predicted, the modelled PM2.5 concentrations for the three plume rise scenarios generally span the observed PM2.5 concentrations.

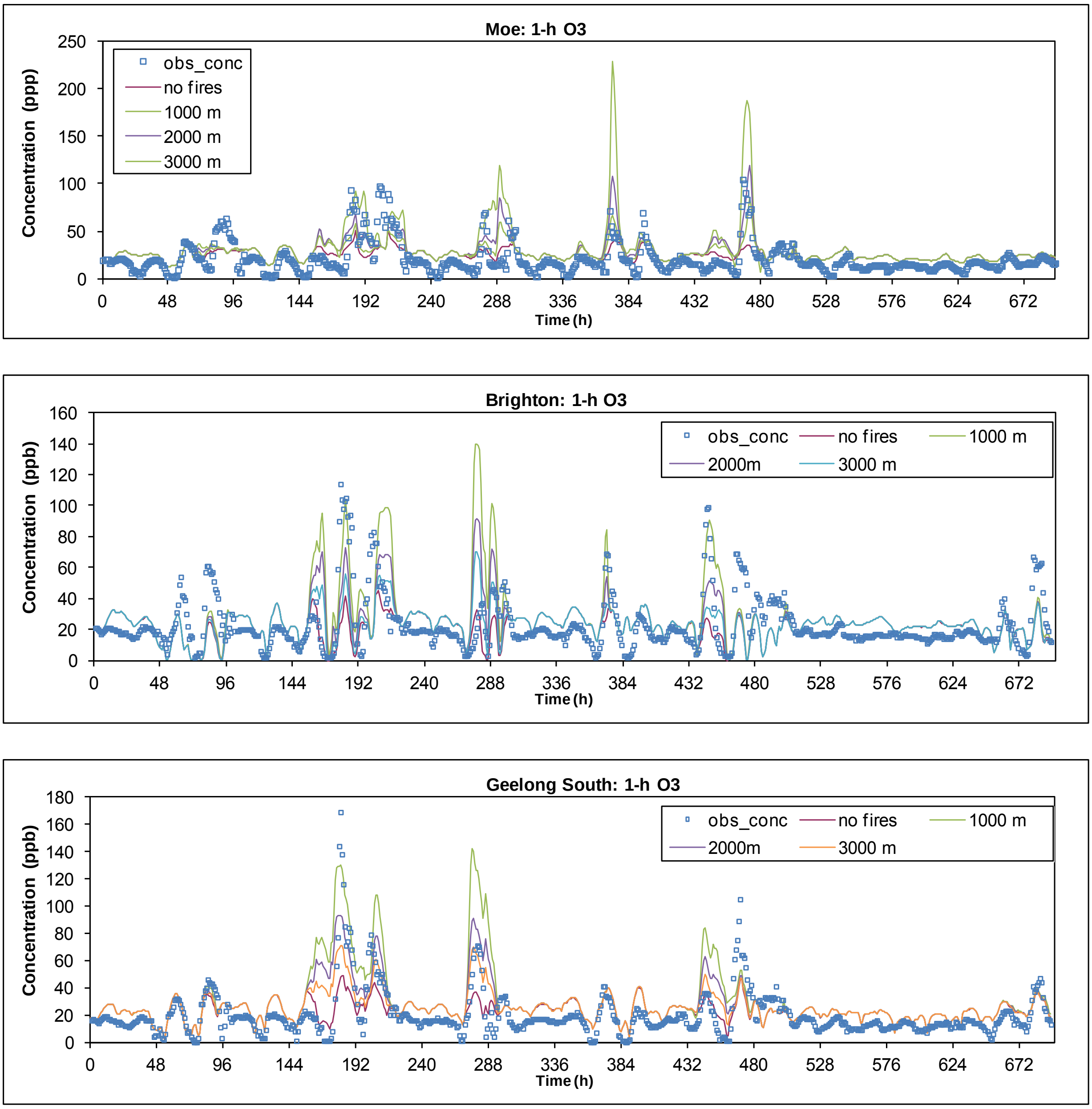


***Figure 4.5*** *Observed and modelled 1-h concentration time series for ozone for Moe, Brighton and Geelong South. The concentration time series are for December 2006.The modelled concentrations are shown for three scenarios: 1- 'no fires' anthropogenic and non-combustion natural sources only; 2- '1000 m' the Alpine fire smoke plume is assumed to level off at 1000 m above ground level (agl); 3- '2000 m' the plume is assumed to level off at 2000 m agl; '3000 m' the plume is assumed to level off at 3000 m agl.*

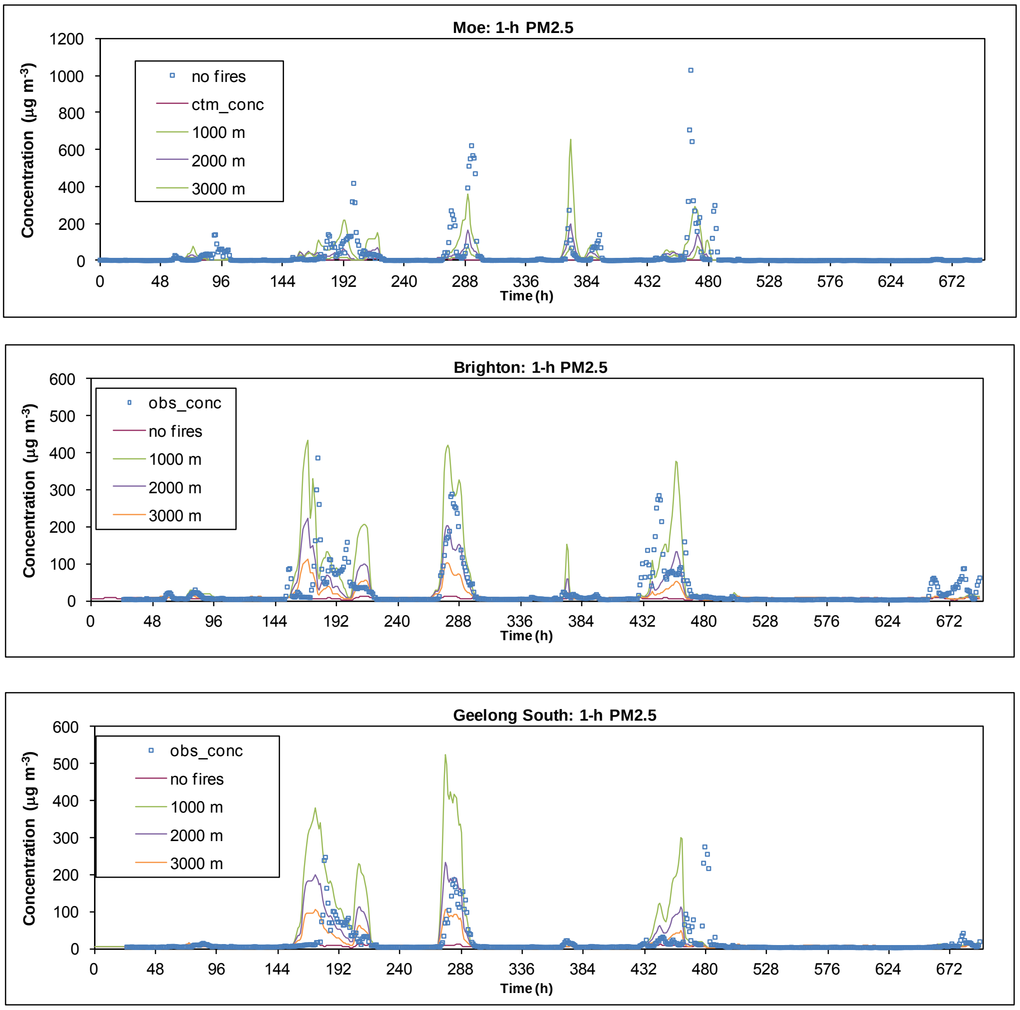


***Figure 4.6*** *Observed and modelled 1-h concentration time series for PM2.5 for Moe, Brighton and Geelong South. The concentration time series are for December 2006. Note that the observed PM2.5 has been generated from 1-h nephelometer backscatter observations using a linear regression between PM2.5 and nephelometer data derived from observations at Footscray and Alphington monitoring stations in Melbourne for December 2006. An explanation of the legend is given in Figure 4.5.*

Figure 4.7 shows a comparison of the observed and modelled 1-h ozone and PM2.5 concentration distributions throughout December 2006 at the Brighton monitoring station. Again, it can be seen that the modelling system accurately estimate the observed distribution of extreme events (for either ozone or PM2.5) only when emissions from the Alpine fires are included. With respect to ozone it can be seen that the 3000 m scenario tends to underestimate the observed range, the 1000 m scenario over estimates the range and the closest agreement occurs with the 2000 m plume rise scenario. In the case of PM2.5, the modelling is more challenged to reproduce the inter-quartile range (25$^{th}$ to 75$^{th}$ percentiles) than for ozone, and that the best agreement occurs for the 1000 m plume rise scenario.

MODIS imagery was used to evaluate the effectiveness of the modelling system to predict the dispersion of PM2.5, black carbon produced from the Alpine fires. Figure 4.8 shows a comparison of the modelled spatial distribution of elemental carbon and visible light images from the MODIS. The figures cover the period 3rd to 10th December for days where the fire plume can be easily distinguished from the cloud cover. This period also included two days when smoke was detected in the Melbourne airshed at the CSIRO atmospheric monitoring station and across the EPA observing network. The figure demonstrates qualitatively that the model has effectively modelled the plume transport.

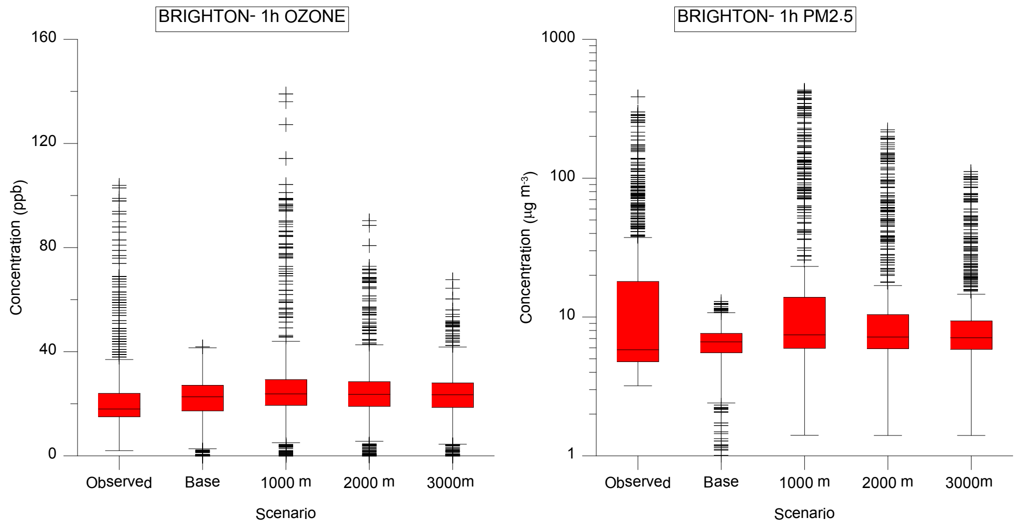


***Figure 4.7*** *Box and whisker plots of the observed and modelled distributions of (left) 1-h ozone, (right) 1-h PM2.5 (derived from nephelometer data) for Brighton monitoring station for December 2006. Base- anthropogenic and non fire combustion natural sources; 1000 m- Alpine fire plume injected at 1000 m above ground level; 2000 m- injected at 2000 m above ground level; 3000 m- injected at 3000 m above ground level.*

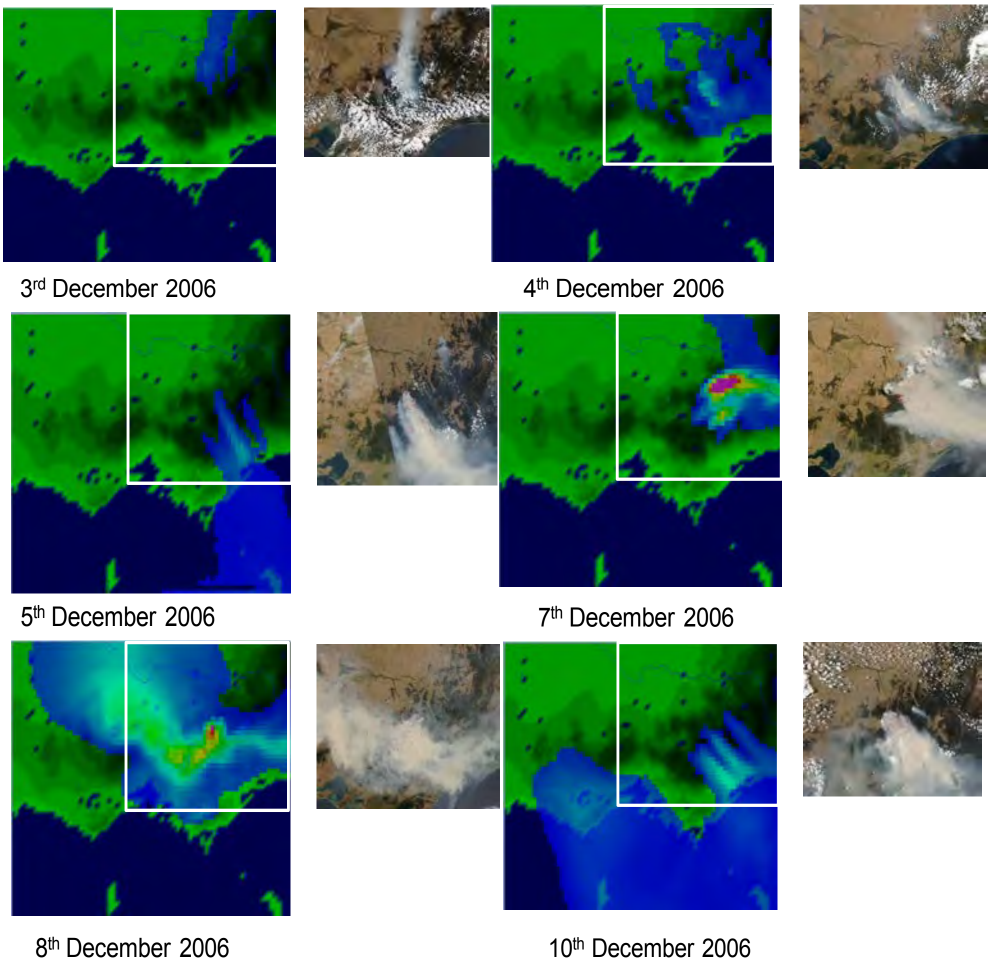


***Figure 4.8*** *Comparison (inset) of the modelled spatial distribution of modelled elemental carbon (PM2.5) with MODIS AQUA satellite visible images. Comparisons are shown for $3^{rd}$, $4^{th}$, $5^{th}$ $7^{th}$, $8^{th}$ and $10^{th}$ December 2006 (selected for having a relatively clear sky view of the Alpine fire smoke plume).*

# 4.4 Scenarios

To assess the significance of smoke impact on health risk RQ(6d), three recent fire events that cover a wide range of potential impacts were investigated. They were (1) the Victorian Alpine fires of 2006/2007 (2) the Kilmore East fire on Black Saturday (7 February 2009) and (3) a series of high intensity prescribed burns in the Huon Valley, Tasmania in Autumn 2010. The first was a large fire event of long duration, the second was an extreme event, large in area and intensity, but of relatively short duration, and the third was a series of prescribed burns that consumed a very large fuel load and created an extensive smoke plume that created a major controversy due the perception that it would have a significant impact on the local population.

## 4.4.1 Big wildfire - Victorian Alpine Fire Complex (2006/2007)

During the summer of 2006/2007 (December 2006 – February 2007), Victoria was affected by the longest recorded fires in the State's history. During this time the State was ravaged by 690 separate wildfires, including the major Great Divide Fire, which devastated 1,048,238 hectares over 69 days. On several occasions, thick smoke haze was transported to over Melbourne's central business district and PM10 concentrations at several EPA Victoria air quality monitoring sites peaked at over 200 μg m$^{-3}$ (four times the National Environment Protection Measure Ambient Air Quality Standard (NEPM AAQS) for 24 hour PM10.

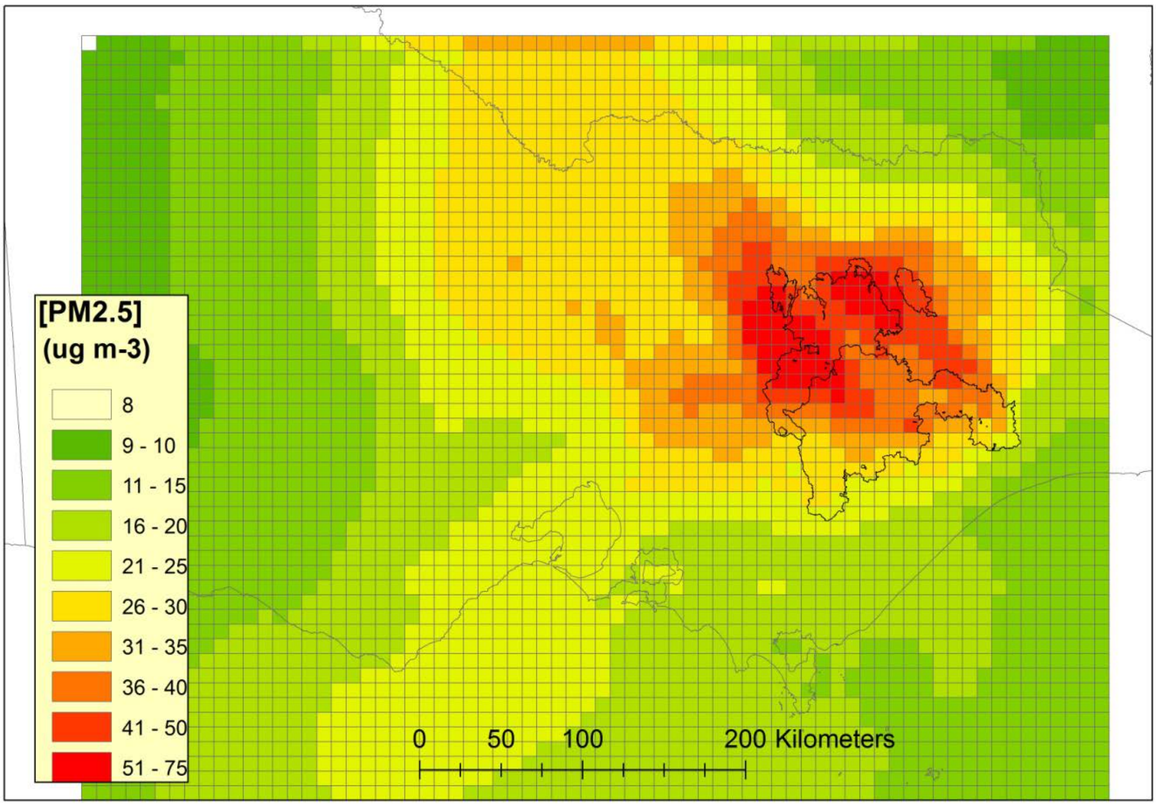


***Figure 4.9*** *Average surface mean 24h PM2.5 concentration during the 2006/2007 Alpine fires.*

Using methodologies reported in Meyer *et al.* (2012), the emissions of trace species from the smoke were estimated and incorporated into TAPM-CTM to predict daily PM2.5 concentrations across Victoria and Southern NSW. The model grid was 80 x 80 cells each 9 km square. The model was run from 2 December 2006 to 31 January 2007. The mean daily PM2.5 concentrations were calculated for each cell and then averaged across all days of the model run to produce the distribution of average 24-h surface PM2.5 (Figure 4.9) This was corrected for the background PM2.5 to estimate the increase in mean 24-h PM2.5. The background PM2.5 concentration (i.e. The average PM2.5 due to all sources other than the Alpine fire was estimated as the 5$^{th}$ percentile of the frequency distribution of 24-h PM2.5 in each cell.

As a first approximation we can take the increase in mortality to be a useful indicator of health risk associated with exposure to smoke. As discussed above, the impact on health (Table 4.1) varies widely across groups and studies, however the average impact reported by Pope and Dockery (2006), R= 1% per 10 µg m$^{-3}$ increase in mean 24-h PM2.5 across the total population should give a conservative estimate of risk that will support comparisons across the three scenarios. The study can be extended in the future to account for variation in risk with age group and health status. Applying Equation 1 to each grid cell produces the distribution of health risk across the domain (Figure 4.10). Most of the risk is located in the Melbourne airshed, particularly the inner eastern and southeastern suburbs, however the large regional towns, particularly Geelong, Ballarat, Bendigo, Shepparton and Albury/Wodonga were affected. Integrating across the model domain indicates an addition 84 deaths may have occurred due to exposure of the Victorian population to smoke from this fire, which is an increase in the average annual death rate of approximately 0.3%. This is a very substantial health impact.

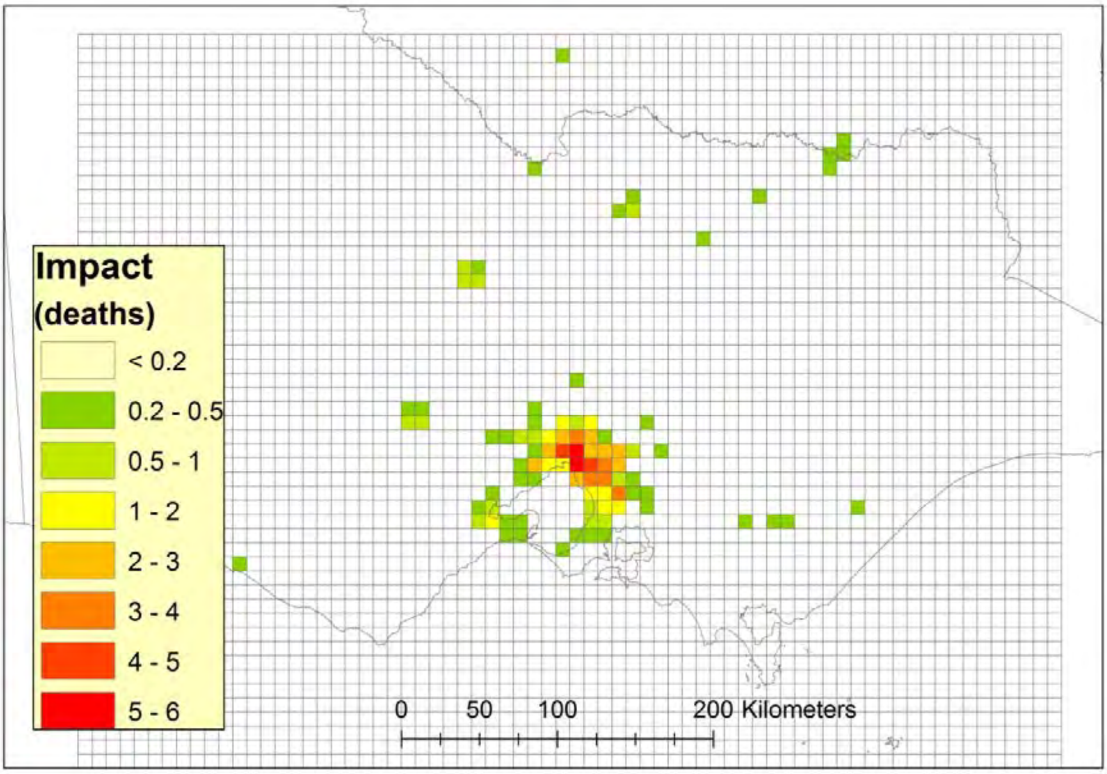


***Figure 4.10*** *Mortality increase in Victoria due to PM2.5 associated with smoke from the Victorian Alpine Fire complex. PM2.5 increase above the background PM2.5 concentration for the 60 days of impact was multiplied by the population distribution from the 2011 census and the standardised death rates for 2006-2011. For this analysis we assumed a 1% increase in mortality per 10 µg m$^{-3}$ increase in 24h mean PM2.5.*

## 4.4.2 High intensity, short duration - Kilmore East Fire

The Kilmore East fire was the most significant contributor to fatalities during the Black Saturday fires. It burned 50,000 ha in less than 12h on 7 February 2009 and accounted for 70% of the fatalities. Cruze *et al.* (2012) provide an analysis of the development of the fire that was driven by a combination of extremely dry fuel and near-gale to gale force wind. The rate of fire spread was very fast (between 68 and 153 m min$^{-1}$). In addition strong winds aloft and the development of a strong convection plume led to the transport resulted in the lighting of spotfires up to 33 km ahead of the main fire front. The change in wind direction between 17:30 and 18:30 turned the 55 km long eastern flank of the fire into a headfire and a pyrocumulonimbus cloud formed that injected smoke into the lower stratosphere. Cruze *et al.* (2012) report the extremely fast development and progression of the Kilmore fire, which poses significant difficulties for the modelling of the dispersion of smoke associated with this fire. In particular uncertainty exists around the points of ignition, the fire progression pattern and the effects of the grid size employed in the modelling framework.

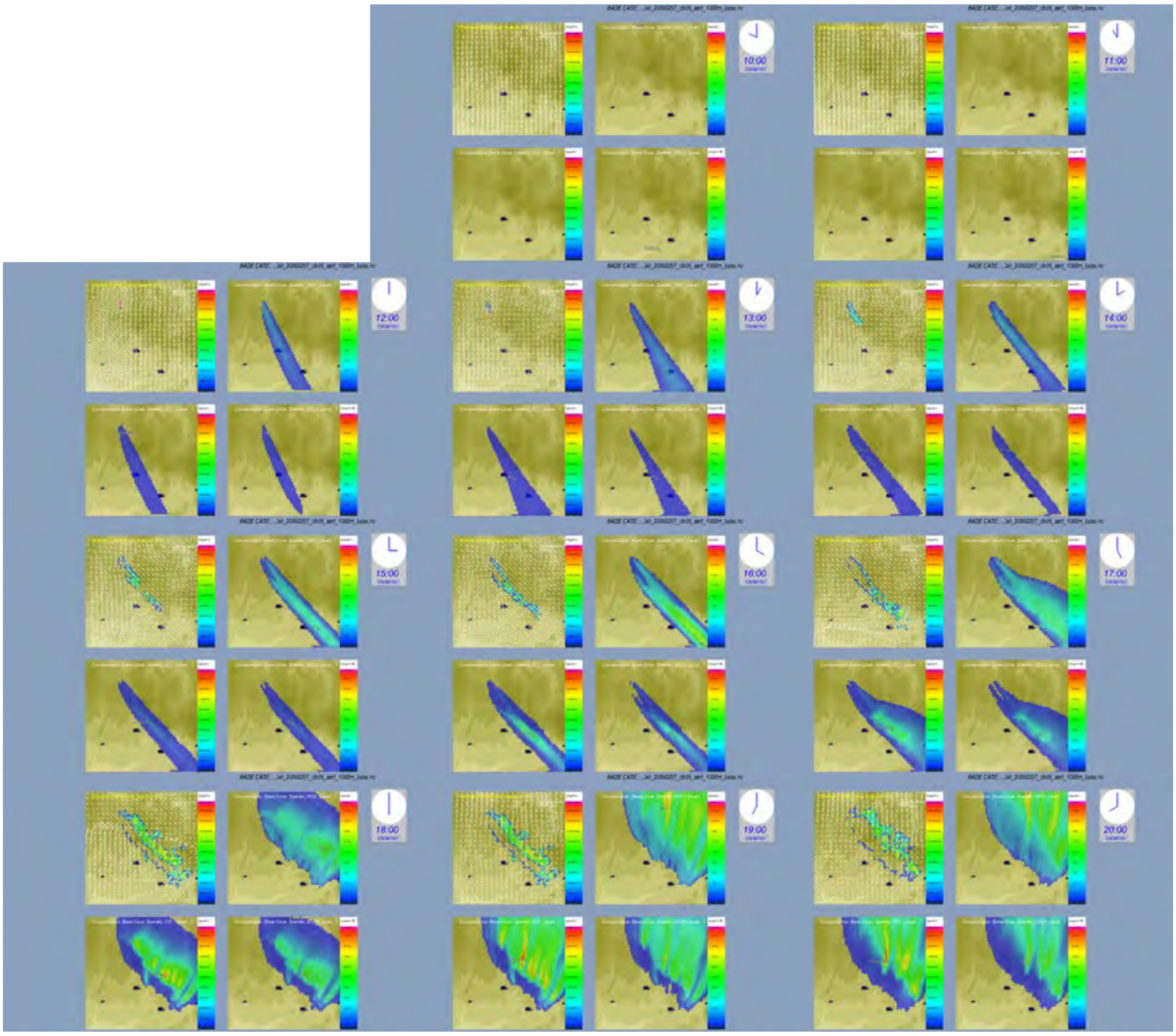

***Figure 4.11*** *TAPM-CTM model output of the Kilmore fire. Top left plot of each set is the emission field (representing the fire), right top plot of each set is $NO_2$ concentration (ppb), bottom left plot is CO concentration (ppm) and the bottom right plot in each set is the elemental carbon concentration (µg m$^{-3}$).*

The influence of each of these factors on estimates of the number of people impacted by smoke dispersion was assessed using TAPM-CTM model Figure 4.11 shows progression of the smoke plume from ignition at 11:45 until containment at approximately 20:00 eastern summer time. Strong northerly winds caused the fire to progress along a SE track and the fire front grew extensively over the next 8 hours. The smoke plume follows this track until 17:00 when the change in wind direction to a south-easterly moves the plume to northwest. This is associated with a dramatic increase in the area covered by the plume and the concentration of species such as CO, $NO_2$ and elemental carbon in the plume.

The distribution of surface PM2.5 concentration (Figure 4.12) was determined mostly by dispersion following the wind change in the late afternoon when the plume rise diminished and the depth of the mixed layer declined thus mixing the plume down to the surface.  Consequently, it was the regions to the north and east of the fire that were most affected; the smoke plume prior to the wind change passed high above the regions to the southeast of the fire zone and dispersed in the troposphere and lower stratosphere over the Tasman Sea.

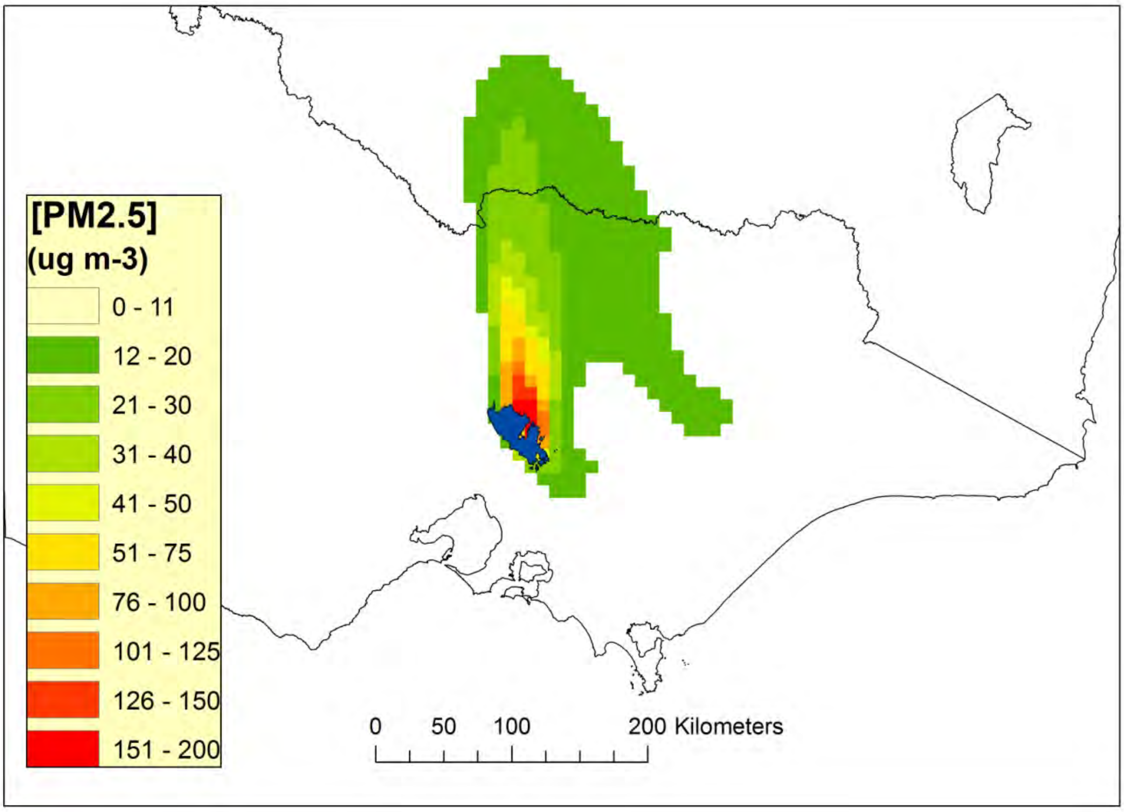


***Figure 4.12*** *Mean 24-hour surface concentration for PM2.5 resulting from the Kilmore East fire on the 8$^{th}$ and 9$^{th}$ February 2009. The final fire affected area is shown in blue.*

The population density in the impacted region is quite low; the only substantial towns and cities impacted are Seymour and Shepparton (Figure 4.13). Integrating across the domain gives a total increase in deaths of 0.1; a very minor risk, and trivial compared to the deaths on the fire ground.

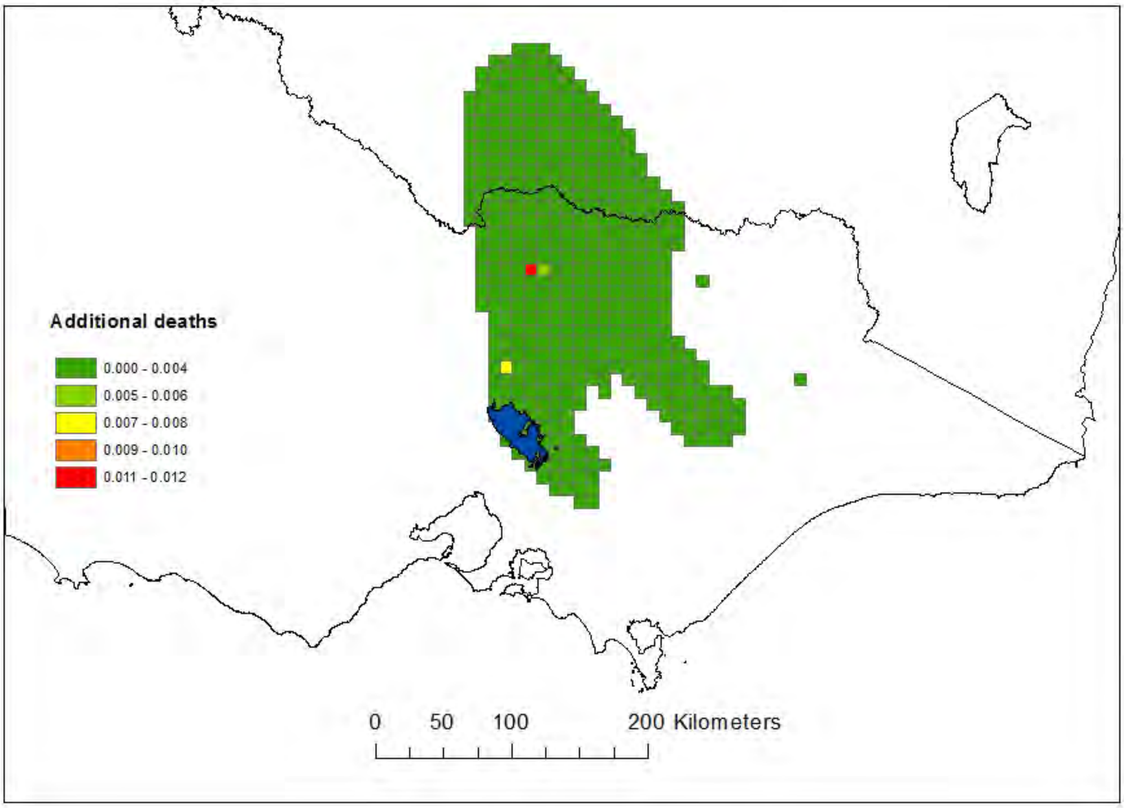


***Figure 4.13*** *Increase in deaths due to potential exposure to PM2.5 emitted from the Kilmore East fire.*

## 4.4.3 High intensity regeneration burns-Huon Valley

In rural areas, air quality is generally good, however there are occasions when this is not the case. Rural pollution events mostly result from domestic, agricultural or forestry activities, and often involve smoke from biomass combustion. In the Huon Valley, Tasmania, smoke from prescribed burning has been subject to public debate. The commonly accepted view is that regeneration burning following logging operations is the major source of PM pollution; however, in the absence of reliable ambient air quality monitoring it is impossible to confirm the veracity of this perception.

The major anthropogenic sources of PM in the Huon Valley are prescribed burning (PB), domestic wood-fuelled heaters (WH), and windblown dust from roads, motor vehicles, and domestic waste incineration. To determine the contribution of these sources to the ambient surface concentration of PM in the Valley, two air quality monitoring stations were installed; one at a rural site, the Department of Primary Industry Research Station near Grove; and one in an urban area, Geeveston. The rural site was expected to be affected mostly by PB while the urban site was expected to be influenced by all anthropogenic PM sources. Ambient surface PM concentration was monitored continuously between March 2009 and November 2010; Both sites were impacted by smoke from the two biomass combustion sources, prescribed burning (PB) and domestic woodheaters (WH). However these sources are active in different seasons; the PB season is March and April, and the WH season extends from May to September (Meyer *et al.,* 2011). The summer is a period of negligible biomass combustion. The study concluded that most of the PM pollution in the towns was due to WH emissions; however PB caused significant pollution events in both years of monitoring. The most severe event was the period from 10$^{th}$ April to 21$^{st}$ April; it lead to widespread public criticism and concern about health impacts and was probably the most publicised smoke impact event in recent years in Tasmania. However, the study did not investigate in detail the patterns of smoke dispersion in the region and therefore was not able to comment on the regional PM exposure and health impacts and therefore it provides an excellent case for scenario 3 of this project.

The modelling challenges in this system involve the time course of the emissions and plume rise. Neither the fuel load, nor the rate of fuel consumption have been measured for high intensity burns in this region however we estimated fuel loads at 100 t ha$^{-1}$ as described in Meyer *et al.* (2011). Based on the fuel consumption model FEPS (Anderson *et al.*, 2004) we assume that the fuel will burn at an approximately exponentially declining rate over a period of 24 hours (Figure 4.14). We also set the ignition time of each burn at 12:00 h. The effect of variations in these parameters is explored by Meyer (2013), and the impact on the dispersion pattern was found to be relatively minor. Based on boundary layer mixed height during the event, plume injection height was set at 100 m, 300 m and 1000 m. A injection height of 100 m represents conditions occurring in the late evening, while an injection height of 1000 m models a plume that has sufficient energy to penetrate to the free troposphere.

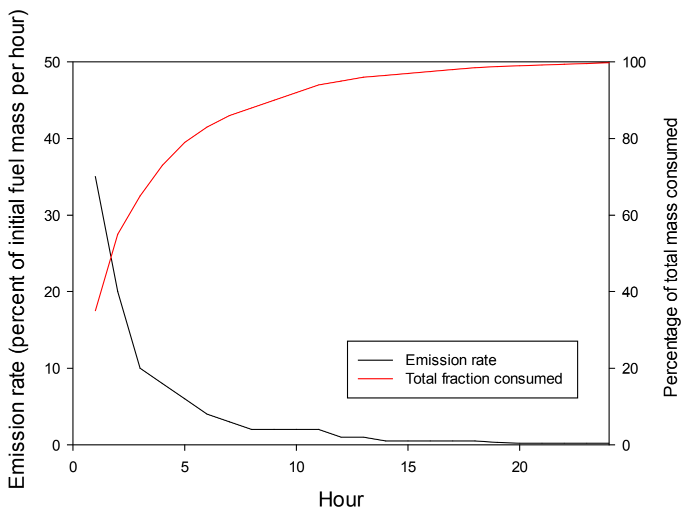


***Figure 4.14*** *Prescribed rate of fuel consumption in high intensity regeneration burn*

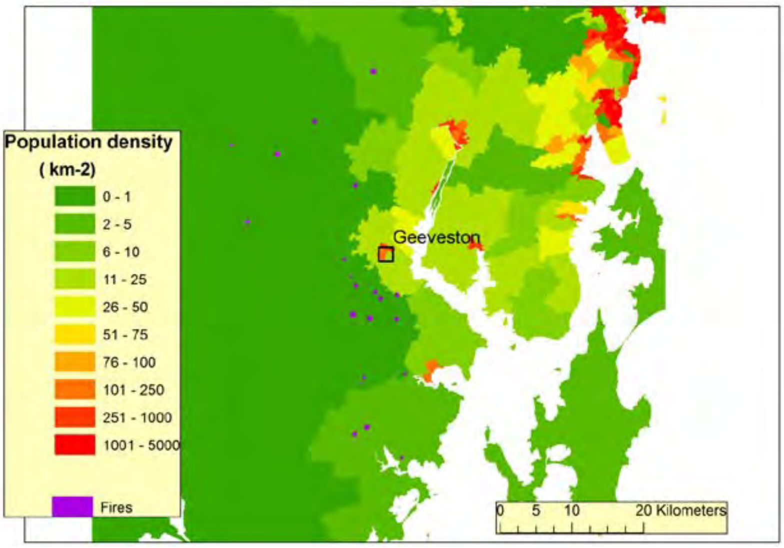


***Figure 4.15*** *Distribution of population density in the Huon valley (based on Australian Bureau of Statistics 2011 Census).*

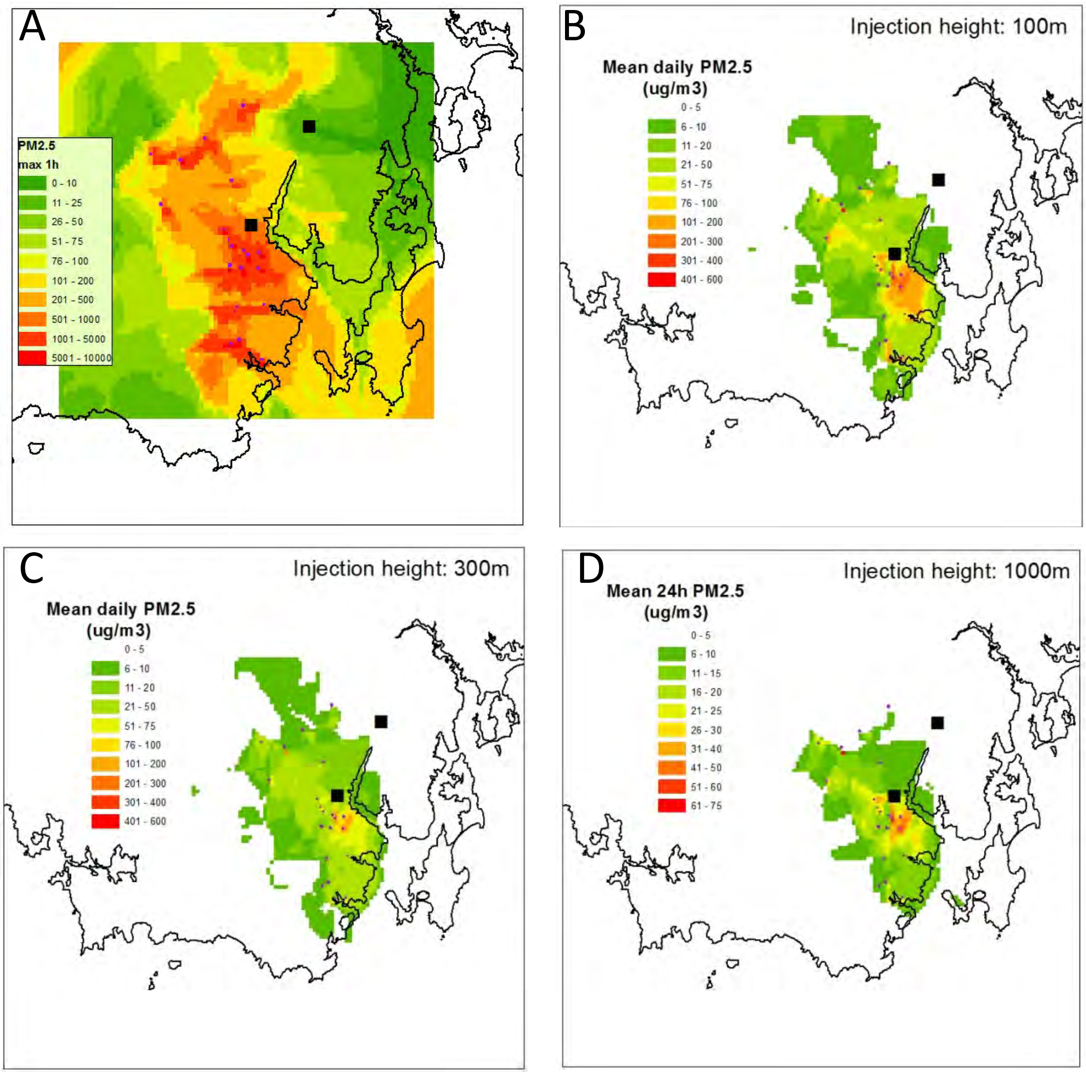


***Figure 4.16*** *Modelled surface of PM2.5 concentration during the 2010 smoke event in the Huon Valley, Tasmania. A: maximum 1-h PM2.5 concentration, Plume injection height 300m. B: mean 24h PM2.5 concentrations during the event, plume height 100 m. B: mean 24h PM2.5 concentrations during the event, plume height 300 m. D: mean 24h PM2.5 concentrations during the event, plume height 1000 m. The location of the monitoring stations is indicated by a black square. Locations of the fires areas shown by purple points.*

Most of the prescribed burns were south and west of Geeveston, the closest less than 7 km away. The extent of the smoke plume impact is shown by the distribution of maximum 1-h PM concentrations during the event (Figure 4.16A), and was largely confined the lower regions of estuary and the upper reaches of the Huon Valley west of Huonville. The monitoring site at Grove was unimpacted. This confirms that the smoke was not widely dispersed contrary to public perception, but mostly affected uninhabited regions of the Valley. The degree of impact is shown (Figure 4.16A, B and C) as the mean 24h surface PM2.5 concentration. There is little difference in the dispersion pattern of the 3 scenarios; quantitatively scenario 1 (100 m injection height) which predicts a mean PM2.5 concentration increase above background at Geeveston of 32 µg $m^{-3}$ agrees best with the observations at Geeveston of 27 µg $m^{-3}$. The significant smoke impacts mostly occurred at night suggesting that it was smouldering emissions from the heavy fuel continuing through the late afternoon and evening that contributed most of the observed PM2.5.

The three scenarios are summarised and compared in Table 4.2, The dispersion of smoke from persistent fires, such as the 2006/2007 Alpine fires, is determined by the seasonal climatology, with the likelihood that even when population centres are upstream of the prevailing winds, there will be occasions when dispersion carries plumes to the city airsheds. In contrast, severe wildfires of short duration (e.g. Kilmore East fire ) develop strong convection columns that disperse smoke high into the troposphere, minimising the risk of ground strike; although local regions downwind of the event will invariably be impacted to some degree. Prescribed burns, because they are managed, can be timed to avoid plume strike on sensitive regions. It is also clear from Table 4.2 that the magnitude of the smoke emission does not imply the magnitude of the smoke impact. This is particularly relevant to scenario 3, which caused significant public comment at the time largely due to the visibility of the plume. Contrary to perception, the modelling of this event showed that smoke did not accumulate in the Huon valley, and, as was confirmed by Meyer *et al.,* (2011) and Reisen *et al.,* (2013) posed only a relatively minor risk to the population.

***Table 4.2*** *Summary of the relative risk of health impact due to PM2.5 emitted during the fire event*

| | | | | | Impacted zone | | | |
|---|---|---|---|---|---|---|---|---|
| Fire | Start date | Days | Area ($km^2$) | Emission (k t C) | Area ($km^2$) | Population (1000s) | Baseline (deaths $y^{-1}$) | Impact (deaths) |
| Alpine | 8/12/2006 | 60 | 11,400 | 28,700 | 212,600 | 5,370 | 34,611 | 84 |
| Kilmore | 8/02/2009 | 1 | 925 | 1,340 | 50,200 | 270 | 1,745 | 0.10 |
| Huon | 16/04/2010 | 6 | 5.5 | 25 | 1,275 | 4.36 | 30 | 0.015 |

### 4.4.4 Ensemble analysis of smoke dispersion from the Kilmore East fire

A key feature of FireDST is the capacity to analyse the effects of uncertainties in the model inputs. For smoke dispersion, the uncertainty derives from uncertainties in the fire location and rate of spread, plume rise, and uncertainties in the combustion parameters (burning efficiencies, fire patchiness, emission factors for each fuel class). Although all are important, to demonstrate the feasibility of the ensemble approach to smoke spread, we considered uncertainty in one area only, the fire ignition point. The analysis was performed using the Kilmore east fire scenarios, for a high resolution domain, a grid of 80 x 80 cells of 1 km square dimension centred on Kilmore. The Kilmore fire was simulated using PHOENIX RapidFire five times with different ignition locations; once at the location specified in the base case, plus four alternatives in which the ignition point was offset by 500 m to the four cardinal points of the compass (N, E, S, and W). The concentration maps for each fire scenario were overlayed on each other to produce maps of the maximum hourly tracer concentration (Figure 4.17), which is a good measure of exposure risk, and a map of the percentage overlap of the fire simulations for each species (Figure 4.18) which shows the degree of consistency between scenario predictions. A full description of the process is contained in French *et al.* (2014a). Production of both the ensemble maps will be helpful in quantifying and displaying the uncertainty in the smoke maps due to variability in the underlying fire. Probabilistic maps will be possible once we are able to quantify (estimate) the likelihood of a number of the input parameters utilised by the fire spread model.

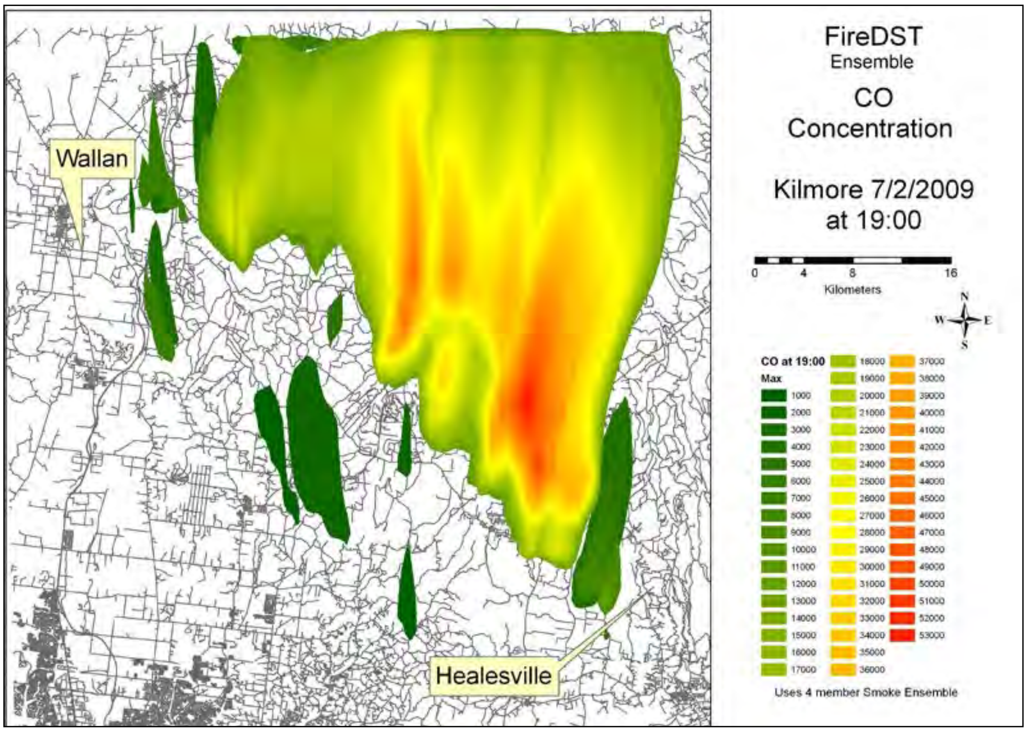


***Figure 4.17*** *Ensemble map of the concentration of CO at 1900 for the four simulations of the Kilmore fire. This concentration map must be used in conjunction with the overlap map.*

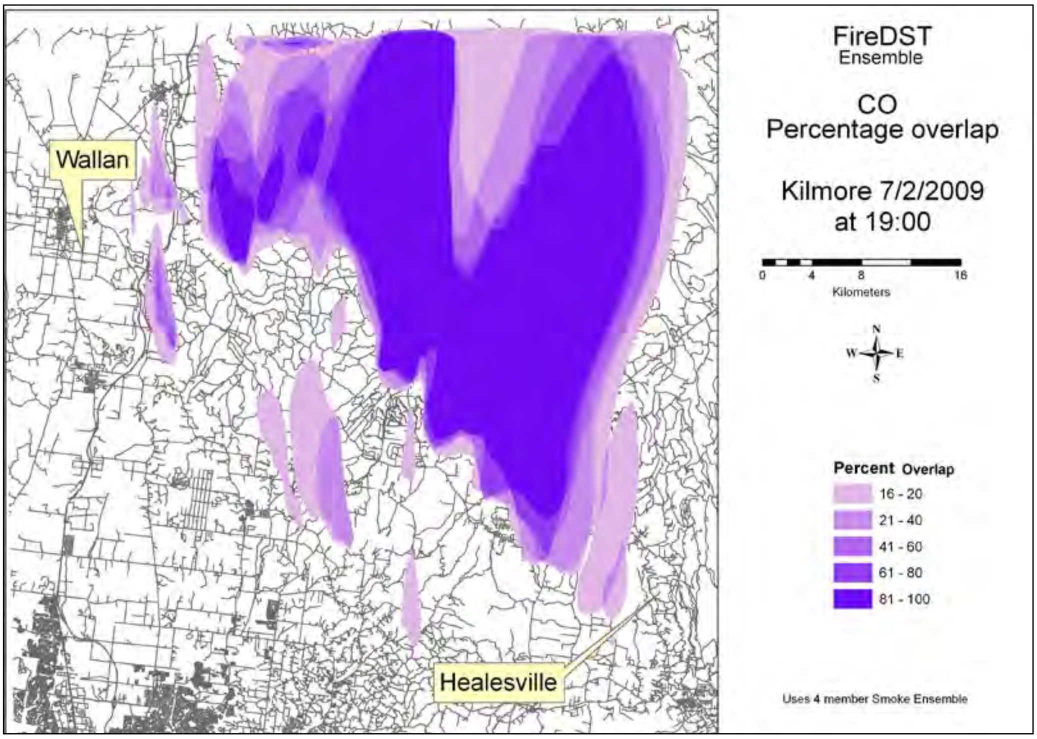


***Figure 4.18*** *Ensemble map of the percentage overlap (probability) of CO at 1900 for the four simulations of the Kilmore fire. This ensemble map must be used in conjunction with the ensemble concentration.*

## 4.5 Areas for development in the emissions model.

The current emissions model, though effective is weak in a range of areas. These are:

(1) quantifying the hourly time-course of combustion within the fire scar boundaries. Where the time-course of fire spread is resolved to an hour or less, the challenge is to accurately describe the emissions of each of the fuel component. Fine fuel combustion is relatively rapid and therefore its hourly timecourse is coincident with the timecourse of fire spread, however the duration and extent of combustion of other fuel components (coarse woody debris (CWD), elevated fuels and the canopy) is slower and, at this stage, poorly known.

(2) quantifying emission factors for some of the key trace species. Emission factors of PM2.5, greenhouse gases and reactive organic compounds that affect plume chemistry are relatively poorly characterised for Australia forests and woodlands. The first can be addressed through linking the fire spread predictions of area and intensity to the smoke emission model. With improved knowledge of combustion dynamics in CWD and living fuels and the combustion processes that determine emission factors, it may be possible to estimate variations in emission factors with properties of fire intensity (e.g. flame length and heat release rate).

(3) Quantifying the correlation between population exposure to PM2.5 and morbidity. There is still significant uncertainty about the health effects of bushfire smoke mainly because of the challenges associated with exposure assessment. Exposure is unpredictable, pollutants are diverse and complex, and the impacted population size is often small, all of which add complexity to the statistical analyses. Studies examining the health impact of severe bushfire smoke pollution are limited and therefor further research is needed to understand the potentially unique health effects of smoke exposure from bushfires. The PhD study undertaken through this project which is currently in the final year of a three-year program, was designed to assess the cardiovascular and respiratory health effects from exposure to particulate matter air pollutants emitted from bushfire smoke.

The study has three components:

(1) A review and, to the extent possible, a meta-analysis of published studies of impacts of bushfire smoke on health. This component is complete and has been prepared for publication. Due to the diversity of methodologies applies a detailed meta-analysis was not possible.

(2) A retrospective analysis of surface PM2.5 concentration in regional Victoria during the 2006/2007 Alpine fire event and

a. Hospital admission episodes codes for cardiovascular & respiratory disease;
b. Emergency department visits for cardiovascular & respiratory disease; and
c. Ambulance attendance for out of hospital cardiac arrest (non-traumatic).

The smoke concentrations were modelled in case study 1. With the caveat that the work is still in progress there appears to be an increase in the percentage of emergency department visits for asthma cases correlated with exposure to bushfire smoke.

(3) An analysis of Health impacts from smoke exposure during the 2013/2014 prescribed burning season. This component of the study is not funded by the Bushfire CRC.

The experimental component of the study is complete and results are being prepared for publication. They show statistically significant increased risks of asthma and cardiac diseases in regional populations exposed to bushfire smoke. This work has substantially improved the capacity to assess regional risks in Southern Australia by identifying the diseases and the susceptible population groups, and by quantifying the risk response rate.

## 4.6 Tools for agencies

A proof of concept for a tool has been developed to provide agencies with the information they need to decide where and when prescribed burning can occur that will minimise impact of smoke on populated centres. The concept was applied for the Ovens Valley, Victoria. The Ovens Valley's main population centre is Myrtleford. The Ovens valley channels smoke emitted from fires in the surrounding forest to the plains to the West. Smoke tends to accumulate in the valley, dispersing slowly. In extreme case such as 2003 and 2006 wildfire seasons, dense smoke persisted in the valley for several weeks. This site is characterised by protracted fumigation events with smoke originating from a combination of different sources, either fresh or aged.

The approach, described in detail by Meyer *et al.* (2013b) applies an inverse modelling technique to assess the relative contribution of emissions in each cell of the grid domain on defined receptor cells. The spatial pattern of impact risk for the test month, April 2009, (Figure 4.19) was not predictable from topography or distance from the source and therefore that the modelling approach offers promise of developing detailed climatologies of smoke dispersion relent to fire districts.  Development of the method will continue beyond the life of the current project.

Some of the modelling tools applied in the FireDST project are sufficiently well developed to provide some potential for application in regional offices.  The CSIRO dispersion model TAPM, which was developed, in part for use by environmental consultants, is sufficiently robust, simple to apply, and fast to run to be of use for planning and analysis by staff in regional offices. A report describing how to configure and run the model for several practical applications has been prepared by Meyer (2014).

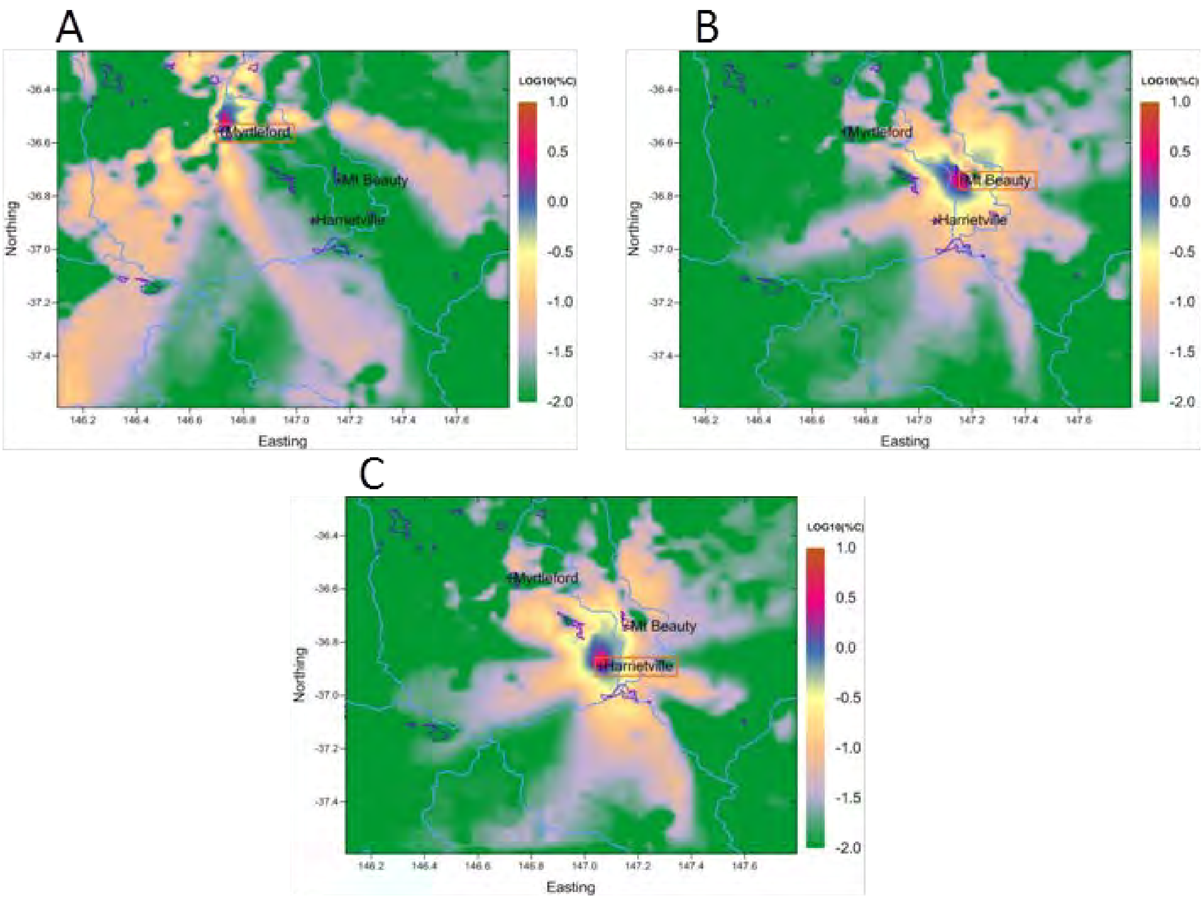


***Figure 4.19*** *The percentage relative contribution (plotted on a log scale) of smoke emissions released from every 3 x 3 km$^2$ grid cell in the modelling domain to A: Myrtleford, B: Mt. Beauty, and C: Harrietville*

## 4.7 Summary and Future Directions

The study has demonstrated that smoke impact on regional populations can, on occasions, be the greatest risk from a fire event, far outweighing the direct risks at fire front. Given the imperative to increase the extent of prescribed burning to 5% of public managed lands in Victoria, smoke impact on people is only likely to increase. New modelling approaches and applications of extant modelling systems have been developed to assist fire managers and planners to limit the risks of these impacts and will continue to be a priority of the FireDST team members beyond the life of the current Bushfire CRC.

# CSIRO MAR publications for this project

## Peer-reviewed publications


Keywood, M., C.P. Meyer, M.E. Cope, Y. Iinuma and K. Emerson (2013). Impact of Bushfires on Air Quality in an Australian Urban Centre, *Atmospheric Environment*. (in *review).*

Meyer, C.P., M.E. Cope and S. Lee (2013a) Assessing the population exposure risk of regional population to smoke from fires. 20th International Congress on Modelling and Simulation, Adelaide, 1st to 6th December.

Meyer, C.P., M.E. Cope and S. Lee (2013b) Smoke impacts from prescribed burning in Victoria; developing a risk climatology, 20th International Congress on Modelling and Simulation, Adelaide, 1st to 6th December.

Meyer, C.P., (2014). Tools to assist fire agencies to minimise smoke impact from prescribed burning. *(in internal review).*


## Bushfire CRC/Internal-reviewed publications


Meyer, C.P., K. Emerson and M.D. Keywood (2012). Review of Smoke Models, report to the Bushfire CRC. CSIRO, 22p.

Meyer, C.P. (2012). Smoke Emission Modelling and Verification in Southern Australian Forests, progress Report to the Bushfire CRC, CSIRO.

Meyer, C.P., M.E. Cope and S. Young (2012). Modelling the Air Quality Impacts of Bushfires for Risk Scenarios, Report to the Bushfire CRC, March 2012, CSIRO Marine and Atmospheric Research, 30p.

Meyer, C.P., M.E. Cope, M.D. Keywood and S. Lee (2014). Assessing smoke exposure from bushfires and prescribed burns, Bushfire CRC Fire Note (i*n preparation).*

# 5. Risk Assessment Decision Toolbox (Geoscience Australia)

The research and development work for Geoscience Australia (GA) within the FireDST project focused on the estimation of the exposure impact of extreme fires on a community. This work led to the implementation of an ensemble simulation system that was built around enhanced versions of existing methods and tools, as well as newly developed modules. This system drew together the outcomes from across the FireDST research team. To underpin this work, Geoscience Australia developed a computational risk assessment framework (Jones *et al.,* 2012), as well as methods and tools to evaluate and summarise the impacts associated with a bushfire. This development included a computationally efficient methodology to account for the role that human intervention may play in reducing ember attack on a building affected by a bushfire.

Research questions (RQ) in the FireDST science plan that are addressed in this Chapter include:

- RQ(2b) Identify, quantify and communicate uncertainties in model predictions,
- RQ(1a) Determine the sensitivity of extreme fire behaviour to particular atmospheric conditions in the vertical atmosphere,
- RQ(1b) Include detailed topography in local weather conditions,
- RQ(7) How do we integrate the research components to produce a tool that assesses the potential impact of fire on specific community values and assets (specifically life, human health, and housing) in relation to fire weather, fuel conditions and fire characteristics?

This last section includes a discussion of the following research question,

- RQ(5) What are the requirements of a comprehensive and up-to-date spatial database of values and assets to be accessed prior, during and after bushfire events?

Finally, this chapter discusses work on developing an approach to informing regional or even national-scale risk assessments.

Appendix A describes a range of extension activities for FireDST, many led by Geoscience Australia.

## 5.1 RQ(2b) Identify, quantify and communicate uncertainties in model predictions.

FireDST has introduced ensembles of fire simulations to demonstrate and quantify the impact of uncertainty in bushfire modelling by introducing variability in inputs.

FireDST provides several interactive screens to process and manage inputs, fire spread simulations, and the fire ensembles and impact calculations. As an example, an ensemble for the Victorian ‘Black Saturday’ Kilmore fire is considered. FireDST generated an ensemble from 30 simulations for this fire which sampled mainly sensitivity of the modelled fire spread to the weather parameters.

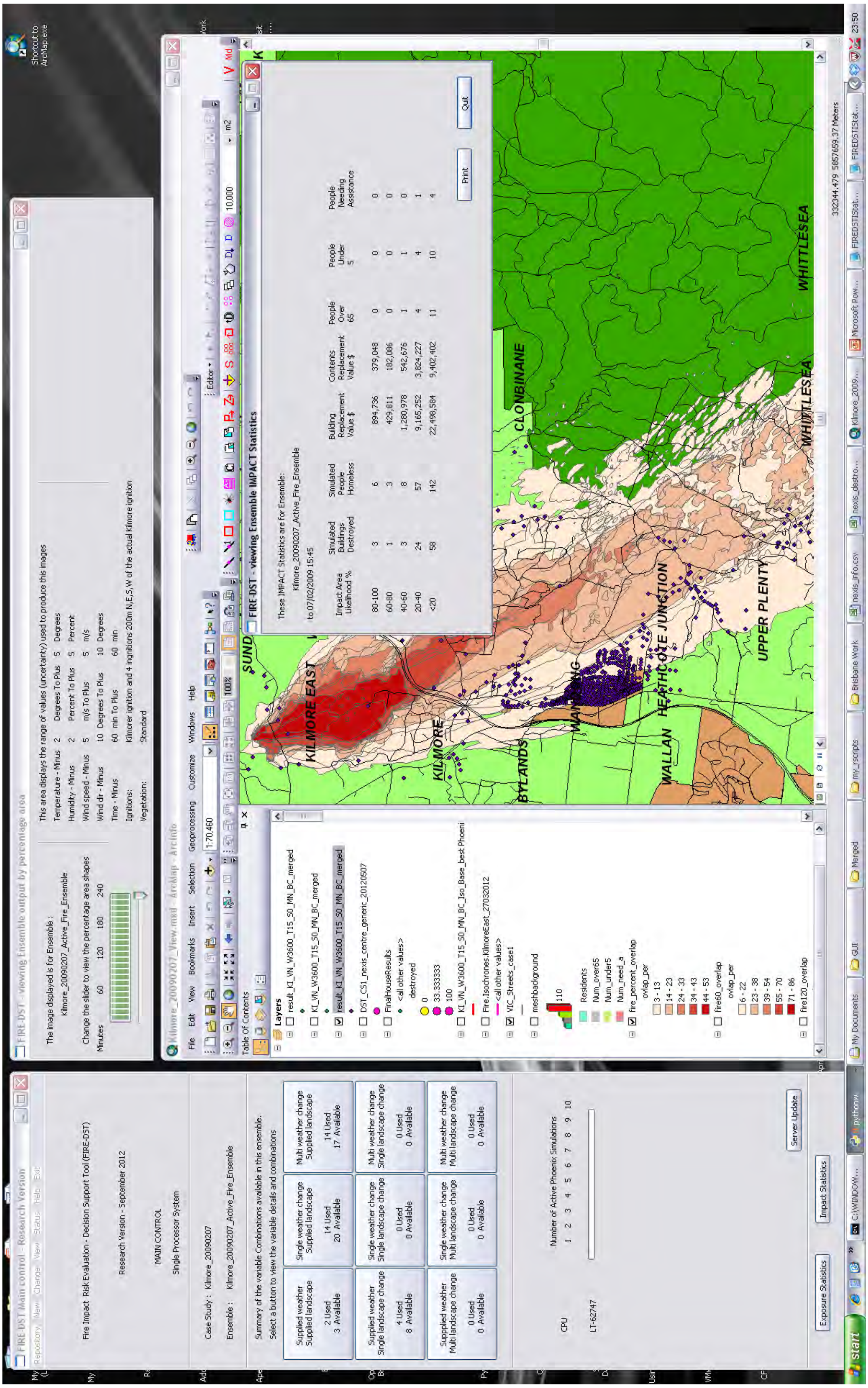

***Figure 5.1** Example FireDST screen showing the Kilmore fire Active Research Ensemble.*

Figure 5.1 displays the screen of FireDST processing an *Active Fire Ensemble* for the Kilmore case study region. There are two individual control panels: the left panel controls the FireDST engine, and the top panel controls the ensemble viewing tools. The user interface allows the user to change the inputs, for example to create new scenarios, add or delete simulations from an ensemble, or which ensembles are available to view.

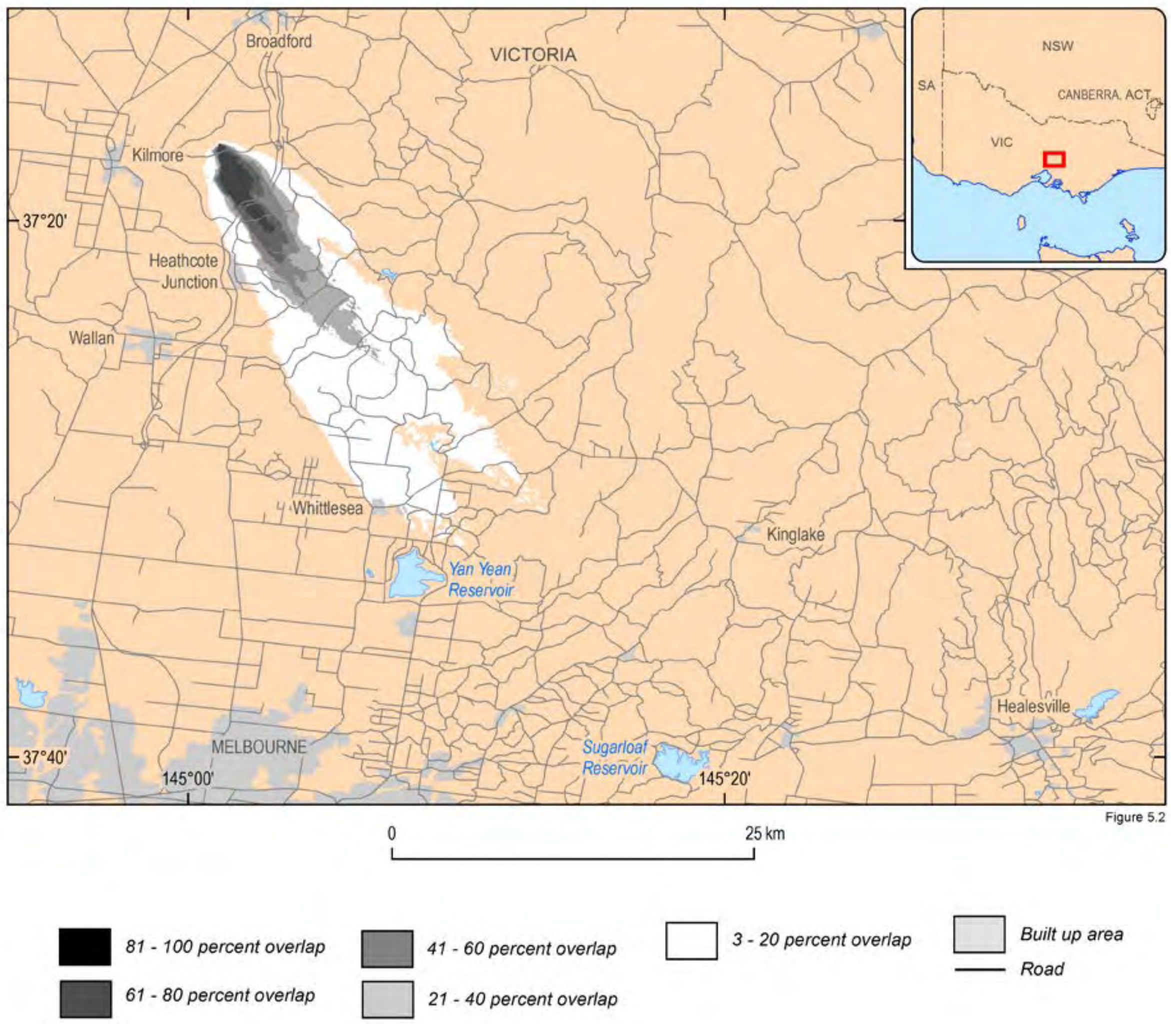


***Figure 5.2*** *FireDST ensemble fire spread for an ensemble of weather scenarios for the Kilmore fire (black areas 80-100%) down to white areas which represent <20% probability for the ensemble fire spread. This ensemble represents the fire four hours after ignition.*

The variability of scenarios within an ensemble reflects the sensitivity of the modelled fire spread or fire impact to the input parameters. This sensitivity is visualised by displaying the simulations as 'scenario maps'. An effective way of viewing the results is to display overlays of all fire spread scenarios in the Kilmore case study. Initial experiments with display techniques included a grey-scale display and different numbers of intervals (Figure 5.2). The final choice of visualisation techniques in FireDST (Figure 5.3) adopted the preliminary recommendations from a related research project on visualising uncertainty in fire spread (Cheong *et al.,* 2013). In Figure 5.3, the blue lines show the actual progression of the fire six hours after ignition. The red colour depicts where the fire shapes for the individual scenarios have overlapped for 76-100 % of the simulations; the green colour displays where fire spread shapes have overlapped for less than 25 % of the simulations. The figure shows that the actual Kilmore 2009 reconstruction is within the ensemble fire boundary.

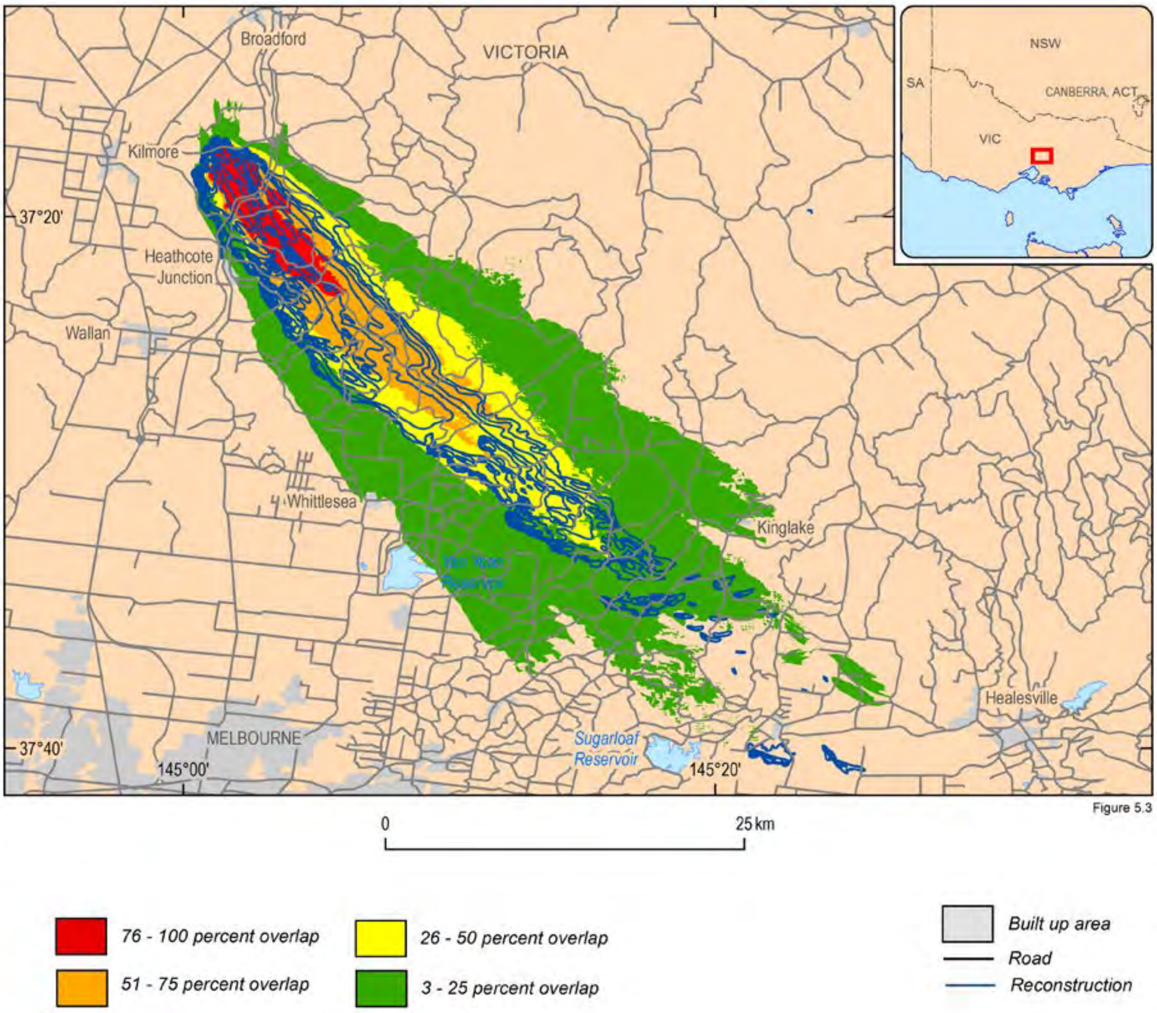


***Figure 5.3** Ensemble view of the Kilmore fire utilising 30 simulations out to six hours after ignition; isochrones of the fire reconstruction are shown in blue.*

FireDST can display information on the potential impact of the fire in terms of summary statistics of the exposed population. Figure 5.4 shows small bar graphs of the population potentially impacted by the simulated fire. The graphs show the ABS Census mesh block statistics for the total population, the population over sixty five years of age, under five years of age, and those in need of assistance. This breakdown of the demographic profile can provide context on the exposed population and their likely resilience in an event. There are other demographic fields available for display (see Canterford, 2011, for more details). Figure 5.5 shows the location of houses that are exposed to the modelled ensemble fire spread.

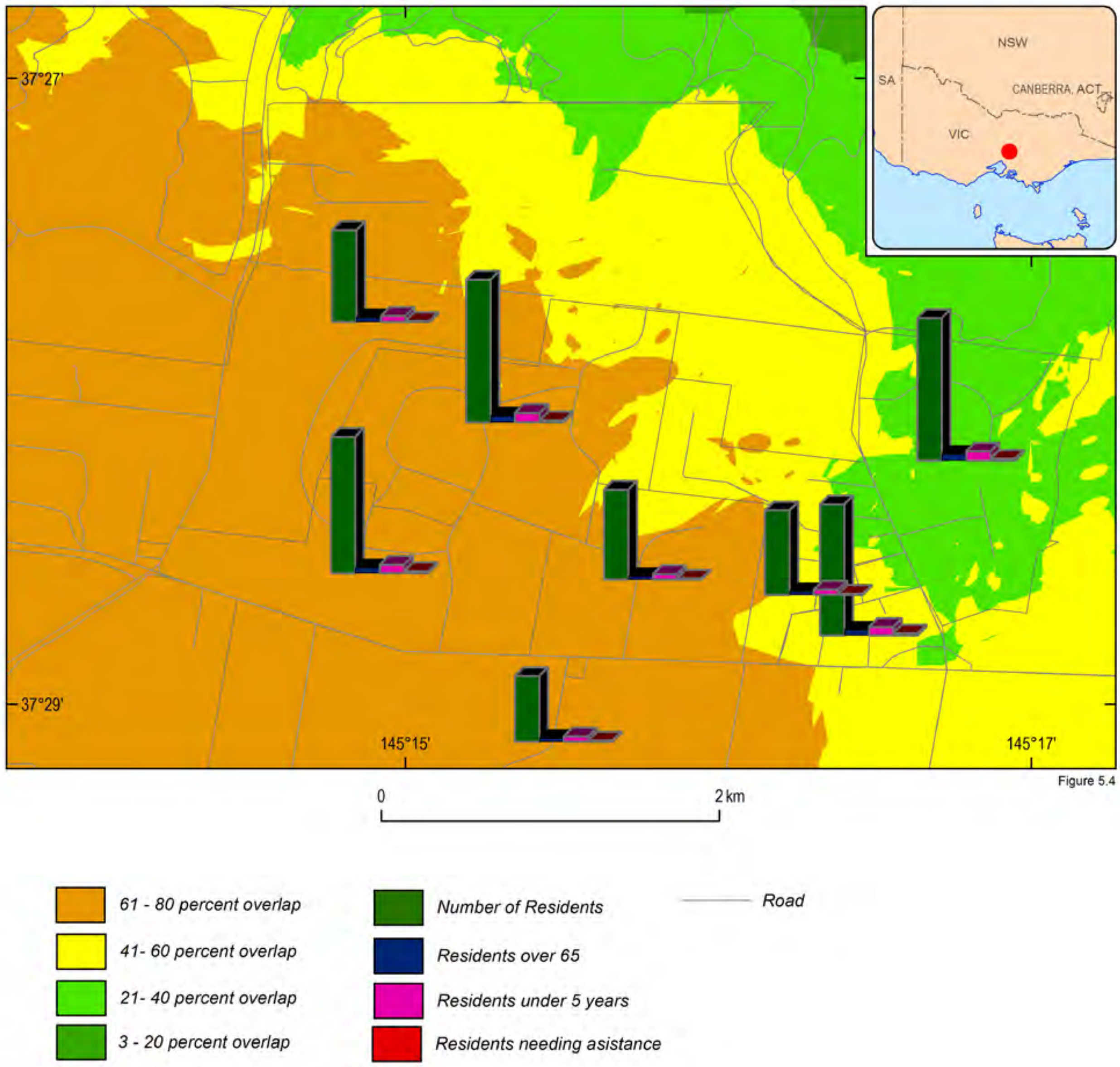


***Figure 5.4*** *Population statistics graphs for Kinglake West overlayed over the ensemble fire spread.*

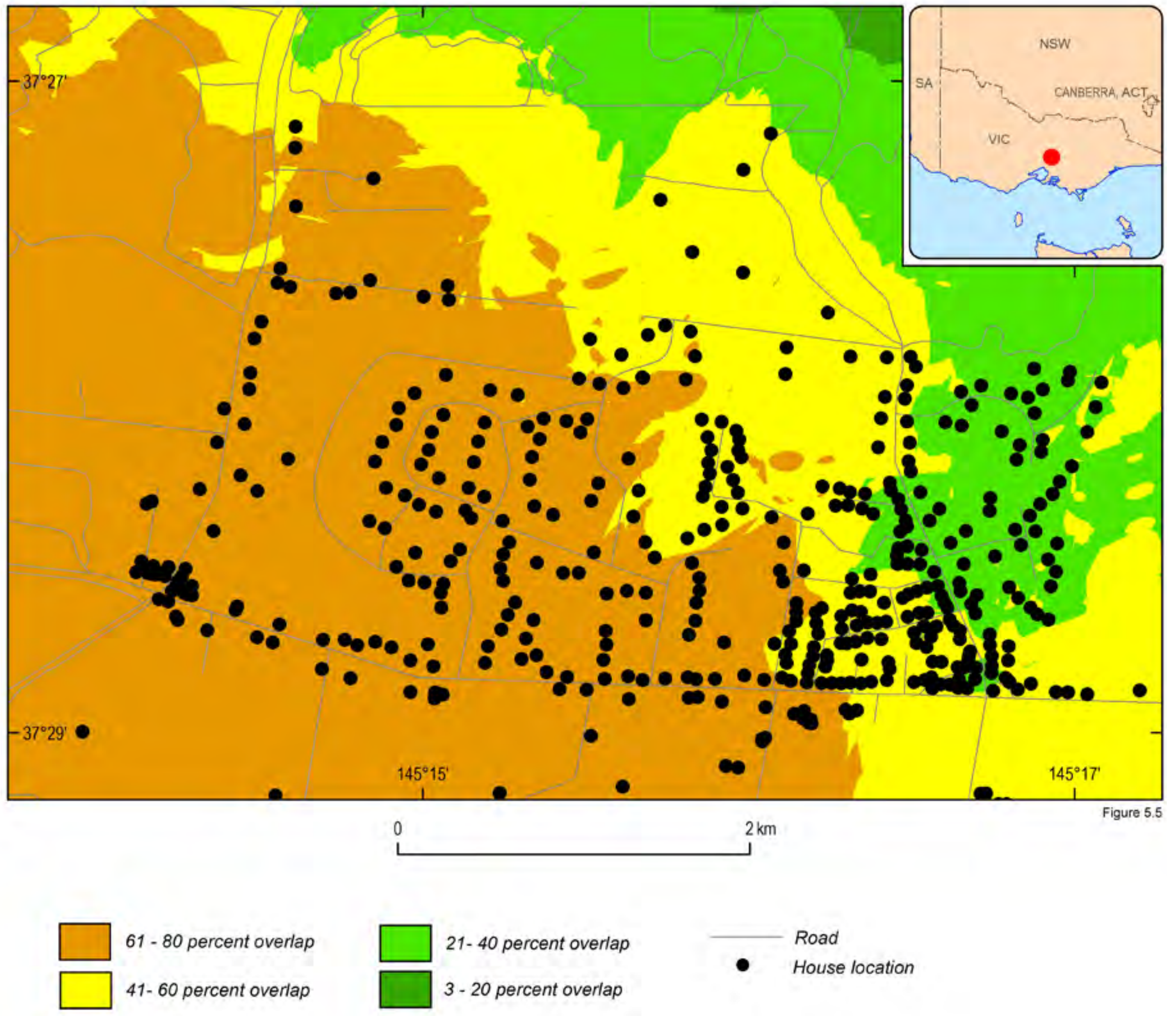


***Figure 5.5*** *Initial view of houses likely to be exposed to the ensemble fire spread.*

## 5.2 RQ(1a) Determine the sensitivity of extreme fire behaviour to particular atmospheric conditions – influence of vertical atmosphere

The version of PHOENIXRapidFire available at the start of the FireDST project did not consider wind speeds in the vertical atmospheric profile above the height commonly defined as 'surface' winds at 10m. As a consequence, the simulated vertical winds were not used to drive the lofting of embers in the fire spread modelling; instead, lofting was calculated using a convective bubble method only (Chong *et al.,* 2012b). As part of the FireDST project, PHOENIX RapidFire was modified to consider a single upper level transport wind speed and wind direction (Chong *et al.,* 2012b). An analysis was then conducted using this new version of PHOENIX RapidFire. Winds in the vertical profile of the atmosphere were extracted from the ACCESS weather model output for 48 hours surrounding the Kilmore fire in 2009. This vertical profile has 4 kilometre horizontal grid-spacing, 15 minute time steps for fifty layers in the atmosphere (ranging in the vertical from about 10 metres above the surface to 60 kilometres above mean sea level). Full results for each case study are detailed in the individual case study results documents (French *et al.,* 2014a; French *et al.,* 2014b; French *et al.,* 2014c). This section summarises the key results across all case studies.

In case study one, the Kilmore fire initially spread to the south east across variable terrain and vegetation. The FireDST results using a single atmospheric layer conditions throughout the boundary layer provided varied results. The lower layers (up to 400 m) produced simulations that matched the Kilmore fire reconstruction very well. Using winds from altitudes around 610 m to the edge of the boundary layer (in this case taken to be at 3130 m) produced larger shapes that still followed the main Kilmore fire direction. Simulations using altitudes higher than the boundary layer found that the dominant wind direction was completely different to the main directional spread of the Kilmore fire. This shows that despite the Kilmore plume possibly reaching over 15 km in altitude (Cruz *et al.,* 2012), the levels above the boundary layer could not be used to transport ‘active’ embers to spread the Kilmore fire.

In contrast to the Kilmore fire, the Wangary and Mt Hall case studies demonstrated a low sensitivity to the vertical atmosphere. In the Wangary case study, this was attributed to the fact that the fire traversed predominantly grassland and low crop fuel types, which generated few embers in the model. The radiation driven fire spread is much less sensitive to the winds in the vertical atmosphere than the ember-driven fire spread. Similarly, the Mt Hall fire also was shown to generate relatively low ember numbers in the model because of its limited size.

The major outcome of this research is that information on conditions in the vertical atmosphere can improve the accuracy of fire spread simulation, especially where embers are a significant contributor to the fire spread. The ACCESS model atmosphere contains more than the boundary layer information, including the vertical air movement between layers, and this could be the subject of further research into ember transport.

## 5.3 RQ(1b) How are weather conditions influenced by terrain and topography?

Geoscience Australia has contributed to modelling the atmospheric conditions driving the fire by adjusting the meteorological information to produce a more realistic representation of the local wind affecting the fire spread. A commonly applied wind engineering approach involving wind ‘multipliers’ based on the national wind loading standard was used to represent the effect of terrain and topography on the local wind speed at very high resolution.

Wind multipliers enable the calculation of local wind speeds by modifying the broad-scale regional wind speeds to reflect the effect of local-scale topography, vegetation and shielding. The study examined the influence of the wind multipliers on fire spread, focusing on the ability to modify the regional wind speed over complex terrain.

Geoscience Australia has developed a computational wind multiplier methodology, described in Yang *et al.* (2014), which is based on (but not exactly the same as) the national standard (Australia – New Zealand Wind Loadings Standard; AS/NZS 1170.2, 2011). Initially these wind multipliers were applied to modify the ACCESS wind strength at 25 metre horizontal resolution (Yang *et al.,* 2013).

The PHOENIX RapidFire bushfire simulator uses the Wind Ninja wind multiplier system which works in a similar way to the Geoscience Australia multipliers but uses the terrain at a horizontal resolution of 100 metres.

To investigate the influence of topography on the local weather conditions the equivalent fire simulation was run without any multipliers, with the Wind Ninja Multipliers and with the Geoscience Australia Multipliers. To allow comparison, the multipliers were transformed to be at 100 metre horizontal resolution (Yang *et al.,* 2013).

The analysis of the wind multipliers was undertaken for Case Study 1 (Kilmore), since this case study provided contrasting ground terrain and topography that was traversed by the fire. It utilised the best-prediction ACCESS weather data for the three available horizontal resolutions (4.0 kilometre, 1.2 kilometre and 440 metre, see Chapter 2) at the 15 minute time-step interval.

Yang *et al.* (2013) shows that the fire spread based on ACCESS winds adjusted with the multipliers produced more accurate simulations of the Kilmore fire, compared to the unadjusted ACCESS winds. This suggests that applying the wind multiplier methodology to numerical model output can produce more realistic local wind profiles.

## 5.4 RQ(7) Integration of research components to assess the potential impact of fire on a community

In its full form the research question was '*How do we integrate the research components that address the other questions posed to produce a tool that assesses the potential impact of fire on specific community values and assets (specifically life, human health and housing) in relation to fire weather, fuel conditions and fire characteristics'*. The FireDST 'proof of concept' system provided a functioning working environment to model integrated fire spread and impact, as well as evaluate their sensitivity to uncertainties in the input data. A brief overview of the FireDST system is given in Section 1.2, and Figure 1.1 shows how the research components have been integrated to form the FireDST system. A more complete description of the operation of FireDST is contained in French *et al.* (2014c).

The following sections discuss research that underpinned the development of particular features of the FireDST impact modelling system.

### 5.4.1 RQ(5) Exposure information requirements

Exposure information is fundamental in the development of risk-assessment models for natural hazards. Exposure information is defined in this study as the assets impacted. This could include people, buildings, community assets and infrastructure including emergency services, hospitals, local government, emergency shelters and food storage facilities.

For impact modelling, an understanding of exposure requires not only identifying the assets, but also their location and characteristics. Building type, construction (roof and wall) type, building age, number of storeys, business type and replacement value (and their spatial location at the building level) are critical parameters for understanding the potential impact from various hazards. In addition to building exposure, the number and type of businesses, essential infrastructure and population demographics exposed are also required.

The exposure information that underpinned the impact assessments in FireDST drew heavily on the National Exposure Information System database (NEXIS). NEXIS (Nadimpalli 2009; Canterford 2011) has been designed to provide exposure information for impact and risk assessments. It provides comprehensive and nationally consistent exposure information, derived primarily from 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. NEXIS information currently includes population demographics, income demographics, number and type (construction) of buildings (residential, commercial and industrial), and age of the buildings.

***Table 5.1*** *Spatial, structural and demographic/economic data fields for residential exposure extracted from the 2011 version of NEXIS for FireDST.*

| | **RESIDENTIAL** |
|---|---|
| **SPATIAL** | Latitude<br>Longitude<br>Address<br>Block size<br>Floor area |
| **STRUCTURAL** | FCB type<br>Roof type<br>Wall type<br>Age |
| **DEMOGRAPHIC/ ECONOMIC** | Income group<br>No. residences<br>No. people<br>Structural value<br>Tenure<br>Contents value<br>Motor Vehicle Access<br>Age Group<br>Need Assistance<br>Volunteer<br>Years at residence |

The NEXIS information model is categorised into residential, business (commercial and industrial), institutions and infrastructure exposure. The FireDST exposure information adopted the residential building information available in a previous version of NEXIS for the three case study regions, to be as consistent as possible with the exposure during the case study events. The 2011 version of NEXIS that was used contains information from the 2006 ABS Census. Table 5.1 details the attributes (spatial, structural and economic) used in the FireDST exposure database based on the 2011 NEXIS residential exposure information.

The FireDST exposure also contains a variety of other socio-economic information that was 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. In addition, the FireDST building information was augmented with additional data for buildings located within the three case study regions, shown in Table 5.2. This data included building damage recorded in post-event surveys in the respective fires, as well as parameters specifying the vulnerability curve (see Section 5.3.2). The historical event damage record was not required for the actual modelling, but allowed assessment of the accuracy of the modelled damage.

*Table 5.2* *Additional data parameters available within the FireDST exposure database utilised for the three case-studies.*

| Parameter name | Parameter description |
|---|---|
| **DAMAGE** | Results of the building survey after each fire. Contains DESTROYED, MINOR or NONE |
| **MB_CODE** | 2006 Census code for the Mesh block that the building is located in |
| **SLA_CODE** | 2006 Census Statistical local area code where the building is located. |
| **CD_CODE** | 2006 Census Collection District code where the building is located. |
| **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 |

### 5.4.2 Vulnerability of buildings

The FireDST system computes the probable damage for buildings within the modelled fire spread. The probable damage is a function of the hazard, modelled in terms of the radiation and ember density generated by the fire at specific locations. The total impact of a fire is derived by aggregating the probable damage across all buildings within a fire spread scenario or ensemble.

The FireDST building damage model contains vulnerability curves developed by CSIRO and Geoscience Australia for the vulnerability of residential buildings. Four vulnerability curves were used to model the response of each house to the fire conditions it was exposed to. The curves related the building damage to radiation intensity and to ember density, the latter specific for three different levels of local fuel moisture content. Ember load is defined as the sum of the embers received per square meter over the period of the whole fire event.

The radiation curve specified that 100 % building damage (total loss) occurred at 12.5 kW/m2 of radiation, as this is the point where a standard glass window will fail. The ember curves are shown in Figure 5.6 and define three 'failure points' for differing ember load and fuel moisture content.

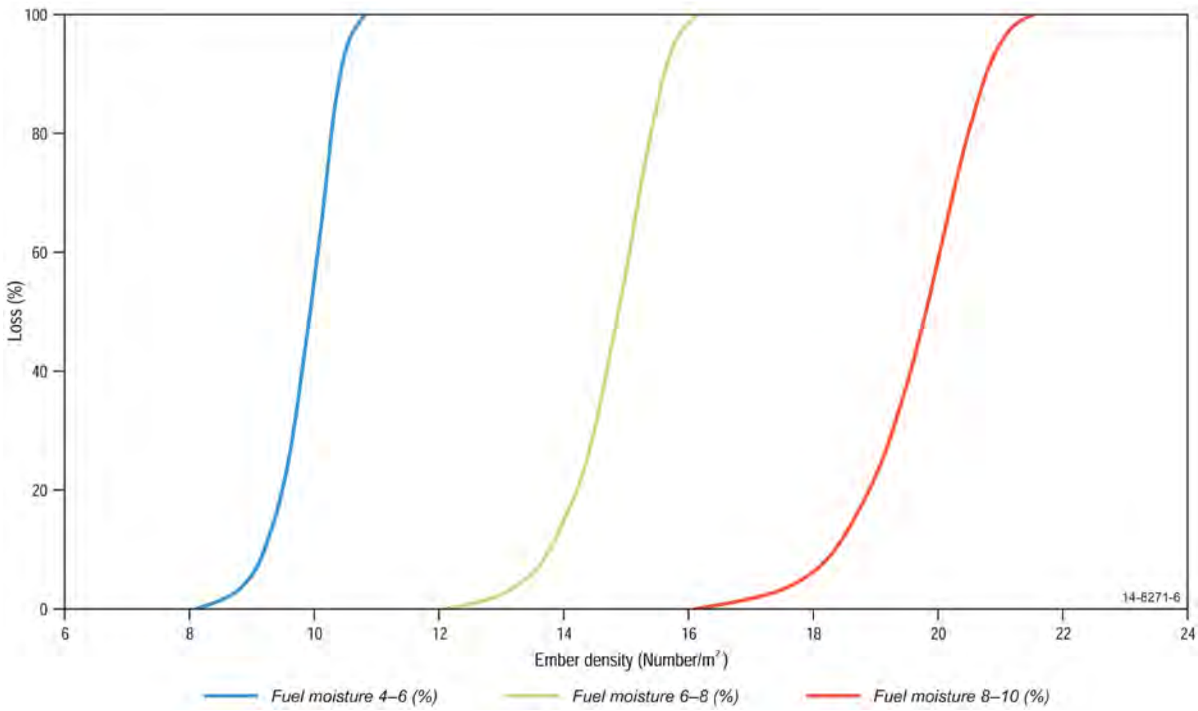


***Figure 5.6*** *Vulnerability curves relating building loss (as a percentage of its value) to the ember density for varying fuel moisture content.*

Accuracy of the impact modelling was assessed by comparing modelled losses against data from impact surveys, available for each event. The number of houses actually destroyed for these case studies was 1178 for Kilmore, 62 for Wangary and 17 for Mt Hall. The model achieved an accuracy of modelled house loss of 55% for the Kilmore case study, 100% for the Wangary case study, and 33% for the Mount Hall case study, using the default vulnerability curves with the modelled fire spread footprint that best matched the historical event. The impact of the Mt Hall event was particularly poorly estimated by the model.

A range of factors is likely to contribute to the difference in accuracy of modelled losses between the case studies.

- *Fire hazard modelling uncertainties:* The accuracy of the fire spread modelling ultimately limits the potential accuracy of the impact modelling; if the modelled fire spread does not cover the correct exposure, even a perfect damage model cannot compensate. The modelled fire spread for the Kilmore and Mt Hall case studies does not correspond as well to the historical event, compared to Wangary. This is caused by a range of uncertainties around the fire modelling, discussed in earlier chapters in this report. This may not only affect the accuracy of the fire spread, but also of the hazard conditions in the fire such as radiation or ember density, which could not be validated. The Mt Hall fire spread was especially difficult to match because of the lack of reliable data. Furthermore, Kilmore and Mt Hall have comparatively complex terrain, with significant variability in the local micro-meteorology and fuel that are not captured by the modelling. In comparison, Wangary has the more uniform terrain, with possibly lower levels of such uncertainties.

- *Impact modelling uncertainties:*
    - Variability in the building characteristics leads to error in a simple vulnerability model such as that used in this study. Kilmore has more variability in the building stock, partly because of the quantity of the affected exposure, which is not reflected by the generic vulnerability model.
    - Variability between other processes that are not captured in the impact model, such as house-to-house ignition or defensive action. Potential approaches to modelling this will be discussed in more detail in the next section.

Although it is not possible to be certain without further work, it is likely that the fire spread modelling is the main factor that determines the accuracy between the case studies. The FireDST ensemble approach sheds some light on the relative importance and interaction between these factors, as the following demonstrates.

Modelled impacts showed sensitivity to changes in the radiation curve. This was tested by assessing the accuracy using curves from the default that assumed 100% loss at 12.5 kW/m$^2$ and 19, 26 and 40 kW/m$^2$, respectively, for the same fire spread scenarios (Table 5.1). In each scenario, the highest accuracy was achieved by the curves assuming 100% loss at 12.5kW/m$^2$, which were used as the default curves in FireDST. The modelled impact for the Kilmore and Mt Hall case studies showed a decline in accuracy with an increasing radiation vulnerability threshold, particularly when the threshold was raised to 40 kW/m$^2$. This suggests that the model estimates are reasonably robust when using the 'default' curves at 12 kW/m$^2$. If results were to benefit from a more specific set of curves to represent variability in the building stock, for example based on house age or building type, the focus should be on the more vulnerable buildings.

***Table 5.3*** *Accuracy of modelled house loss using different radiation vulnerability assumptions. The fire spread for each case study was based on the scenario that best matched the historical footprint.*

| Radiation value (kW/m$^2$) | Kilmore Average Accuracy | Wangary Average Accuracy | Mt Hall Average Accuracy |
|---|---|---|---|
| 12.5 | 55 | 100 | 33 |
| 19 | 55 | 100 | 32.8 |
| 29 | 54.6 | 100 | 32.1 |
| 40 | 52.1 | 100 | 20.3 |

Table 5.4 again shows the sensitivity of the house loss modelling for all case studies assuming the respective vulnerability curves. However, the figures in Table 5.4 present the average accuracy across an ensemble that samples the error in the input conditions, in terms of the surface weather, fuel and ignition error, as described in Section 1.2 and Chapters 6 to 8. The average accuracy is lower than the figures reported in Table 5.3 because it is lowered by fire spread scenarios that did not reflect the historical event. This reinforces the conclusion that the uncertainties in the fire spread modelling provided the key limitations of the accuracy of the damage estimate.

Table 5.4 shows that the Wangary and Mt Hall case study results showed a consistent trend of declining accuracy in modelled losses with an increasing radiation loss. However, the Kilmore event showed an inconsistent trend. As described above, the modelled fire spread of the Kilmore event was very sensitive to variability in fire conditions, partly due to variability in the terrain. These results show that this uncertainty overshadowed the sensitivity to the vulnerability assumptions.

***Table 5.4*** *Average accuracy for each house simulated for the different radiation vulnerability assumptions, averaged across an ensemble sampling variability in surface weather parameters, ignition timing and location, and fuel conditions.*

| Radiation value ($kW/m^2$) | Kilmore Average Accuracy | Wangary Average Accuracy | Mt Hall Average Accuracy |
|---|---|---|---|
| 12.5 | 24.2 | 57.5 | 28.9 |
| 19 | 33.8 | 47.6 | 24.2 |
| 29 | 28.2 | 33.5 | 15.5 |
| 40 | 24.4 | 20.3 | 9.2 |

The results described in this section indicate that there is a need to further refine the impact modelling capability that is used in FireDST. It is likely that the FireDST vulnerability model can be improved by making it more specific for different building types, particularly for more vulnerable buildings. However, the main limitation of the performance of the impact model is likely to be the error in the fire spread modelling itself. This could include the inability to reflect processes such as human intervention, through house defence, and house-to-house ignition. The following section develops an approach to parameterise the impact of these sub-grid scale processes on the building loss.

### 5.4.3 Building Fire Impact Model (BFIM)

Geoscience Australia has developed a computationally efficient methodology to take into account the role that human intervention may play in reducing ember attack on a building affected by a bushfire, which is located in a rural/urban interface region. The methodology is based on a mathematical technique called *Event Tree* (also called a probability tree), which is a way of representing the dependency of events (Thomas *et al.,* 2002). Events are described by a list of dependent variables, such as ‘person(s) being present’, ‘fire plan in place’, and ‘proximity of building to other structures’ (following the methodology of Sanabria (1999) for fires that start within buildings.

The BFIM approximates the impact of intervention on house loss by reducing the modelled fire hazard experienced by buildings, thus indirectly lowering the modelled losses. The BFIM adjusts the modelled ember density received by a structure to reflect ember reduction efforts of the occupants, their neighbours and any emergency service team that may be present. To allow this, the BFIM assimilates information about the residence type, neighbours and fire brigade assistance for each building. The ages and family status of occupants are also taken into account, and relevant information such as whether occupants are active fire brigade volunteers, and whether the household has independent transport. Further information on this model is available in Sanabria *et al.* (2013c) and French *et al.* (2014c).

Conversely, the BFIM increases the modelled ember density if the house has been damaged by wind prior to attack by embers. The effective ember and radiation hazard computed by the BFIM are then applied to a house using generic vulnerability curves (Blanchi *et al.,* 2010) to determine if the house is destroyed by the fire. Figure 5.7 shows that accounting for the impact of intervention to houses in the

Kinglake West region using the BFIM, the majority of houses were modelled to experience lower levels of hazard and correspondingly lower impact.

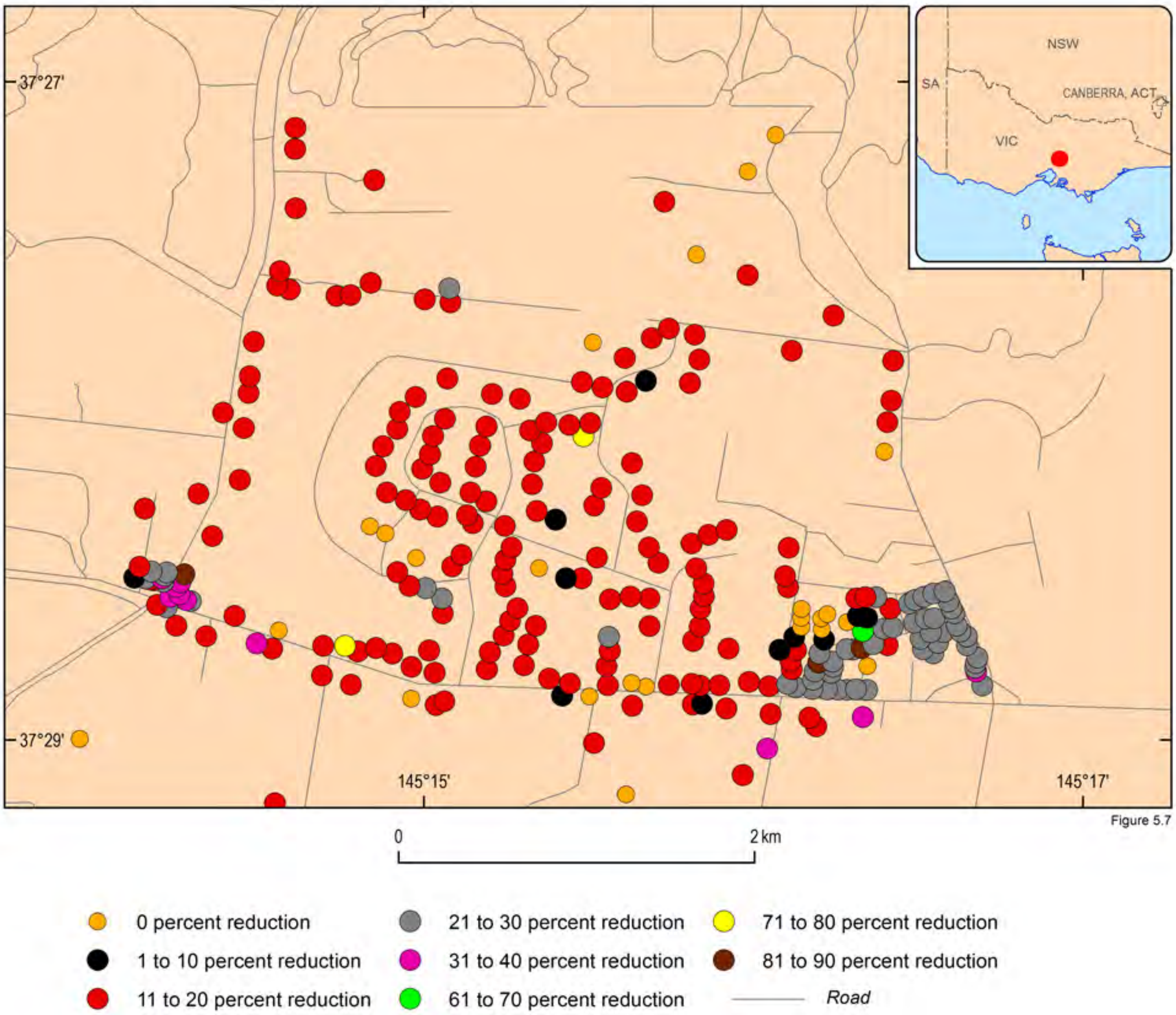


***Figure 5.7** Percent reduction in modelled ember density for Kilmore Fire – Kinglake West Region – after BFIM*

The BFIM also computes the possibility of house to house ignition. This is derived after FireDST has simulated ember ignition and direct radiation ignition. Figure 5.8 shows a final result for the Kilmore event where three houses had a high probability of being ignited by neighbouring houses that were already burning.

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

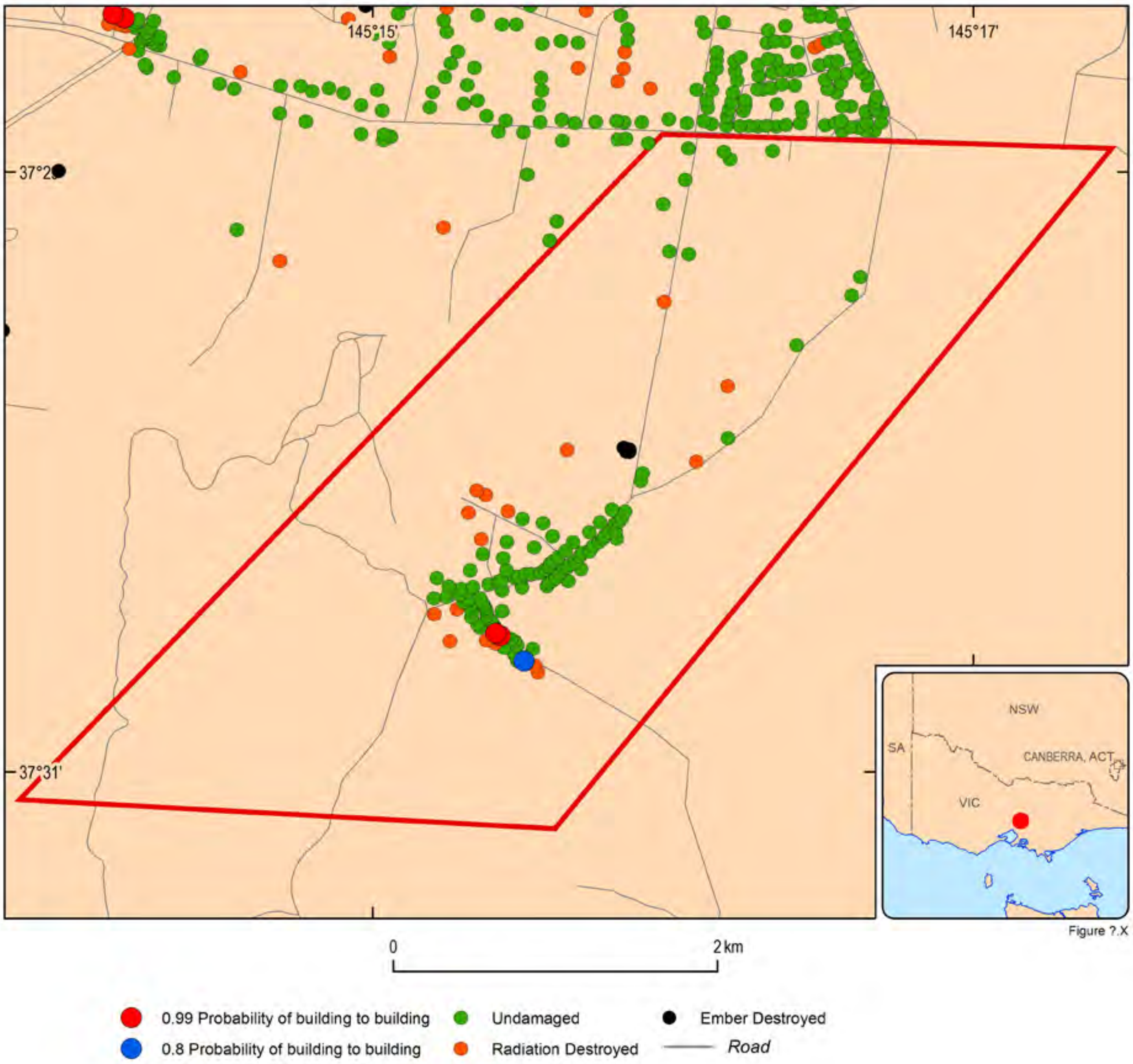


***Figure 5.8*** *BFIM results for Kilmore Fire in the Pine Ridge Road Region*

## 5.5 Informing Risk Assessment

The FireDST project has been primarily focused on fire spread and impact modelling in an operational context. However, it was recognised that the methodologies and data developed in FireDST could also be applied to improve the understanding of risk to communities. To explore the concept of bushfire risk of communities, two approaches were explored in the project.

1. Multi scenario impact assessment for single event risk assessment
2. Long-term risk assessment

A full risk assessment method should consider the distribution of the hazard in terms of probability and severity of events, in combination with the vulnerability of the community at risk given its particular assets and characteristics. A full description of the elements in a bushfire risk assessment is given in Jones *et al.* (2012).

In its current form, the FireDST system develops the first approach listed above: the multi-scenario impact assessment for single event risk. By creating ensembles of the impact for a 'single event' the outputs can inform relative risk for a location for a particular event. This does rely on the ability to weight the ensemble members with their relative probability, which itself requires a quantitative characterisation of the error distribution of the various variables that the ensemble is based on. Risk in this context can inform a range of emergency management applications.

Long-term risk assessments can underpin planning or mitigation applications. As part of a hazard assessment, we have undertaken two studies to inform the long-term spatial return period (RP) of the Forest Fire Danger Index (FFDI):

1. observation-based assessment of the RP of FFDI (Sanabria *et al.,* 2013a)
2. model-based assessment of RP of FFDI (Sanabria *et al.,* 2013b).

These products do not constitute a full risk analysis as they do not consider the relative vulnerability of communities exposed to potential fires. However, these hazard assessments are useful as indicators of priority areas for further risk analysis across large spatial areas, allowing regional or national products that are computationally extensive (relative to scenario-based methods such as those listed above).

Additional to the work described above, FireDST has contributed to a national capability for bushfire risk assessment by compiling the methods and datasets and methods required to undertake such assessments. The ensemble nature of FireDST lends itself to both 'single event' and also 'long-term' risk assessment. For event-based assessment, the demand on the spatial resolution of the input information is higher than for long-term risk assessment. For the latter the aggregation of information tends to average or smooth the local impact assessment. On the other hand, the computational requirements for regional and national risk assessments tend to be high as long-term event sets are generated to cover every location with the full suite of possible scenarios.

# Geoscience Australia publications for this project

## Peer-reviewed publications

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Sanabria L.A., Qin, X., Li, J., Cechet, R.P., Lucas, C. (2013a). Spatial interpolation of McArthur's Forest Fire Danger Index across Australia: Observational study, *Environmental Modelling & Software*, 50, 37-50.

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Sanabria L.A. Cechet R.P., Li J. and Qin X. (in review) Estimating Fire Weather Danger in SE Australia using Climate Simulated Data. *International Journal of Climatology.*

Yang T., French I., Cechet, R.P. and Sanabria, L.A. (2013) Using wind multipliers to determine local wind speed from modelled regional data for fire spread applications. 20th International Congress on Modelling and Simulation (MODSIM 2013), Adelaide, December 2-6th.

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Cechet R.P., Tolhurst K., Leonard J., Meyer M., K.J. Tory, Kepert, J.D. (2011) Bushfire CRC Research Project: F.I.R.E-D.S.T. Fire Impact & Risk Evaluation Decision Support Tool. Poster, Annual Conference of the Australasian Fire and Emergency Services Council and the Bushfire Cooperative Research Centre, Sydney, 29 to 31 August 2011.

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French I., (2012) GA 3-1-3 Case Study One Beta Test Results, 30 September 2012.

French I. A, (2013) GA 3-4-5 Sensitivity analysis results for the three FireDST project case studies, Geoscience Australia, December 2013.

French I.A, Cechet R.P., (2012) FIRE-DST: Fire Impact & Risk Evaluation Decision Support Tool. Poster, Annual Conference of the Australasian Fire and Emergency Services Council and the Bushfire Cooperative Research Centre, Perth, 28 to 30 August 2012.

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French I. A, Woolf, M., Cechet, B., Yang, T., and Sanabria, A. (2014a) GA 4-1-5A Acknowledging and Understanding Uncertainty in Simulating Bushfires - Part 1 - Evaluation of FireDST against the Kilmore fire of 7 February 2009. Geoscience Australia Canberra, GeoCat 77719.

French I. A, Woolf, M., Cechet, B., Yang, T. and Sanabria, A. (2014b) GA 4-1-5B Acknowledging and Understanding Uncertainty in Simulating Bushfires - Part 2 - Evaluation of FireDST against the Wangary fire of 10 January 2005. Geoscience Australia Canberra, GeoCat 79354.

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Mills, G.A., Cechet, R.P. and McRae, R.H.D. (2012) Proceedings of the 2011 Fire Weather and Risk Workshop, Science workshop held following AFAC/BCRC 2011 Conference, Geoscience Australia Record, 2012/35, 90pp.

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# 6 Case-study 1: Overview - 2009 Victorian fires – Kilmore East fire

## 6.1 Introduction

The Kilmore East fire occurred on 7 February 2009. It burnt 125,383 hectares, resulted in the deaths of 119 people and destroyed 1,242 homes. The weather on the day was extreme with Melbourne recording a record highest maximum temperature: in fact, record high temperatures for February were set over 87% of Victoria. The fire weather was catastrophic with fire danger indices (both grass and forest) above 200 at a number of locations (Bureau of Meteorology 2009). Figure 6.1 shows the extent of the Kilmore East fire (taken from VBRC, 2010). A comprehensive assessment of the Kilmore East fire can be found in Chapter 5 of the 2009 Victorian Bushfires Royal Commission report (VBRC, 2010).

The Kilmore East fire started at about 11:47 EDT, on a rocky hill near Saunders Road in Kilmore East, the ignition being due to an electrical failure. The fire burned across the Shires of Nillumbik, Mitchell and Yarra Ranges as well as the City of Whittlesea, about 85 kilometres north of Melbourne. The fire behaviour was extreme. Burning initially in a south-easterly direction, the fire crossed the Hume Highway and went on through Wandong on its way towards Mt Disappointment. As the fire front progressed across Mt Disappointment, the terrain, fuel and meteorology were such that the fire promoted long-distance spotting. This spotting resulted in fires also being reported at Wallaby Creek, Humevale, Strathewen, St Andrews, Steels Creek, Dixons Creek and Yarra Glen, and in the Healesville area. The fire ground region was subsequently influenced by a south-westerly wind change, which passed through between 1740 EDT and 1900 EDT. The eastern flank of the fire subsequently became the front of the fire, and as the fire burned in a north-easterly direction the fire behaviour intensified due to the drier air mass and dynamic atmospheric effects (see below). Following the wind change, the fire impacted on Kinglake, Kinglake West, Clonbinane, Steels Creek, Chum Creek and Strathewen, then it progressed towards Flowerdale, Hazeldene, Castella and Glenburn.

Later in the evening of 7 February 2009, the Kilmore East fire stopped when it reached the area already burnt by the Murrindindi fire. The Kilmore East and Murrindindi fires together burned a total of 168,542 hectares.

A reconstruction of the Kilmore fire on 7 February 2009 has been detailed in a draft report for the Victorian Department of Environment and Primary Industry (Gellie *et al.,* 2012). This report and associated data has been provided by the Victorian Government Department of Environment and Primary Industry (DEPI) for use by the project team for FireDST project purposes only. The Kilmore fire is detailed from pages 98 to page 125 in that report. This reconstruction is used in all fire comparisons. ARC-GIS shapefiles were provided as part of the reconstruction report and the reconstructed fire isochrones were used in all simulation shape comparisons (Figure 6.1).

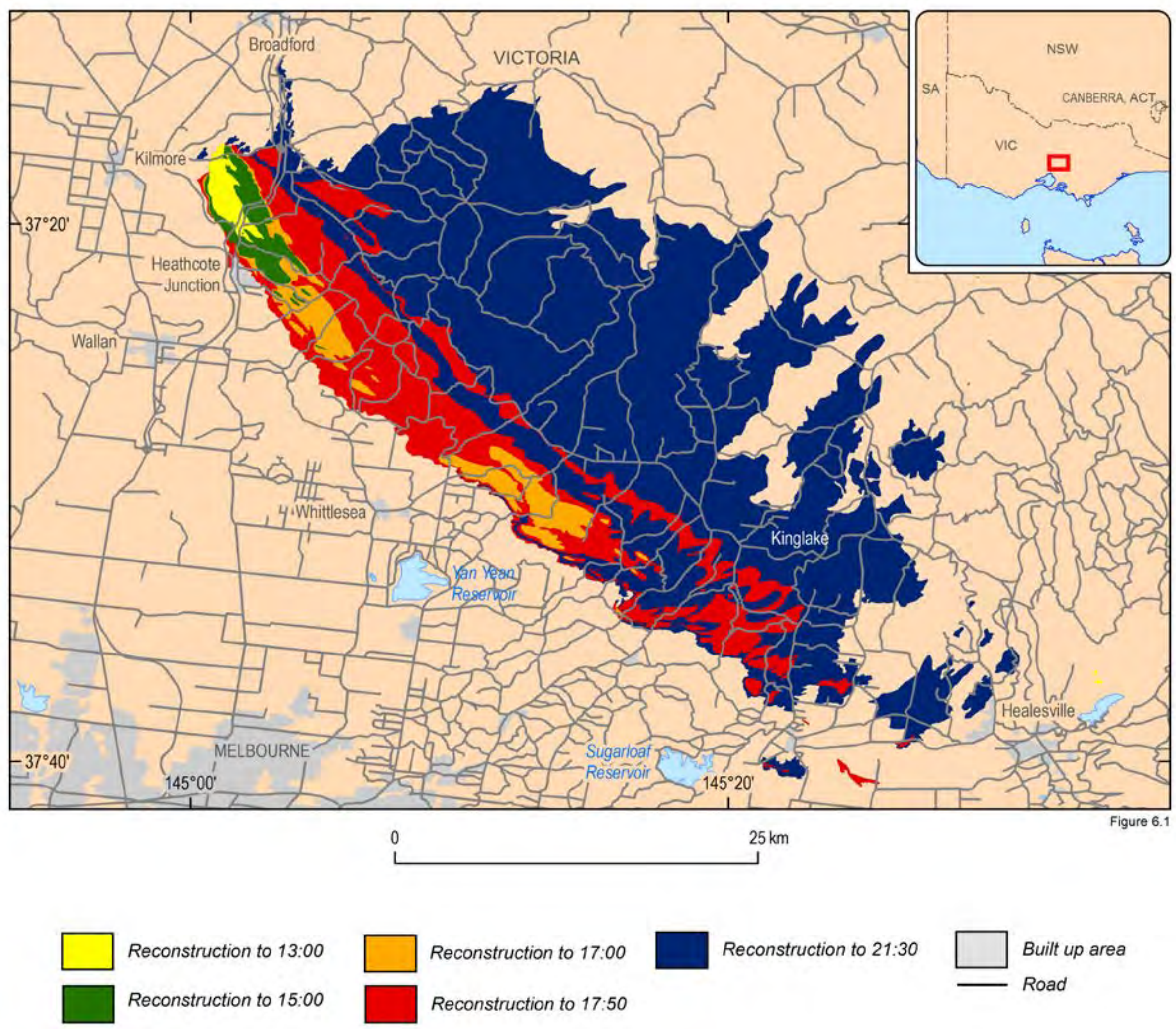



***Figure 6.1****Reconstruction of the Kilmore fire to 21:30.*

## 6.2 Kilmore Weather Results

The synoptic situation on the morning of Black Saturday is shown in Figure 6.2. A low pressure system with embedded cold front was located south of the continent. This, together with a high pressure system in the Tasman Sea was directing hot northwest winds over Victoria. A pre-frontal trough has been analysed (dashed line) crossing the coast of southeast South Australia: this feature became the primary wind change across Victoria in the afternoon of 7 February 2009.

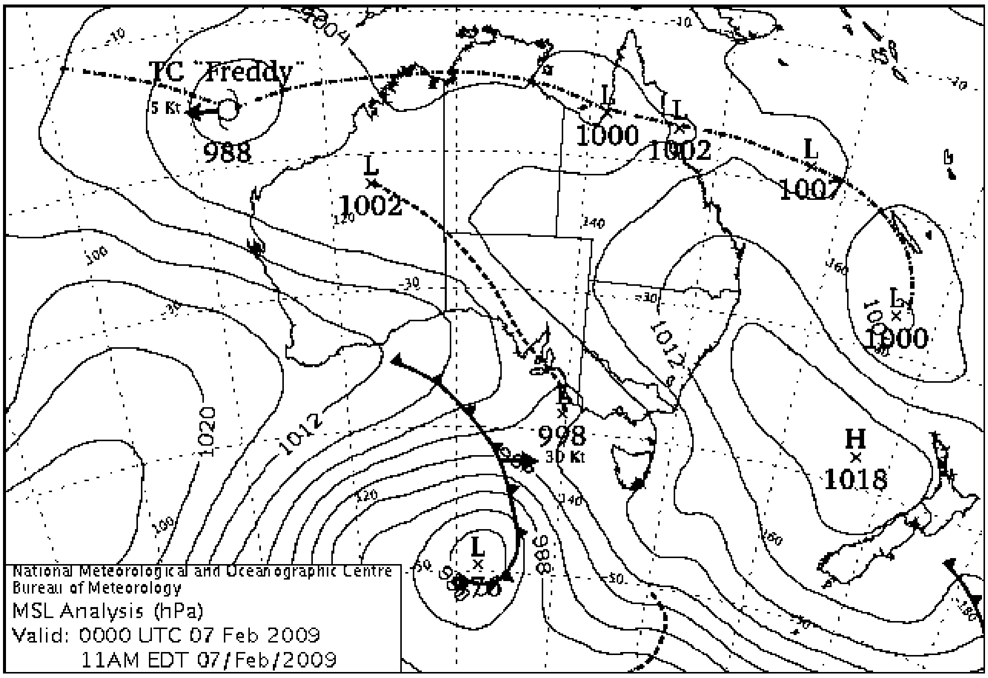



***Figure 6.2*** *Mean sea-level pressure analysis (in hPa) for 1100 EDT (0000 UTC) on 7 February 2009.*

Figure 6.3 shows a comparison between one-minute-interval observations from the AWS (Bureau station number 088162) at Wallan (near Kilmore Gap) and five-minute-interval data from the 440-metre-grid-spacing ACCESS simulation. An analogous comparison for the Eildon Fire Tower AWS is shown in Figure 3.4. At Wallan, the wind change arrives at around 1810 EDT, and the air temperature drops by around 10°C within 10 minutes. This is accompanied by a marked increase in the dewpoint temperature. The wind direction swings by about 90° from northwest to southwest. Prior to the arrival of the wind change, the wind speed had exceeded 10 m $s^{-1}$ for hours and shown marked variability. Extra detail on the weather is contained in Section 3.1.3.

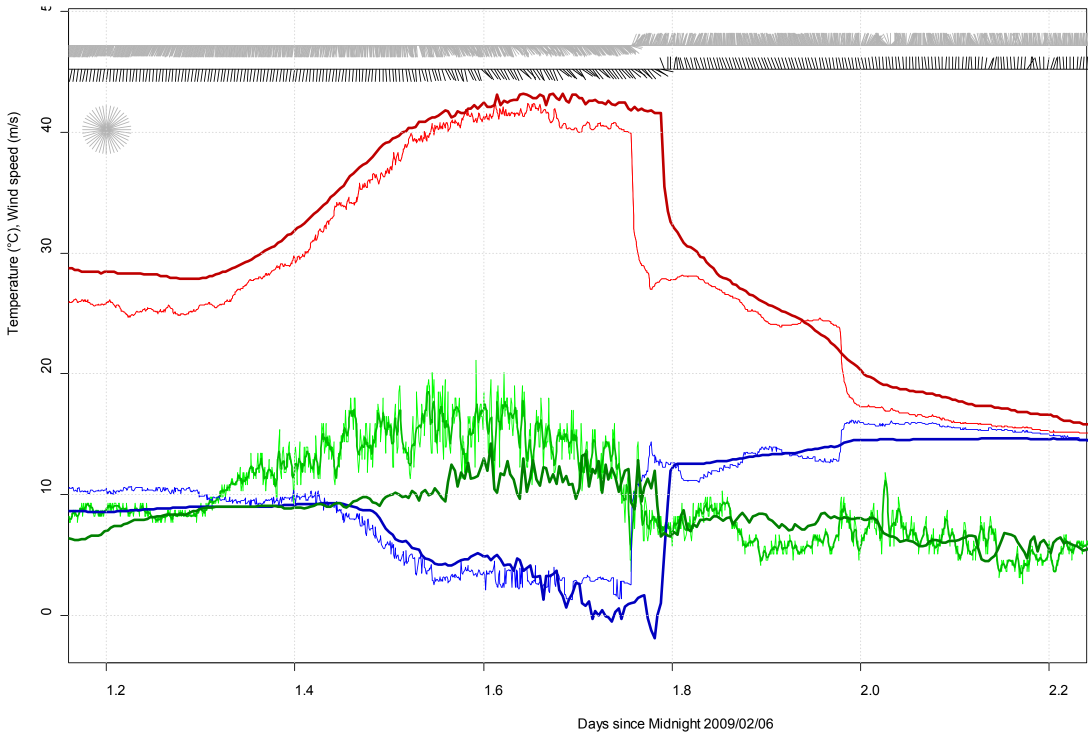



***Figure 6.3*** *As per Figure 3.4, but for the AWS (Bureau Station Number 088162) at Wallan (near Kilmore Gap). From the 440-metre-grid-spacing simulation, the simulation captures the afternoon maximum temperature well, (in RED; model is SOLID line whilst the observation is the THIN line) although it is a little over-forecast, and the magnitude of the changes in air temperature and dewpoint temperature (in BLUE) associated with the primary wind change are well-modelled, even though the change is late in the model. The observed second wind change near midnight is not seen in the modelling. The 10-metre wind speeds (in GREEN) during the day on Black Saturday are not adequately captured by the model, under-forecast by around 5 to 7 m s$^{-1}$ mainly ahead of the cool change (i.e. in the northwesterly flow). The overnight cooling on the night of the 7th is adequately modelled.*

## 6.3 Kilmore Fire Spread Results

The Kilmore fire reconstruction data was used for the development and calibration of an ember transport and propagation model. Once the model was developed, PHOENIX RapidFire was able to simulate the spread of the fire with a high degree of accuracy using observed weather inputs. Weather data produced by ACCESS when run at 440 m and 4000 m grid spacings produced very poor fire spread predictions in their raw state (small regions of fire spread compared to the fire reconstruction). Once the10 m wind speeds were bias corrected and a time offset used to counter the late arrival of the cool change (by comparing model output with observations), the fire spread regions were much better predicted (Figure 6.4).

Outputs from the calibrated fire simulation model that indicated the convective strength of the fire were found to correlate strongly with house loss and may provide a valuable tool in assessing the potential for extreme fire impacts in future. As the model has been calibrated on the Kilmore fire, further evaluation on other fires is necessary to determine whether the assumptions of the new spotting model are robust. Simulations of the Kilmore fire were used for sensitivity analysis of fire spread predictions.

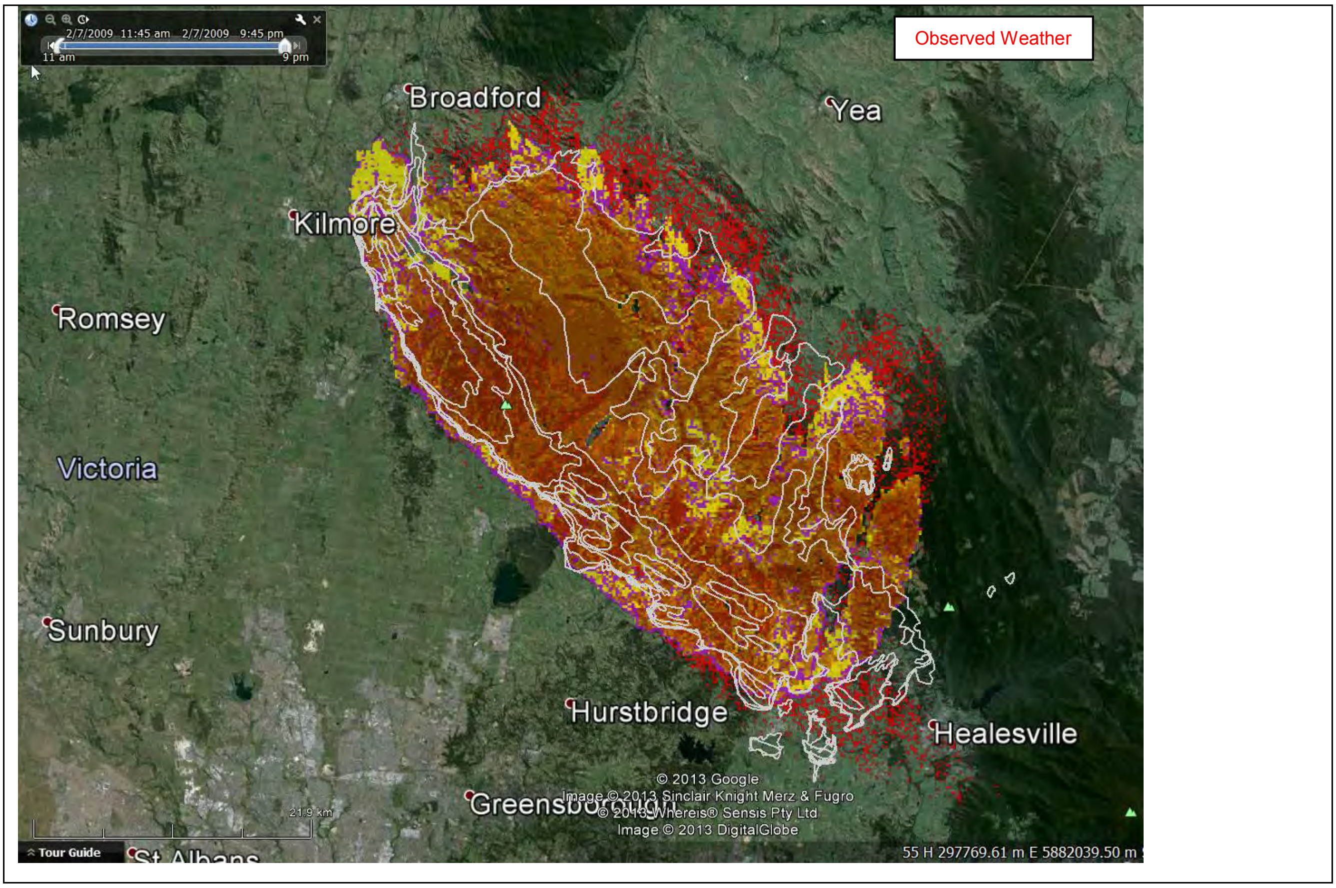
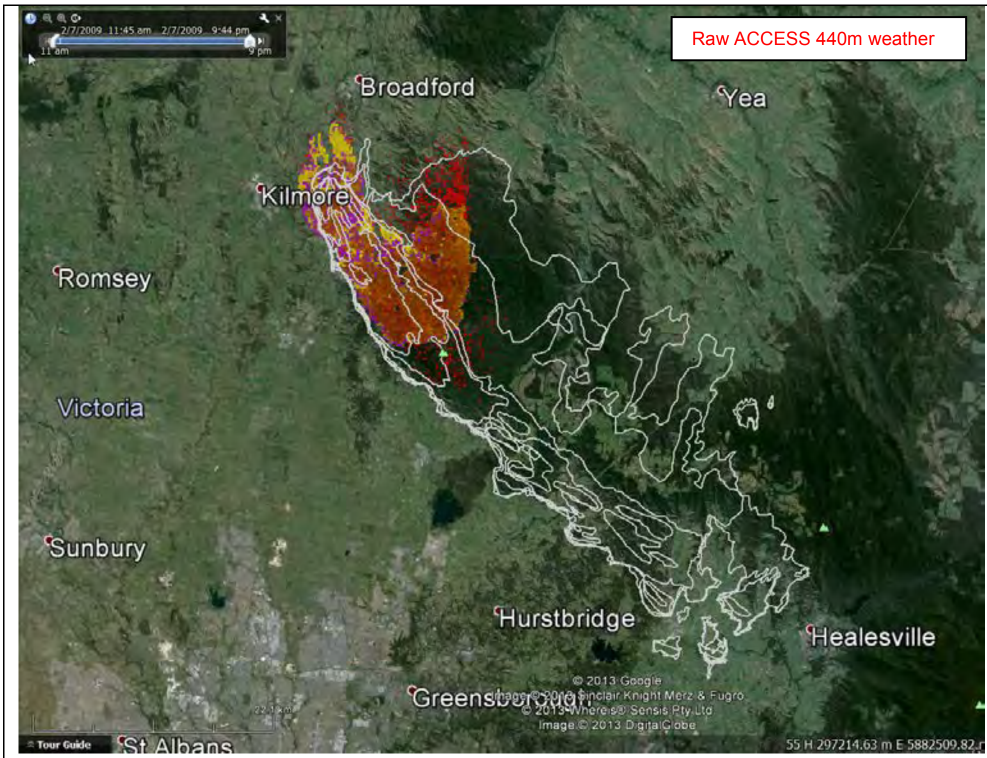



***Figure 6.4(a)*** *PHOENIX RapidFire simulation of the Kilmore East fire using observed weather from the Kilmore Gap AWS. Flame height is shown in solid yellow to brown colours, extent of spotting is shown as red squares, areas of fire self-extinguishing are purple and reconstructed perimeters are illustrated by white lines.*



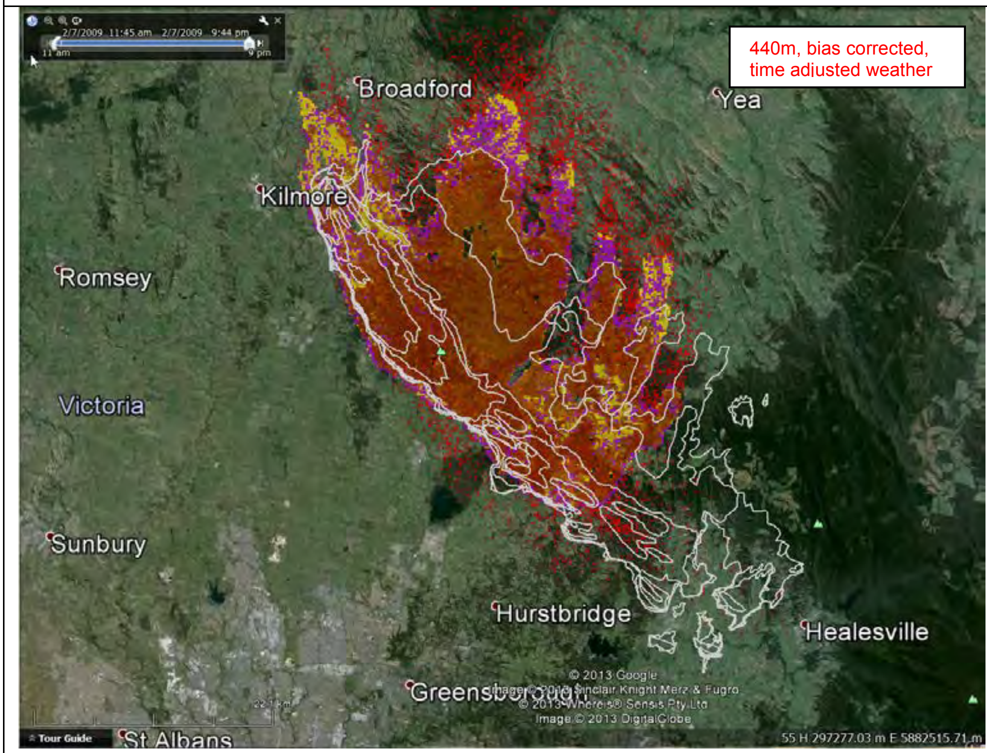




***Figure 6.4(b)*** *PHOENIX RapidFire simulation of the Kilmore East fire using raw ACCESS data produced at 440 m grid spacings, and biased corrected and time adjusted weather from the ACCESS model. Flame height is shown in solid yellow to brown colours, extent of spotting is shown as red squares, areas of fire self-extinguishing are purple and reconstructed perimeters are illustrated by white lines.*

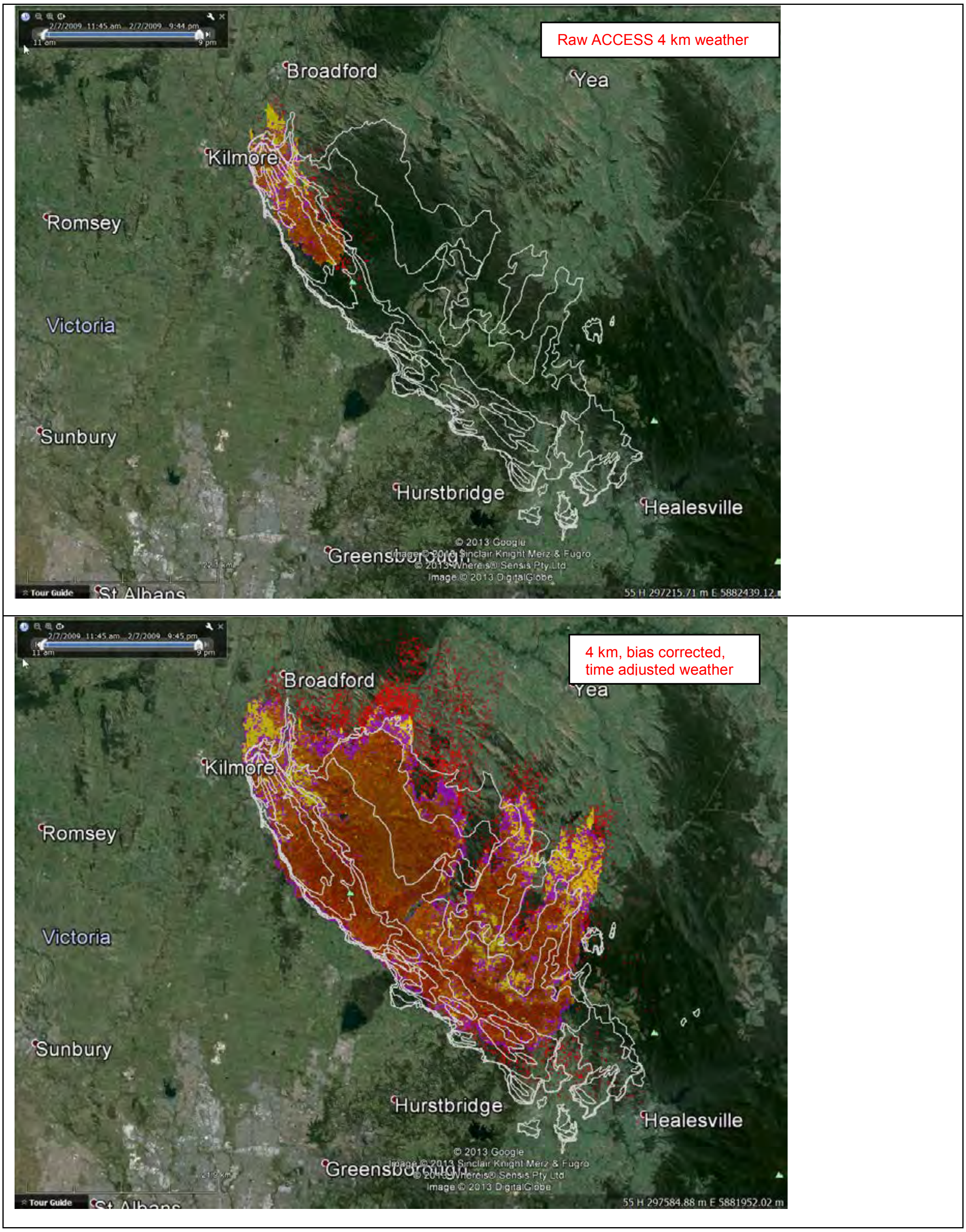



***Figure 6.4(c)*** *PHOENIX RapidFire simulation of the Kilmore East fire using raw ACCESS data produced at 4000 m grid spacings, and biased corrected and time adjusted weather from the ACCESS model. Flame height is shown in solid yellow to brown colours, extent of spotting is shown as red squares, areas of fire self-extinguishing are purple and reconstructed perimeters are illustrated by white lines.*

## 6.4 Kilmore Exposure/Impact

Exposure and impact were modelled based on a FireDST ensemble for the Kilmore event. The 33-member ensemble sampled variability in the weather conditions (humidity, temperature, wind speed and wind direction), as well as the timing and location of the ignition. Figures 6.5 and 6.6 show two of several different ways that FireDST displays exposure and impact information. Figure 6.5 shows an ensemble fire spread simulation of the fire and the table of exposure statistics derived from the mesh block level information. The exposure information covers all the residences in each of the gradients of the ensemble fire spread (e.g., there are 24 houses and 57 people in the 20-40% area of the ensemble spread; Tables 6.1 and 6.2). The total number of houses in the ensemble is lower than the number of houses affected in the Kilmore event, as these results were generated based for a time four hours into the Kilmore event.

***Table 6.1*** *FireDST people related exposure statistics for the ensemble simulation shown in Figure 6.5.*

| Ensemble fire spread overlap % | Number of People affected | Number of people over the age of 65 | Number of people under the age of five | Number of people who need assistance |
|---|---|---|---|---|
| 80-100 | 6 | 0 | 0 | 0 |
| 60-80 | 3 | 0 | 0 | 0 |
| 40-60 | 8 | 1 | 1 | 0 |
| 20-40 | 57 | 4 | 4 | 1 |
| <20 | 1243 | 75 | 80 | 36 |

***Table 6.2*** *FireDST building related exposure statistics for the ensemble simulation shown in Figure 6.5.*

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

Figure 6.6 shows FireDST's on-screen graphs that contain the exposure details. In this case the exposure graphs may extend beyond the envelope of the ensemble fire because the screen is displaying statistics for any mesh block that has some part of the mesh block overlayed by the ensemble fire.

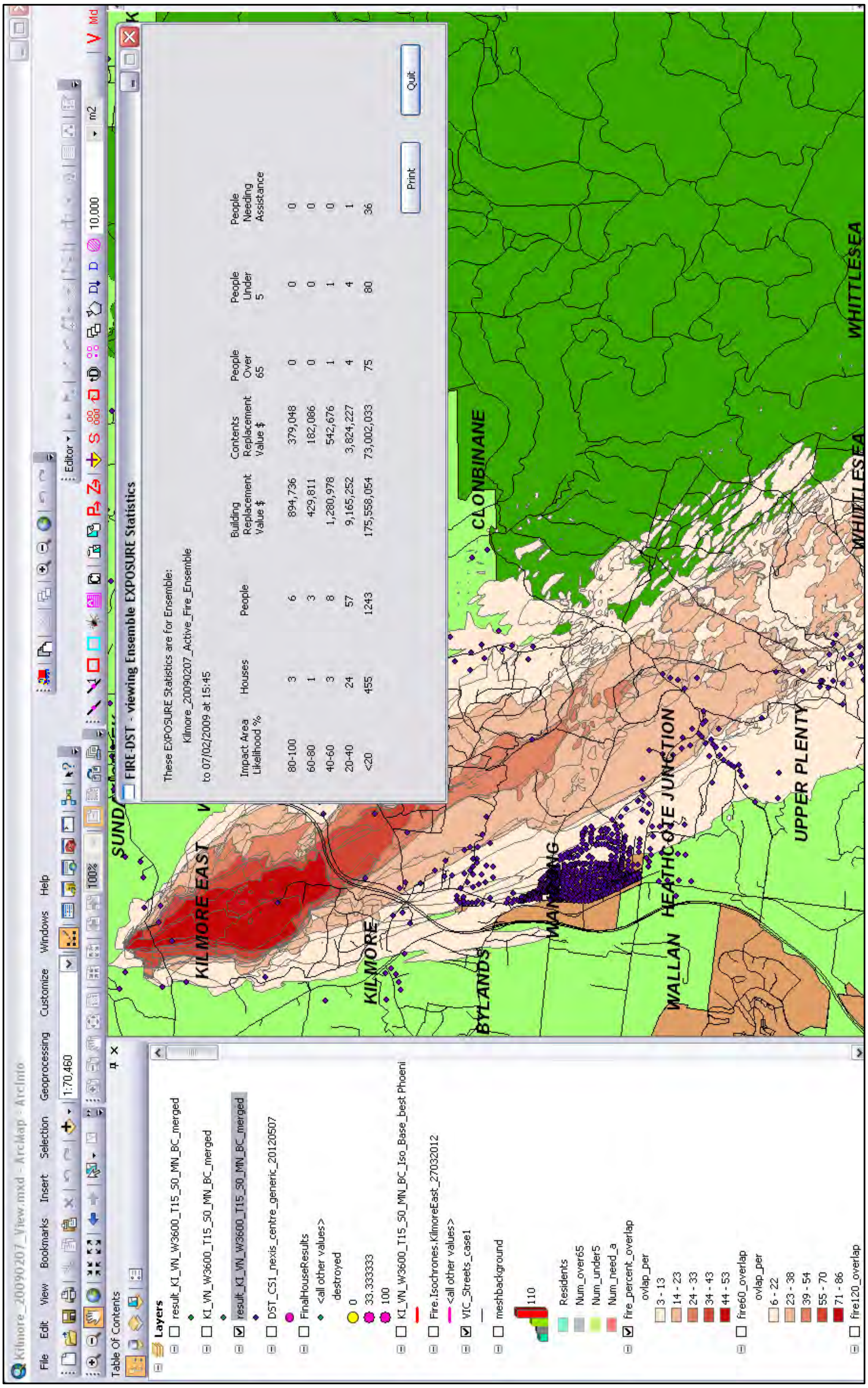



***Figure 6.5*** *Screen shot of the ensemble fire spread and the building level exposure in the fire spread four hours into the Kilmore event.*

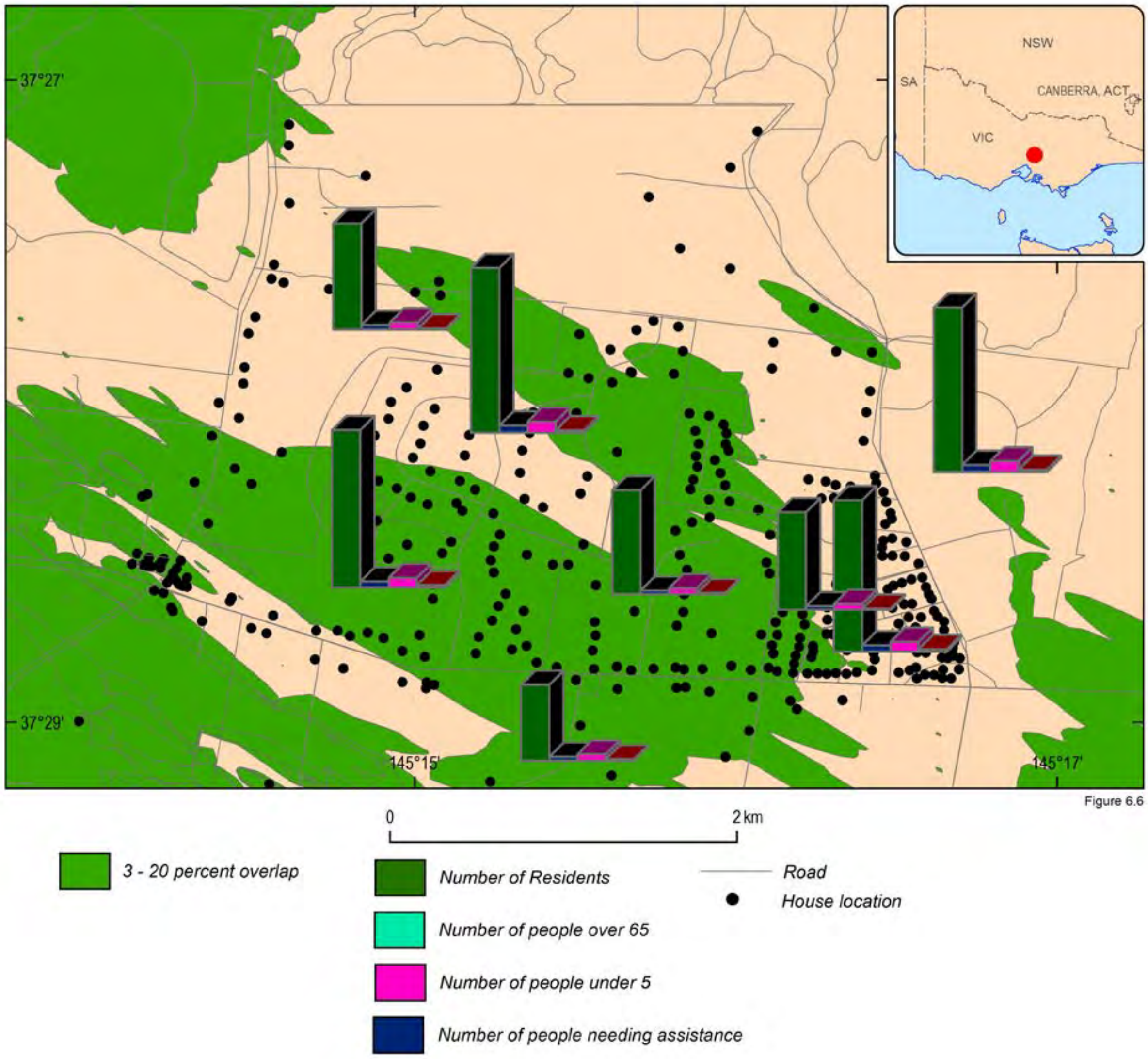



***Figure 6.6*** *Graphical view of exposure graphs for Heathcote Junction region.*

FireDST was used to model the impacts on the buildings identified to be within the fire spread. Tables 6.3 and 6.4 show the modelled impact for the exposure in the ensemble fire spread in Figure 6.5. Table 6.3 summarises the number of people in houses that were modelled to be sustaining damage, and Table 6.4 quantifies the extent of that damage.

***Table 6.3*** *Population statistics for people living in buildings modelled as damaged for the ensemble simulation shown in Figure 6.5.*

| Ensemble fire spread overlap<br>% | Number of people affected | Number of people over the age of 65 | Number of people under the age of five | Number of people who need assistance |
|---|---|---|---|---|
| 80-100 | 6 | 0 | 0 | 0 |
| 60-80 | 3 | 0 | 0 | 0 |
| 40-60 | 8 | 1 | 1 | 0 |
| 20-40 | 57 | 4 | 4 | 1 |
| <20 | 142 | 11 | 10 | 4 |

***Table 6.4*** *FireDST building related impact statistics for the ensemble simulation shown in Figure 6.5.*

| Ensemble fire spread overlap<br>% | Number of houses impacted | Estimated house replacement cost<br>$ | Estimated house contents value<br>$ |
|---|---|---|---|
| 80-100 | 3 | 894,736 | 379,048 |
| 60-80 | 1 | 429,811 | 182,086 |
| 40-60 | 3 | 1,280,978 | 542,676 |
| 20-40 | 24 | 9,165,252 | 3,824,227 |
| <20 | 58 | 22,498,584 | 9,402,402 |

The results in the Kilmore case study demonstrate the potential richness of information that the FireDST methodology can bring to fire event modelling. The integrated fire spread and impact approach allows instantaneous visualisation of the people and assets impacted by an event. By summarising the exposure for the different gradations of overlap of fire spread scenarios, the ensemble information shows the sensitivity of the projected exposure and impact to the uncertainties in the fire spread modelling. In this case study, there is a high certainty that a relatively limited number of people will be exposed to the fire, irrespective of the input parameters. However, assuming a more 'extreme' scenario, the impact could be nearly ten times higher. Decision making processes would benefit from visualising those extreme scenarios, considering their probability and factoring in appropriate contingencies for a worse or 'worst' case.

# 7 Case-study 2: Overview - Eyre Peninsula – Wangary fire

## 7.1 Introduction

On 10 January 2005 at around 15:00 CDT, a bushfire started in the Wangary District on the Lower Eyre Peninsula, South Australia approximately 45 kilometres northwest of Port Lincoln (the ignition was due to a vehicle exhaust coming into contact with long dry grass). The fire ignited sugar gum trees and proved very difficult for farmers and the Country Fire Service (CFS) personnel to quell during the course of the rest of the day and overnight.

The following day was an extreme fire weather day for South Australia (total fire ban for the whole of the State). Just before 1000 CDT (on 11 January), the first of several breakouts from the initial fire occurred. These breakouts spread extremely quickly in a south-easterly direction under the influence of hot and dry, strong north-westerly winds.

The fires that have become known as the Wangary Bushfire are the breakout fires from the ignition that occurred on 10 January. The Wangary Bushfire resulted in the death of nine people, 115 people injured, 47,000 livestock losses were recorded, burning of 77,964 hectares of land, and the destruction of 93 homes, 316 sheds, 45 vehicles and 139 farm machines. Figure 7.1 shows the extent of the Wangary fire (based on a reconstruction provided to the coronial inquiry by Kevin Tolhurst, Melbourne University). The reconstruction shown here has been constructed by Brett Cirulis and Kevin Tolhurst (both from Melbourne University) for this project. More information on the Wangary fire can be found in the Wangary Coronial Investigation Findings (WCIF, 2007).

The breakouts can be seen in Figure 7.1 as the long ‘plume-like’ shapes leading to the southeast from the green region. The green region depicts the extent of the fire on 10 January prior to the breakouts, which broke-out on the south-eastern flank of the green region (at the three locations indicated) on the morning of 11 January 2005. The breakouts eventually merged into one large fire complex and proceeded to the east coast of the Eyre Peninsula reaching the township of North Shields (on the coast) as well as Poonindie, a settlement on the Lincoln Highway to the north of North Shields.

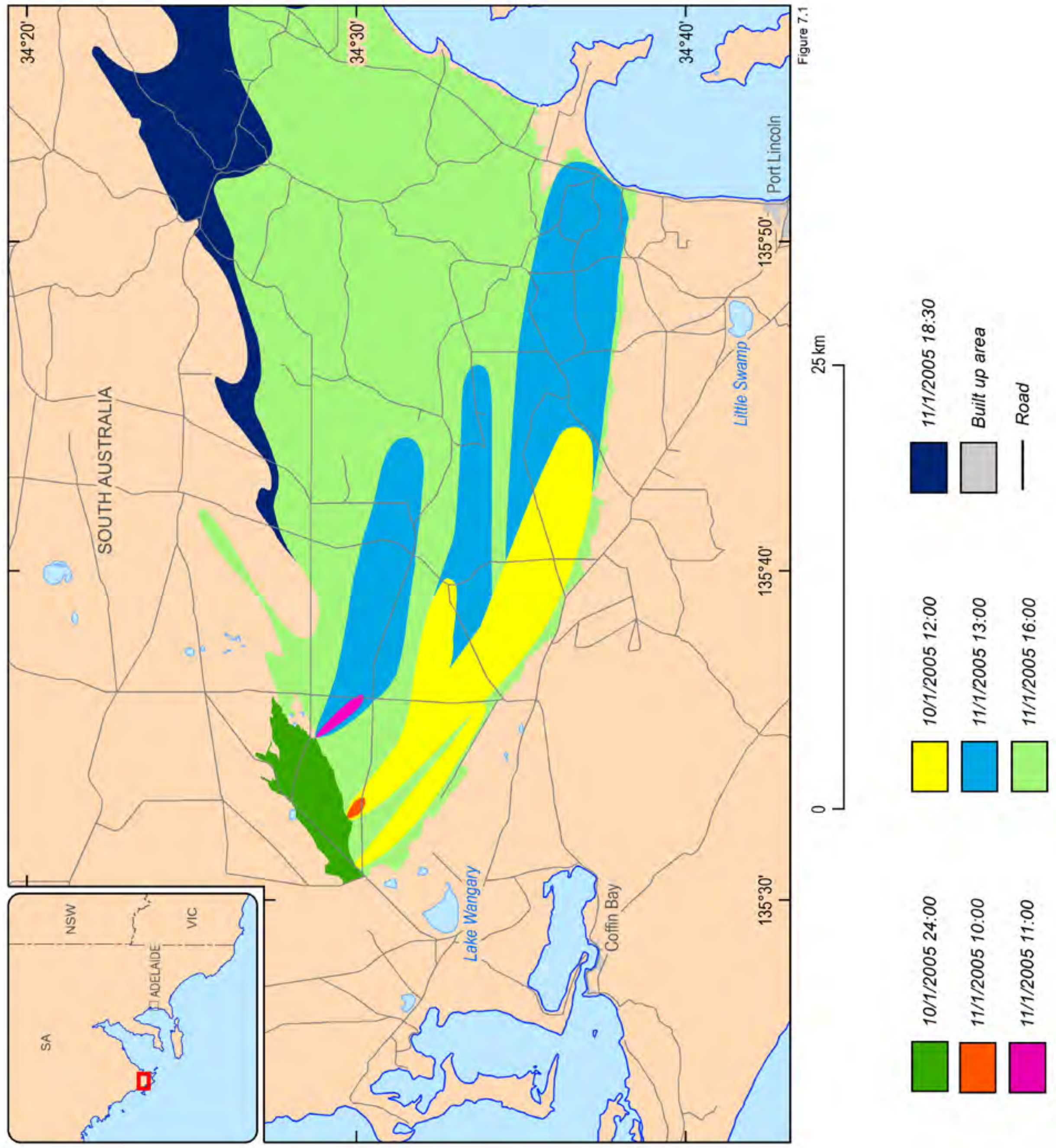



***Figure 7.1*** *Reconstruction of the Wangary fire at 1830 CDT on 11 January 2005.*

## 7.2 Wangary Weather Results

The synoptic situation on the afternoon of 11 January 2005 is shown in Figure 7.2. It shares some basic elements with the Black Saturday situation (Figure 6.2); a low pressure system with embedded cold front south of the continent and a high pressure system in the Tasman Sea, brought north to northwest winds over southeast Australia. In Figure 7.2, the wind change has already crossed the Lower Eyre Peninsula (LEP); a detailed analysis of the timing of the wind change is shown in Figure 3.9.

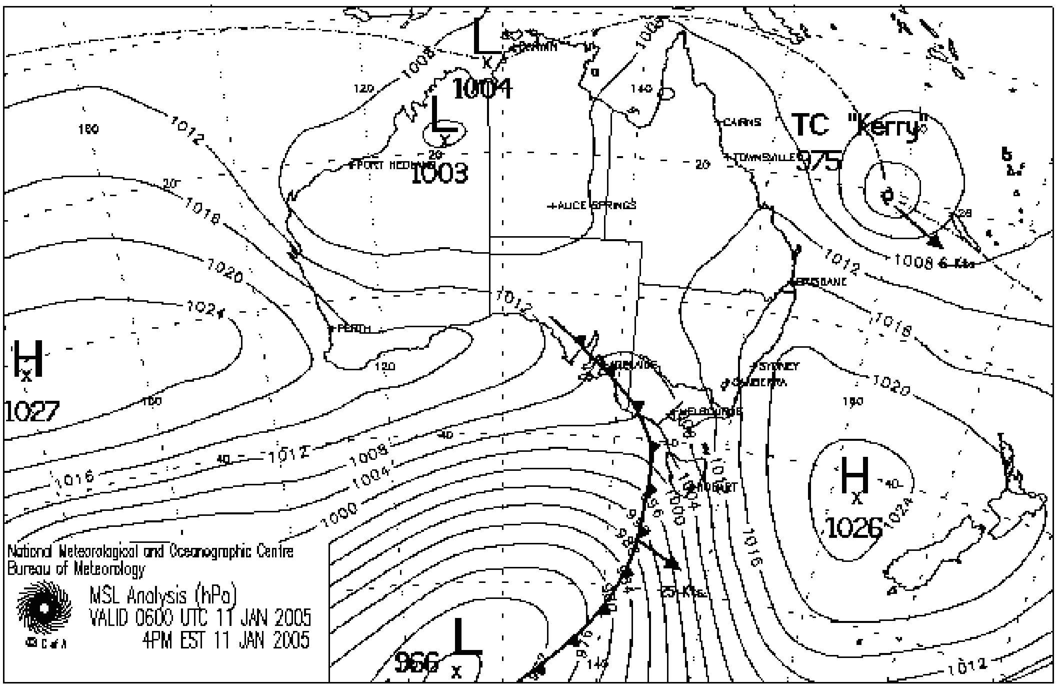
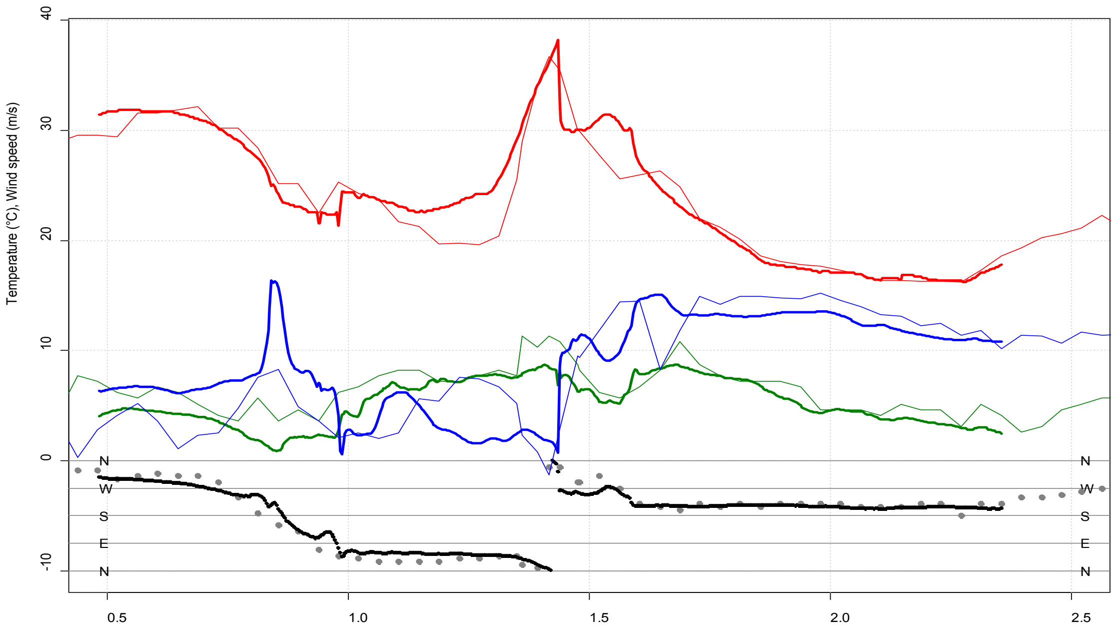
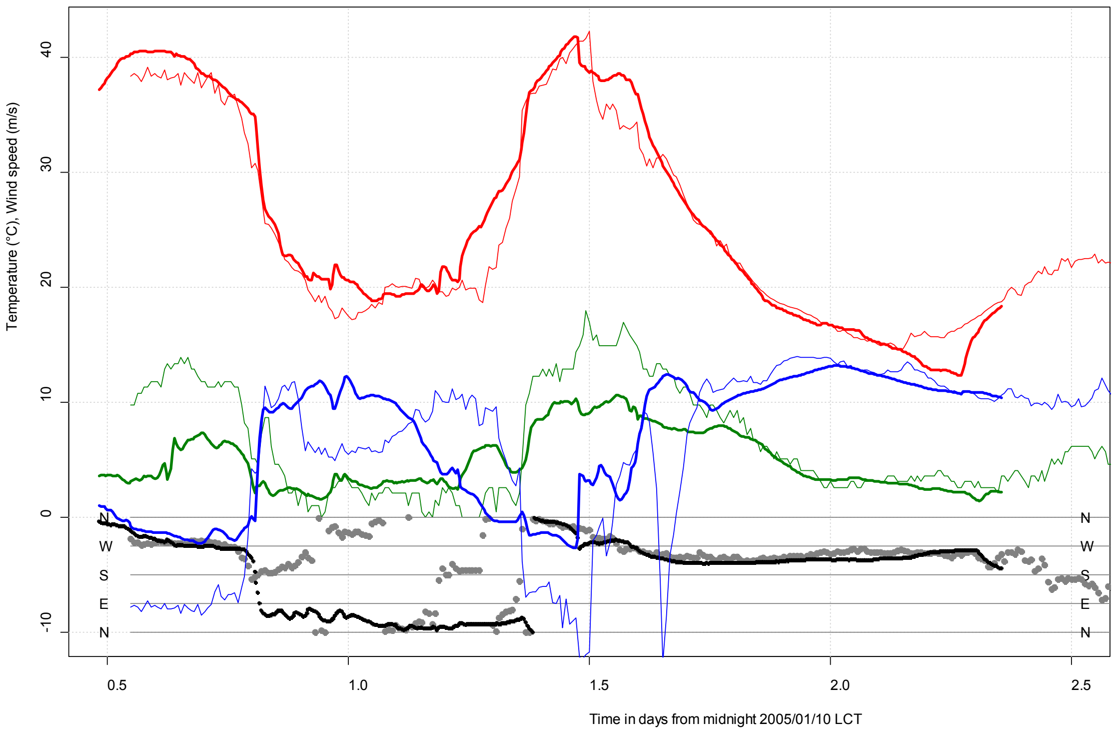



***Figure 7.2*** *Mean sea-level pressure analysis (in hPa) for 0600 UTC (1630 CDT) on 11 January 2005.*

The change crossed the LEP in the middle of the day, and a rapid drop in temperature accompanied the change. Figure 7.3 shows a comparison between observations and simulation for the two AWSs on the LEP (Coles Point on the west coast and North Shields on the east coast). The North Shields data show two significant 'dry slots' (indicated by exceptionally low dewpoint temperatures in Figure 7.3) at North Shields. The first and longer-lasting of the two is captured by the modelling although at reduced amplitude, but the second is not. Peak wind speeds are under-forecast, as was the case in Kilmore East case study. The modelling of the timing of the wind change was done well in this case study. Extra detail on the case study weather is contained in Section 3.1.4.




(a)




(b)

***Figure 7.3*** *As per Figure 3.4, comparison of AWS observational data (thin lines, grey dots) and 0.012°-grid-spacing simulation data (thick lines, black dots) for (a) Coles Point and (b) North Shields. Air temperature is shown in red, dewpoint temperature in blue (both in °C), 10-metre wind speed in green (in m s$^{-1}$) and wind direction (dots). The model output is shown in solid lines whilst the observations are shown in thin lines.*

## 7.3 Wangary Fire Spread Results

The Wangary fires occurred between two weather stations, and due to the coastal nature of the area, observation from neither AWS provided an ideal simulation. However by generating a hybrid weather stream that combined the Port Lincoln AWS (called North Shields AWS in Section 7.2), Coles Point AWS, fire ground observations and measurements from a nearby wind farm, the fires could be effectively simulated. The fires occurred as a number of breaches of a containment line and were simulated as three separate events in PHOENIX RapidFire. An iterative process was used to sensitivity test the results, evaluating variation in start time, location and grid cell resolution. The output of the models were found to be robust when evaluating resolution, but were highly sensitive to the start time and location of ignitions. Figure 7.4 shows a final PHOENIX RapidFire simulation using the hybrid AWS data from the start of the breaches on 11/1/2005 to 18:30.

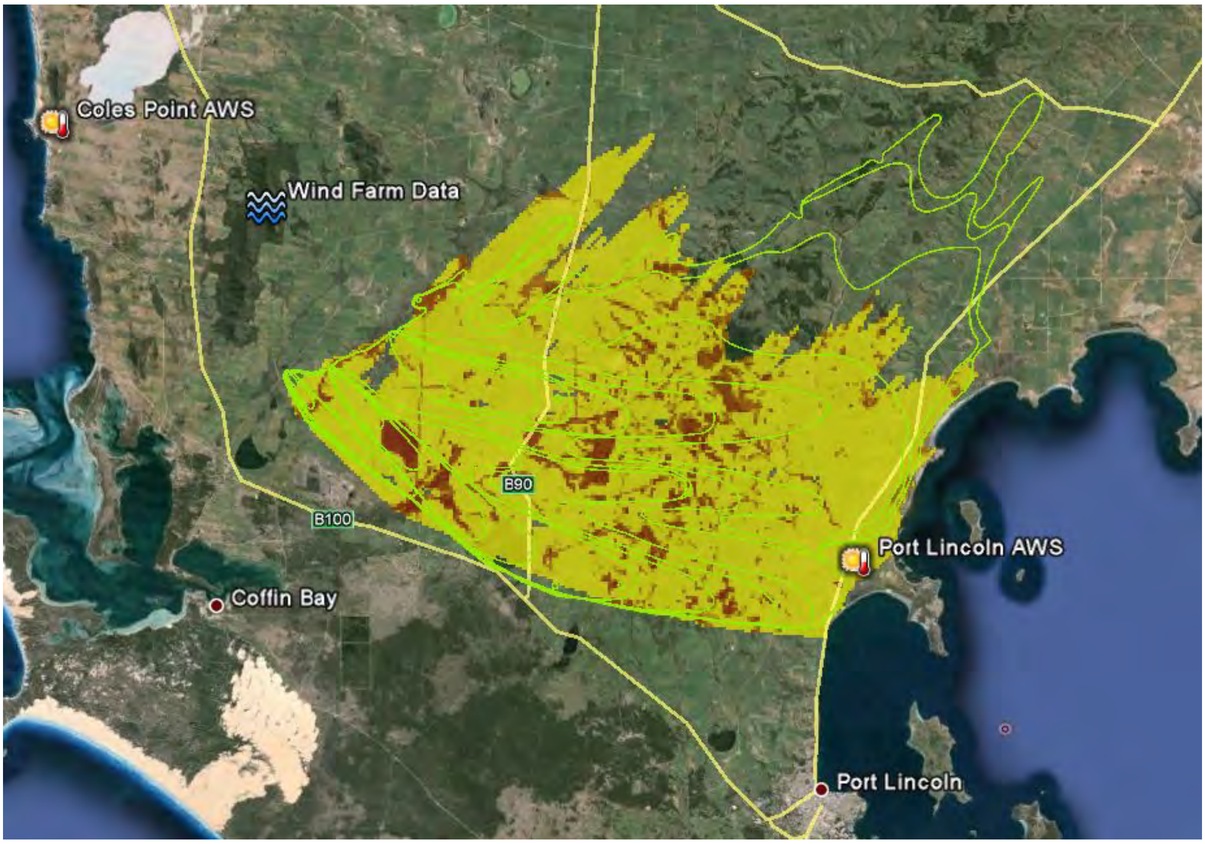



***Figure 7.4*** *PHOENIX RapidFire simulation of the Wangary Fire. Flame height is shown in solid colours, reconstructed perimeters are illustrated by yellow lines.*

Figure 7.5 shows a PHOENIX RapidFire simulation using 400m 5 minute ACCESS weather with bias correction and Wind Ninja multipliers. The simulation is a reasonable estimate of the reconstruction of the Wangary fire at 18:30 however the simulation did not impact North Shields.

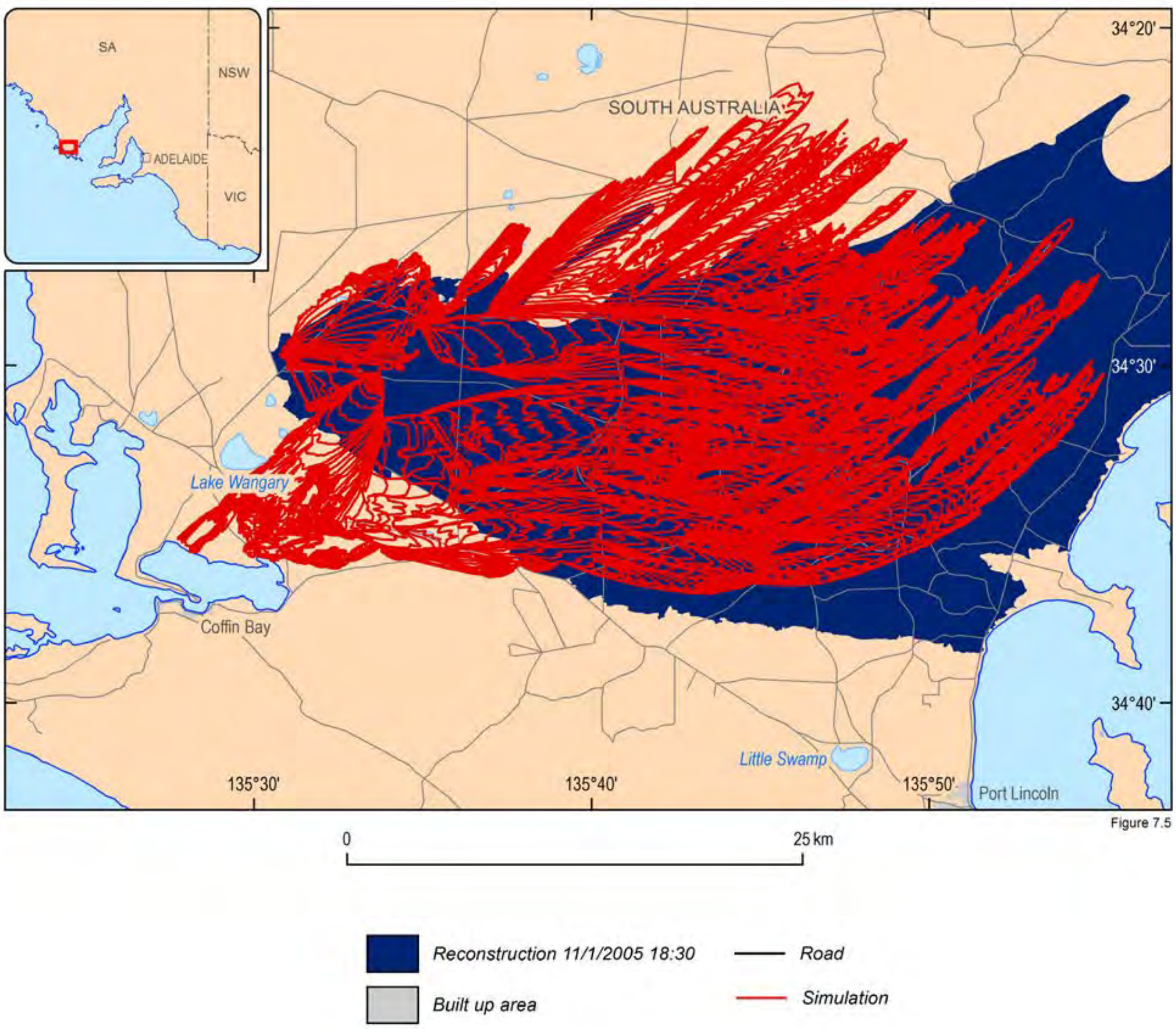



***Figure 7.5*** *PHOENIX RapidFire simulation of the Wangary fire using bias corrected ACCESS data produced at 4 km resolution, 5 minute time steps, with the known fire breakout locations on 11/1/2005, Wind Ninja and no suppression.*

## 7.3 Wangary Ensemble Results

An ensemble fire spread was produced that assimilated the actual times and locations for the breakouts that occurred on the 11/1/2005. This ensemble, shown in Figure 7.6, uses a 44 scenarios with the range of values listed in Table 7.1. Figure 7.6 shows that the ensemble footprint does impact North Shields at around 15:50 CDT.

*Table 7.1 Variations in the ACCESS weather used in the 44 member ensemble.*

| | Minimum | Maximum |
|---|---|---|
| Temperature | Supplied | Supplied plus 10 degrees C |
| Humidity | Supplied Minus 5 % | Supplied |
| Wind Direction | Supplied Minus 5 degrees | Supplied plus 25 degrees |
| Wind Speed | Supplied | Supplied plus 10 m/s |

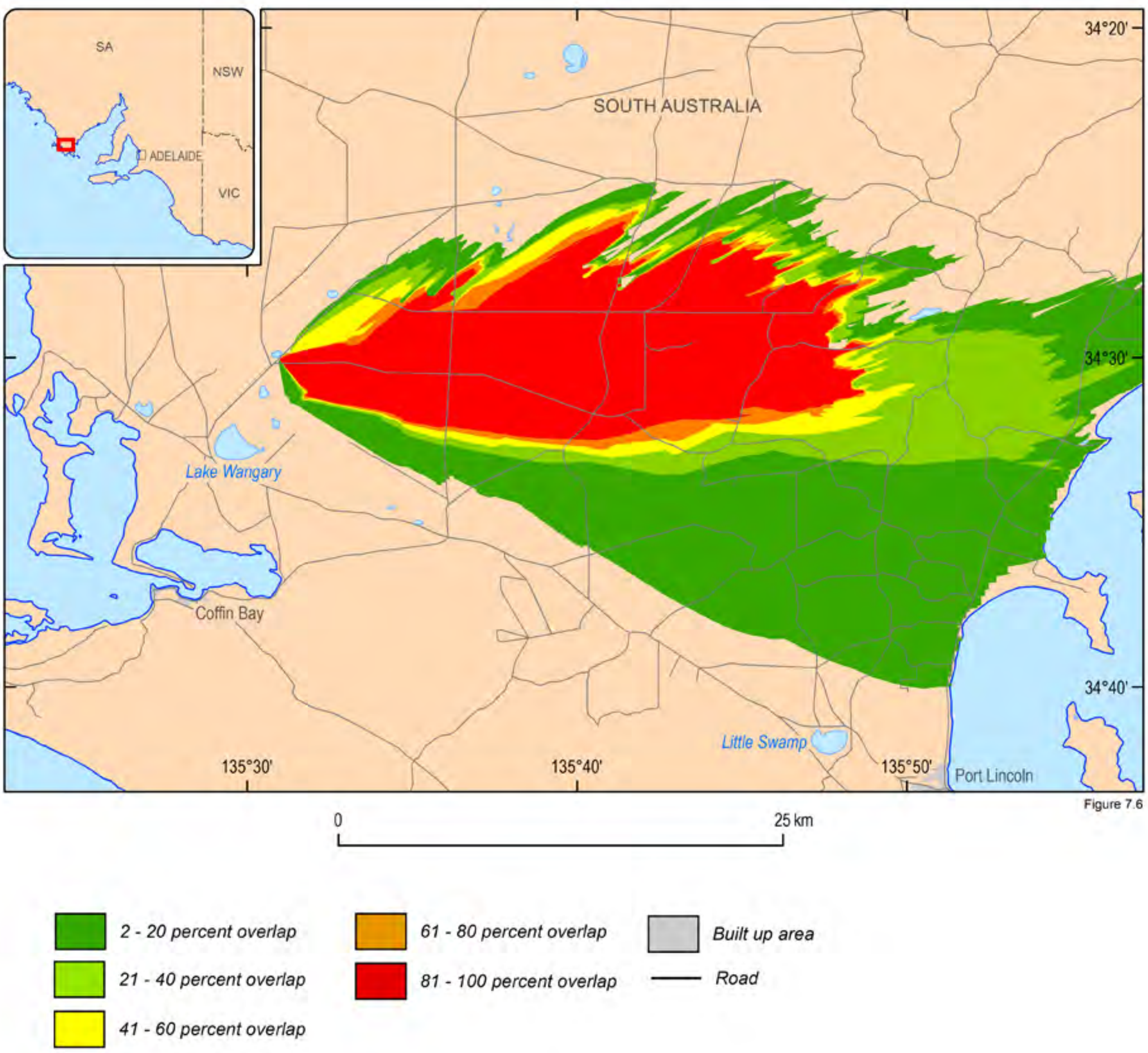



***Figure 7.6*** *A 44 member ensemble fire spread for Wangary fire from 9:50 to 15:50 on 11/1/2005 using the breakout locations as ignition points that impacts North Shields.*

## 7.4 Wangary Exposure/Impact

FireDST produced a 44 member ensemble for the Wangary fire for a time slice to 15:50, sampling uncertainty in the surface weather conditions only. The results are shown in Figure 7.6. The full methodology and results of this work are detailed in the Wangary case study report (French *et al.,* 2014a). The results have been summarised here. The exposure statistics for the ensemble view of the Wangary fire are shown in Tables 7.2 and 7.3. The exposure covers all the residences in each of the gradients of the ensemble fire spread. For example there are 18 houses and 22 people in the 81-100 percent area of the ensemble spread for this Wangary ensemble footprint.

***Table 7.2*** *FireDST people-related exposure statistics for the Wangary ensemble simulation shown in Fig. 7.6.*

| Ensemble fire spread overlap % | 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 7.3*** *FireDST building-related exposure statistics for the ensemble simulation shown in Figure 7.6.*

| Ensemble fire spread overlap % | 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 |

Due to the sparse nature of the population in the region affected by the Wangary fire, the on-screen population statistics would provide little benefit to fire managers. Other graphical information such as the house location would provide a better visual aid about population location.

If a building is simulated as destroyed in one or more individual simulations then it is counted as having been impacted by the fire in the ensemble spread. These impact statistics are calculated using the generic set of vulnerabilities (Section 5.4.2) and do not include any results from using the BFIM (Section 5.4.3). Tables 7.4 and 7.5 show the impact statistics for the ensemble fire spread in Figure 7.6.

***Table 7.4*** *Population statistics for the people living houses that are modelled as being destroyed for the Wangary ensemble simulation shown in Figure 7.6.*

| Ensemble fire spread overlap % | Number of people impacted | 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 7.5*** *Building related-impact statistics for the ensemble simulation shown in Figure 7.6.*

| Ensemble fire spread overlap % | 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 |

The impact information for Wangary is the same as the exposure information, since the vulnerability model predicted that all houses exposed to the fire would be destroyed by the fire.

The Wangary case study demonstrates the value of using the FireDST approach to fire spread and impact modelling, although at the same time it highlighted different issues than were noted for the Kilmore case study. Based on a set of 'best estimate' input conditions for weather, ignition and fuel, individual fire spread modelling could not reproduce the historical event. An important cause of this mismatch is likely to be the weather. By perturbing the weather inputs in terms of both wind speed strength and direction, the modelled fire spread approximated the historical fire spread reasonably well. It has to be noted that this in itself is not conclusive evidence that the weather data are the only cause of error, as the altered weather may be compensating for other issues in the modelling. Nevertheless, it is clear that an ensemble view of the fire includes the scenario that eventuated in the actual event, and that would not have been captured by a single 'best estimate' model output.

# 8 Case-study 3: Overview- Sydney fires – Warragamba/Mt Hall fire

## 8.1 Introduction

The fire started at Mount Hall (southern Blue Mountains region, about 50 km west of Sydney) on the evening of 23 December 2001 after a lightning strike hit a tree. The fire was initially reported via radio to the NSW RFS Blue Mountains District Office from the Narrow Neck Fire Tower at 0957 EDT on 24 December in the vicinity of the area known as Mt Hall in the Blue Mountains National Park; smoke was reported at two nearby locations later referred to as Brereton Bend and Mt Hall. After some initial fire suppression work at Brereton Bend, all resources were withdrawn from the fire ground in the early afternoon due to the deteriorating fire ground conditions (i.e., aerial water-bombing was no longer possible). At the time of withdrawal, the Mt Hall fire was rapidly expanding. No further aerial reconnaissance of this fire was carried out on 24 December due to all available aircraft being committed to property protection on other fires (about 20 fires were active in NSW at the time).

At about 14:00 EDT on 25 December, weather conditions at the Narrow Neck fire tower (30 km northwest of Warragamba) were ‘temperature 24 deg. C; humidity 22 %; wind 35 – 70 km/h southwest to northwest (variable); cloud 10 %’. At about that time, the Mt Hall fire which was moving in a south-easterly direction, jumped across Lake Burragorang and burned in an easterly direction towards the small townships of Warragamba, Silverdale and Mulgoa. In these townships later that afternoon, the fire destroyed 30 properties (homes and businesses) and damaged a number of properties. The initial loss of electricity affected 4,500 homes in these townships and surrounding areas.

On 25 December 2001, more than 4000 firefighters were battling over 100 blazes across New South Wales, mainly in areas within and adjacent to the Blue Mountains. Most of these fires were ignited by lightning or arsonists, and were part of the longest official continuous bushfire emergency in NSW taking place between 21 December 2001 and 13 January 2002. At the end of this fire period some 733,342 hectares had been impacted upon, with the fires burning across 25 local government areas stretching from the Richmond Valley in the north, out to Narromine and as far south as Batemans Bay. According to Emergency Management Australia (2002), 121 houses were destroyed and 360 people were rendered homeless. In addition, 50 people were directly injured by flames and smoke.

The FireDST team were most interested in the fire that impacted on the communities of Warragamba and Silverdale, due to the information that was available on the house losses. This case-study concentrates on the time between the spot fire ignition (jumping the narrow arm of Lake Burragorang) and the fire impacting the townships. The University of Melbourne team developed a reconstruction of the progress of this part of the fire. Figure 8.1 shows the initial spot fire area on the eastern side of the lake at around 13:20 EDT and reconstructed time intervals until 17:14 EDT.

More information on the Warragamba/Mt Hall fire can be found in:

- NSW Rural Fire Service – Bushfire Bulletin / Christmas Fires 2001[3]
- Brief History of Bush Fires in NSW[4]
- Warragamba – local webpage[5]
- Dowdy *et al.* (2009) CAWCR Technical Report No. 10[6].

[3] http://www.rfs.nsw.gov.au/file_system/attachments/State/Attachment_20050302_626D4CE1.pdf
[4] http://www.rfs.nsw.gov.au/dsp_content.cfm?cat_id=1180
[5] http://www.warragamba.net.au/warra/wiki/doku.php?id=2001_bushfires
[6] http://cawcr.gov.au/publications/technicalreports/CTR_010.pdf

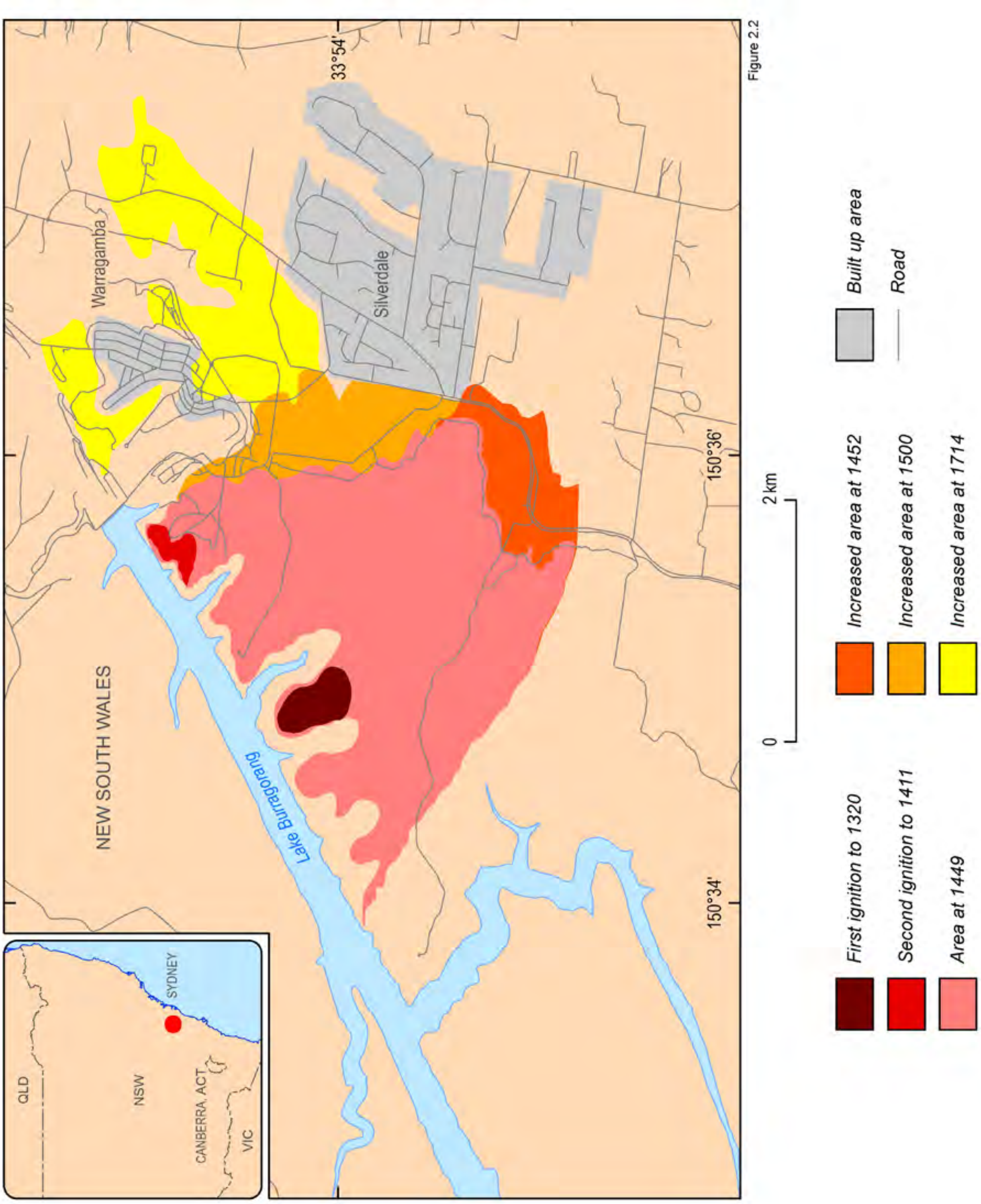



***Figure 8.1*** *Extent of the Warragamba/Mt Hall fire scar (reconstruction) in the region of Warragamba and Silverdale (up to 1714 EDT on 25 December 2001). Reconstruction provided by Kevin Tolhurst, University of Melbourne.*

## 8.2 Warragamba/Mt Hall Weather Results

Figure 8.2 shows mean sea-level pressure analyses for 24 and 25 December 2011. A low-pressure system with embedded cold front passes south of the continent across Tasmania, with a weak high pressure system located in the Coral Sea. The rainfall analysis for the 24 hours to 0900 EDT on 25 December 2001 shows nothing over 1 mm across the entire New South Wales/ACT, although light falls to the west and south of Wollongong are analysed for the 24 hours to 0900 EDT on 24 December. Rainfall for the 7 days to 09:00 EDT on 25 December had some regions west of Sydney receiving rainfalls to around 15 mm.

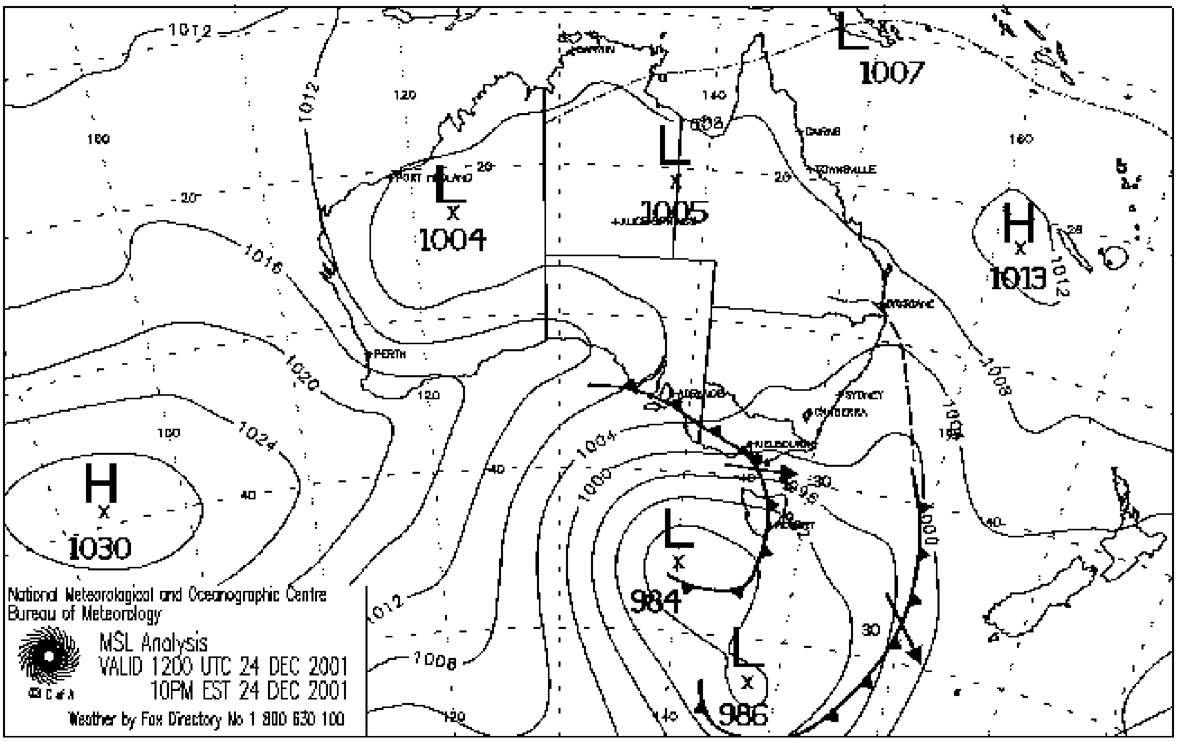



***Figure 8.2(a)*** *Synoptic mean sea-level pressure analyses (in hPa) for 1200 UTC (2300 EDT) on 24 December 2001,*

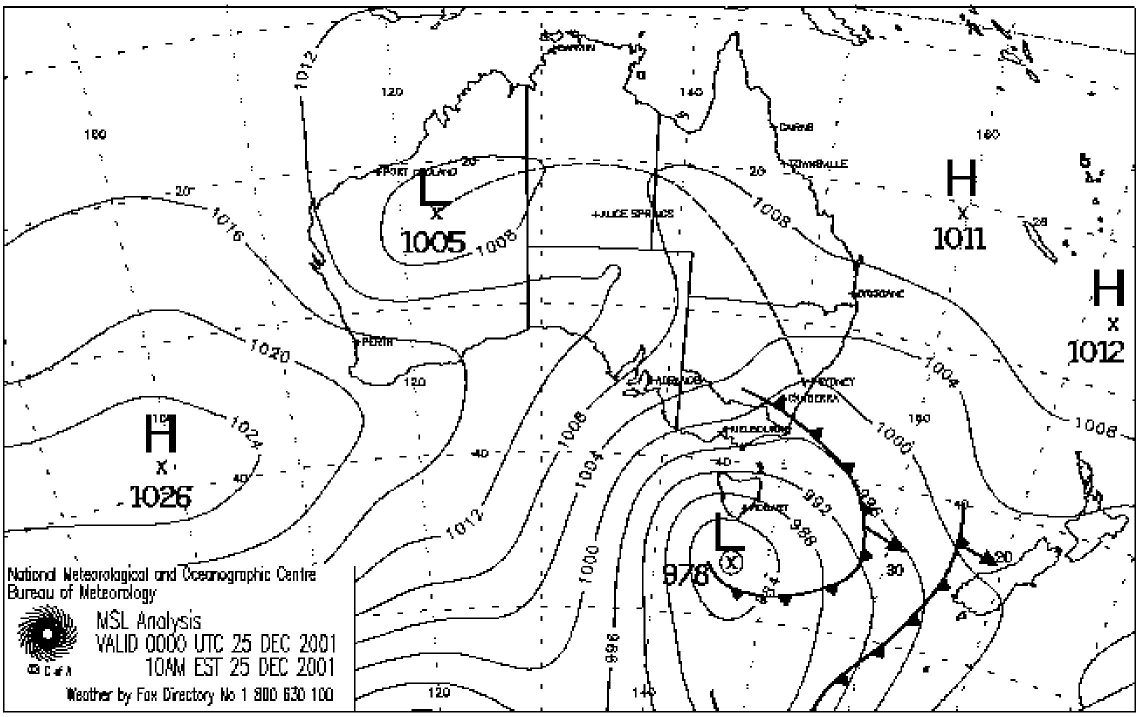



***Figure 8.2(b)*** *Synoptic mean sea-level pressure analyses (in hPa) for 0000 UTC (1100 EDT) on 25 December 2001.*

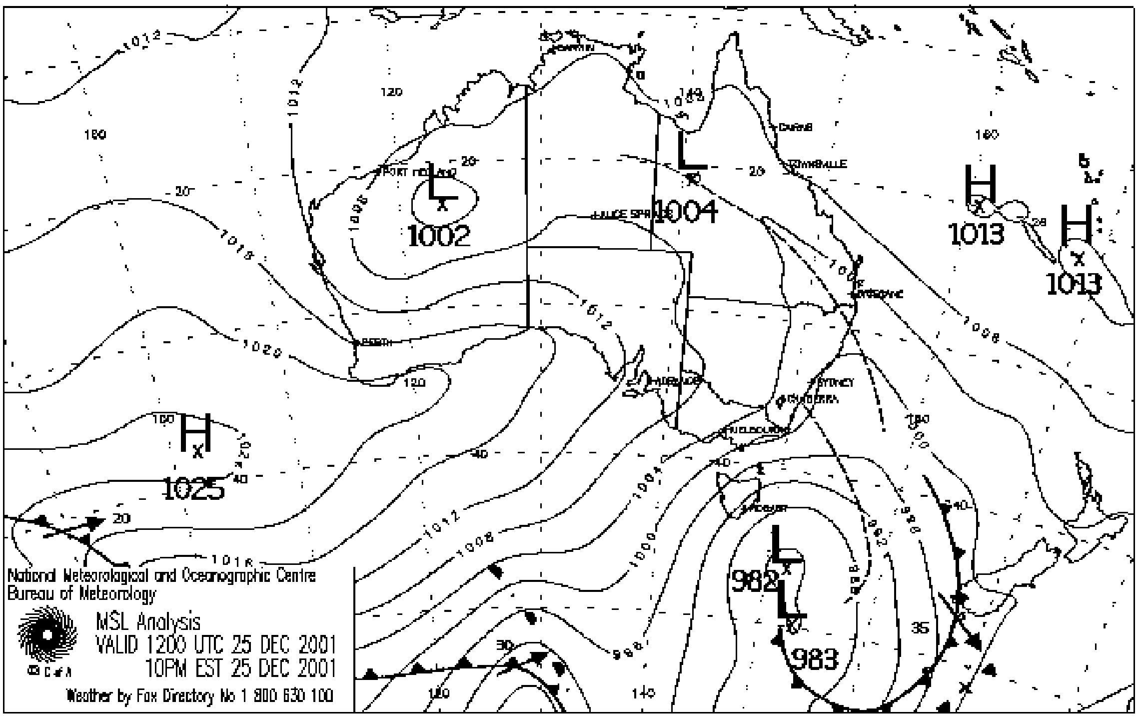
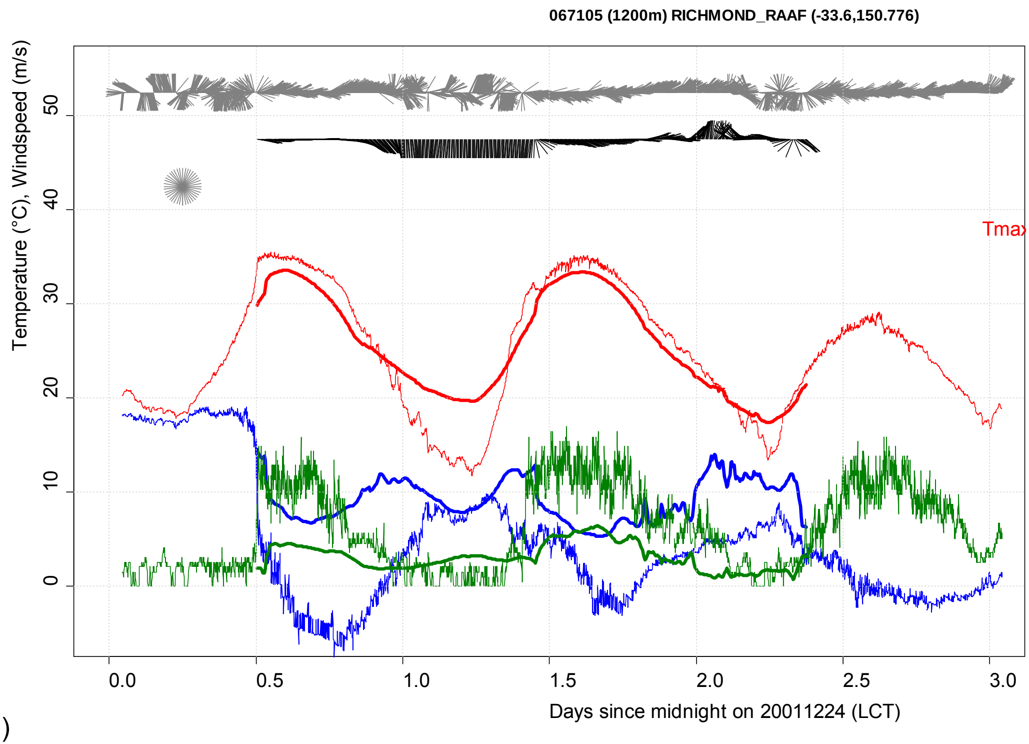
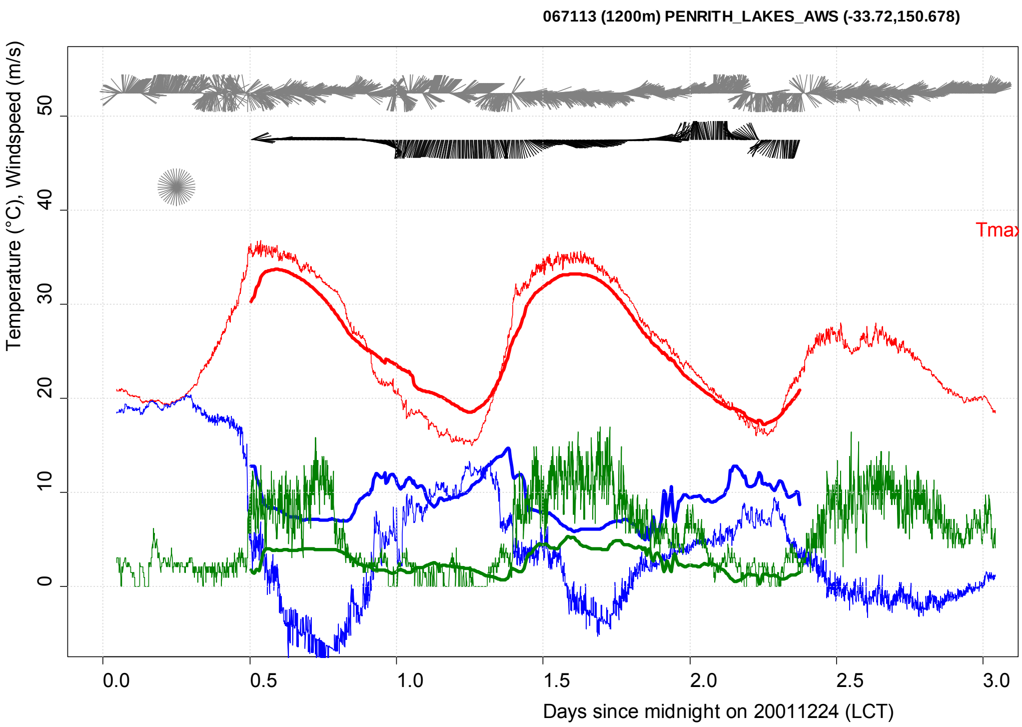



***Figure 8.2(c)*** *Synoptic mean sea-level pressure analyses (in hPa) for 1200 UTC (2300 EDT) on 25 December 2001.*

Figure 8.3 shows a comparison between AWS data from Richmond RAAF (Bureau of Meteorology Station number 067105) and Penrith Lakes (Bureau station number 067113) and modelling results. The afternoon maximum temperature at Richmond RAAF is captured well on both days (24 and 25 December), but while the overnight minimum temperature in the early hours of the 26th is well modelled, the previous night's minimum temperature (i.e., the morning of the 25th) is substantially under-forecast. The very light winds over an extended period of time may have played a part in this. During those periods of very light winds, the observed wind direction became highly variable, and the modelling does not capture this. The dryness of the air in the afternoons is not well captured in the model, nor is the peak afternoon wind speeds. The results from Penrith Lakes are qualitatively similar, although the overnight minimum temperature in the early hours of the 25th are better modelled at this site. Extra detail on the weather is contained in Section 3.1.5.




(a)




(b)

***Figure 8.3*** *As per Figure 3.4, but for (a) Richmond RAAF (Bureau Station Number 067105) and (b) Penrith Lakes (Bureau of Meteorology station number 067113) on 24 to 26 December 2011. Model data from the 0.012°-grid-spacing simulation. Air temperature is shown in red, dewpoint temperature in blue (both in °C), 10-metre wind speed in green (in m $s^{-1}$) and wind direction (dots).* The model output is shown in SOLID lies whilst the observations are shown in THIN lines.

## 8.3 Warragamba/Mt Hall Fire Spread Results

There were limited observations of the progression of the Warragamba/Mt Hall fire which made the reconstruction of events difficult and time consuming. In particular, there were limited weather observations from the fire area, there is limited precision on the location of the ignition, there is no information on progression before 1500 EDT; fire in the town is likely to have burned through a complex matrix of fuel types and the progression of spread through the town was reconstructed from radio traffic (so confidence is low). The fire was simulated in PHOENIX RapidFire using AWS observations from Penrith. Comparison of simulations with reconstructed perimeters indicated a bias in the direction that the fire travelled. Consequently, it was necessary to manually adjust inputs to achieve results that were consistent with reality. The complex terrain to the west of the fire area is likely to have had significant influence on the wind that affected the fire. Iterative adjustment enabled the fire spread to be reconstructed in a realistic manner, however we cannot be confident that the manner of progression using the modified AWS data is consistent with what actually occurred.

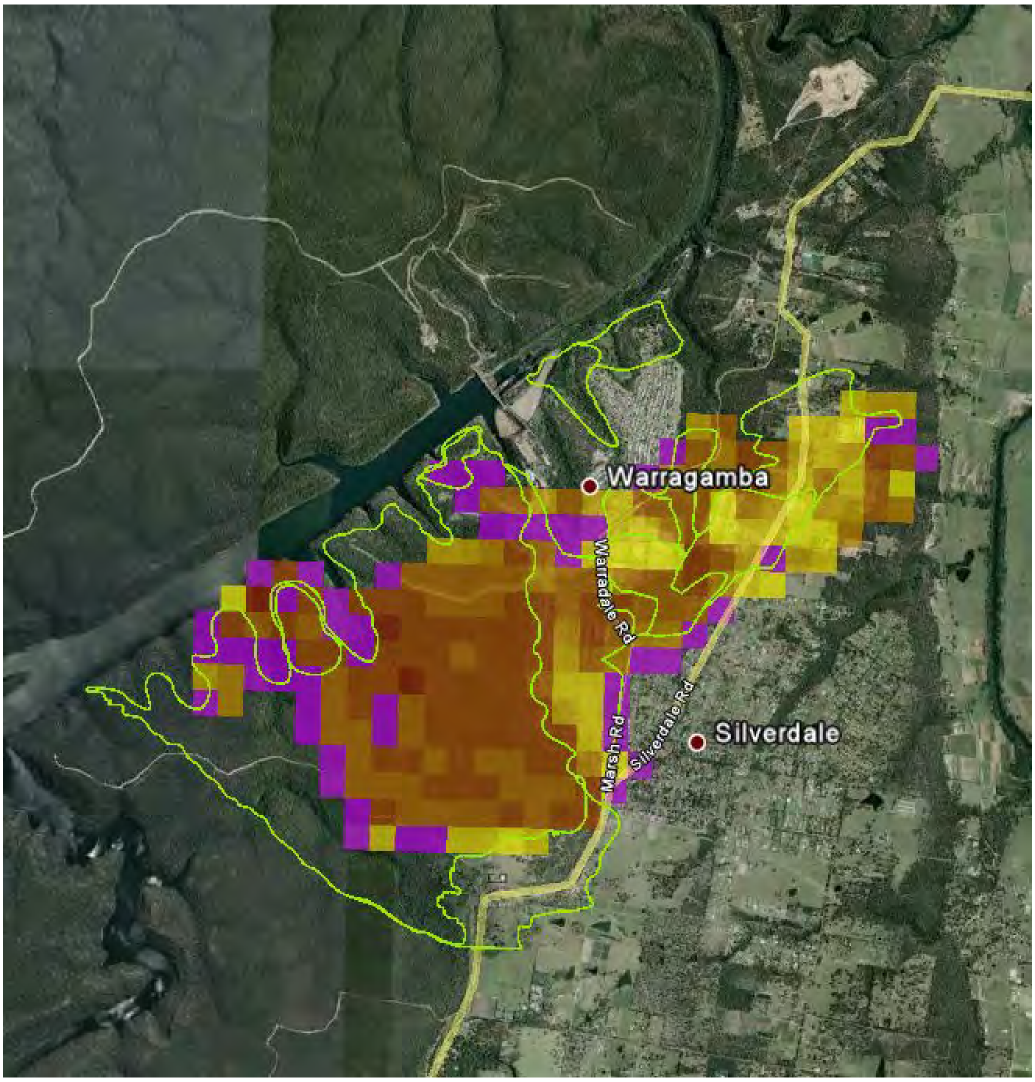



***Figure 8.4*** *PHOENIX RapidFire simulation of the Warragamba/Mt Hall fire using hybrid AWS data. Flame height is shown in solid colours, reconstructed perimeters are illustrated by yellow lines.*

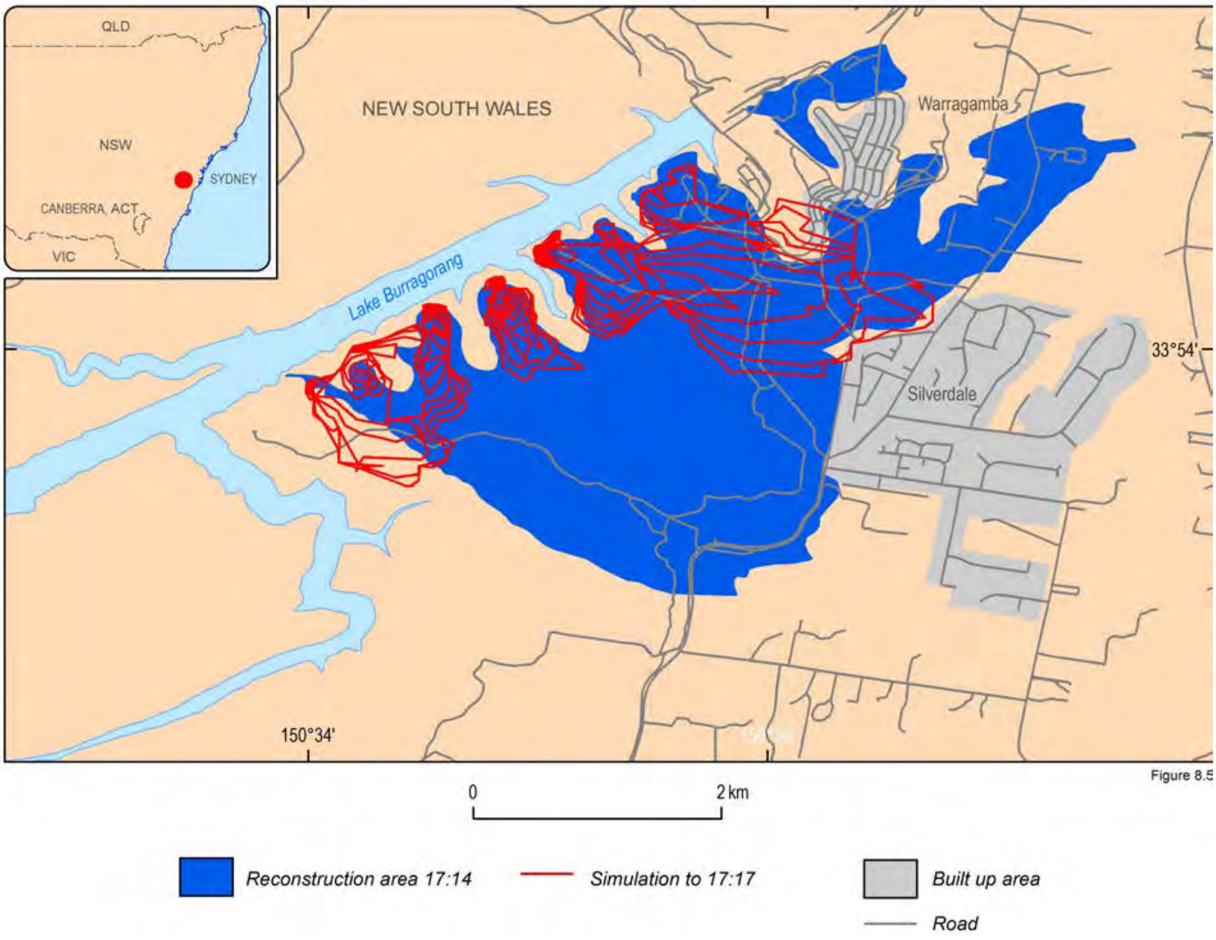



***Figure 8.5** PHOENIX RapidFire simulation of the Warragamba/Mt. Hall fire using ACCESS data produced at 4 km resolution, 5 minute time steps with Wind Ninja and no suppression or bias correction.*

Figure 8.5 shows a PHOENIX RapidFire simulation using the supplied 4 km 5 minute ACCESS weather simulation. Although the simulation has impacted the north of Silverdale at the correct time, there is a serious underestimate of the fire shape in the south. There are three possible reasons for this. The first is that only the Warragamba component of the Mt Hall fire has been modelled and there may have been influences from the actual Mt Hall fire just across Lake Burragorang. Secondly the reconstruction was hard to produce and the spot ignition times for the south westerly ignitions may not have been correct. Finally, the ACCESS weather simulation used in this case study is relatively poor (see Section 3.1.5) and there is no ability to calculate a realistic bias correction of the wind speed due to the large distances to the nearest automated weather station (in the other two case studies a bias correction was easily calculated). However this simulation is a good example for the introduction of variability in the weather conditions and the production of a fire ensemble.

Figure 8.6 displays a PHOENIX RapidFire simulation of the Mt Hall fire where all the wind speeds have been increased by 5 m/s, all the wind directions have been increased by 10 degrees, temperatures have been increased by 5 degrees Celsius and humidity reduced by 5 percent. This example highlights that the selection of the variations in the individual fire simulations is critical in generating an ensemble that matches (or includes) the actual fire. It also highlights that a system like the FireDST is not guaranteed to compensate for severe limitations in the quality of input data, such as the weather information.

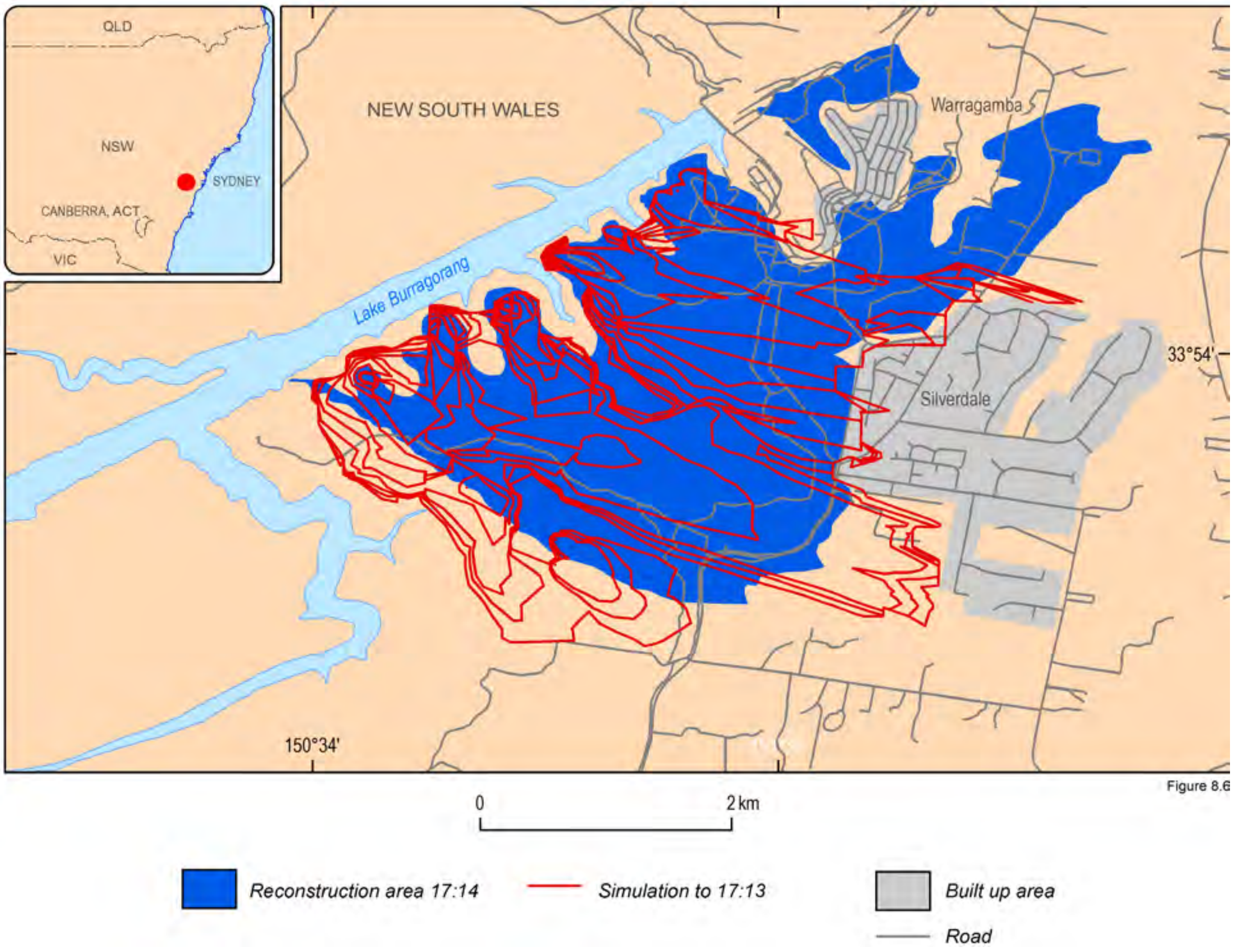



***Figure 8.6*** *PHOENIX RapidFire simulation of the Warragamba/Mt. Hall fire using ACCESS data produced at 4000 m resolution, 5 minute time steps with Wind Ninja, no suppression or bias correction and all wind speeds increased by 5 m/s, all wind directions increased by 10 degrees, temperature increased by 5 degrees Celsius and humidity decreased by 5 percent.*

## 7.3 Warragamba/Mt Hall Ensemble Results

This new ensemble shown in Figure 8.7 used a 25 member ensemble with the range of values listed in Table 8.1. Figure 8.7 shows that this ensemble footprint is a good match for the reconstruction of the fire.

***Table 8.1*** *Variations in the ACCESS weather used in the 25 member ensemble.*

| | Minimum | Maximum |
|---|---|---|
| Temperature | Supplied | Supplied plus 10 degrees C |
| Humidity | Supplied Minus 5 % | Supplied |
| Wind Direction | Supplied Minus 25 degrees | Supplied plus 25 degrees |
| Wind Speed | Supplied minus 5 m/s | Supplied plus 20 m/s |

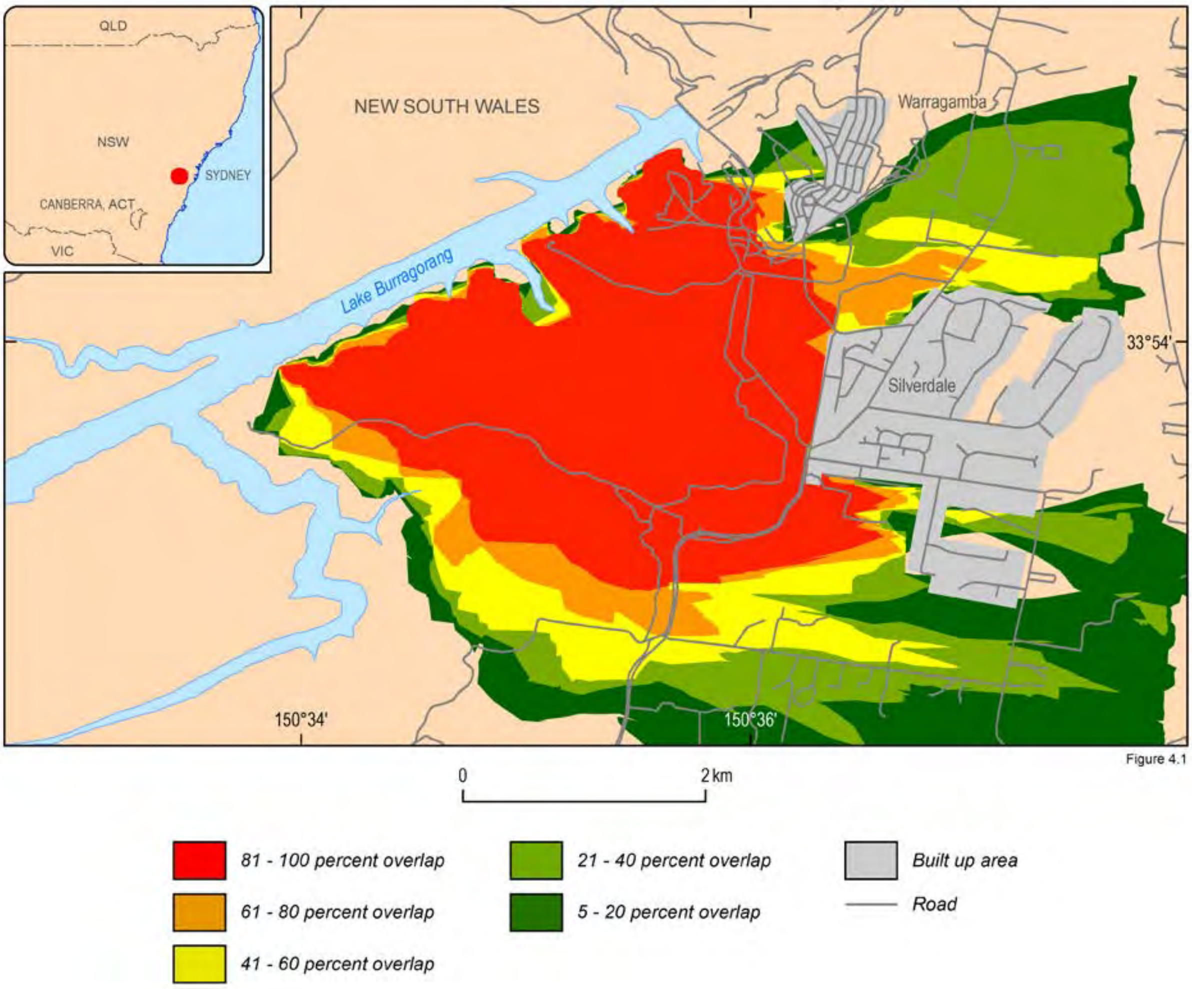



***Figure 8.7*** *A 25 member ensemble fire spread for Mt Hall fire to 19:30 that impacts Silverdale and Warragamba.*

## 8.4 Warragamba/Mt Hall Exposure/Impact

The full results for using FireDST to examine the ensemble exposure and impact for the Warragamba/Mt Hall fire are detailed in French *et al.* (2014c). The results have been summarised here. Table 8.2 displays the exposure results for the Mt Hall 25 member ensemble fire spread (Figure 8.7). For example, there are 24 houses and 58 people in the 81-100 percent area of the ensemble spread for the Mt Hall fire.

***Table 8.2*** *FireDST people-related exposure statistics for the Mt Hall ensemble simulation shown in Figure 8.7.*

| Ensemble fire spread overlap % | 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 | 58 | 6 | 10 | 2 |
| 61-80 | 173 | 22 | 29 | 7 |
| 41-60 | 237 | 38 | 45 | 11 |
| 21-40 | 322 | 53 | 63 | 16 |
| 5-20 | 1175 | 176 | 165 | 60 |

***Table 8.3*** *FireDST building-related exposure statistics for the Mt Hall ensemble simulation shown in Figure 8.7.*

| Ensemble fire spread overlap % | Number of houses exposed | Estimated house replacement cost $ | Estimated house contents value $ |
|---|---|---|---|
| 81-100 | 24 | 8,802,552 | 3,822,748 |
| 61-80 | 63 | 36,039,790 | 6,587,710 |
| 41-60 | 97 | 93,927,330 | 12,114,350 |
| 21-40 | 125 | 79,981,400 | 16,493,360 |
| 5-20 | 380 | 188,575,000 | 55,692,330 |

Figure 8.8 shows that FireDST can also produce on-screen graphs that contain the exposure details. In this case the exposure graphs may extend beyond the envelope of the ensemble fire because the screen is displaying statistics for any mesh block that has some part of the mesh block overlayed by the ensemble fire.

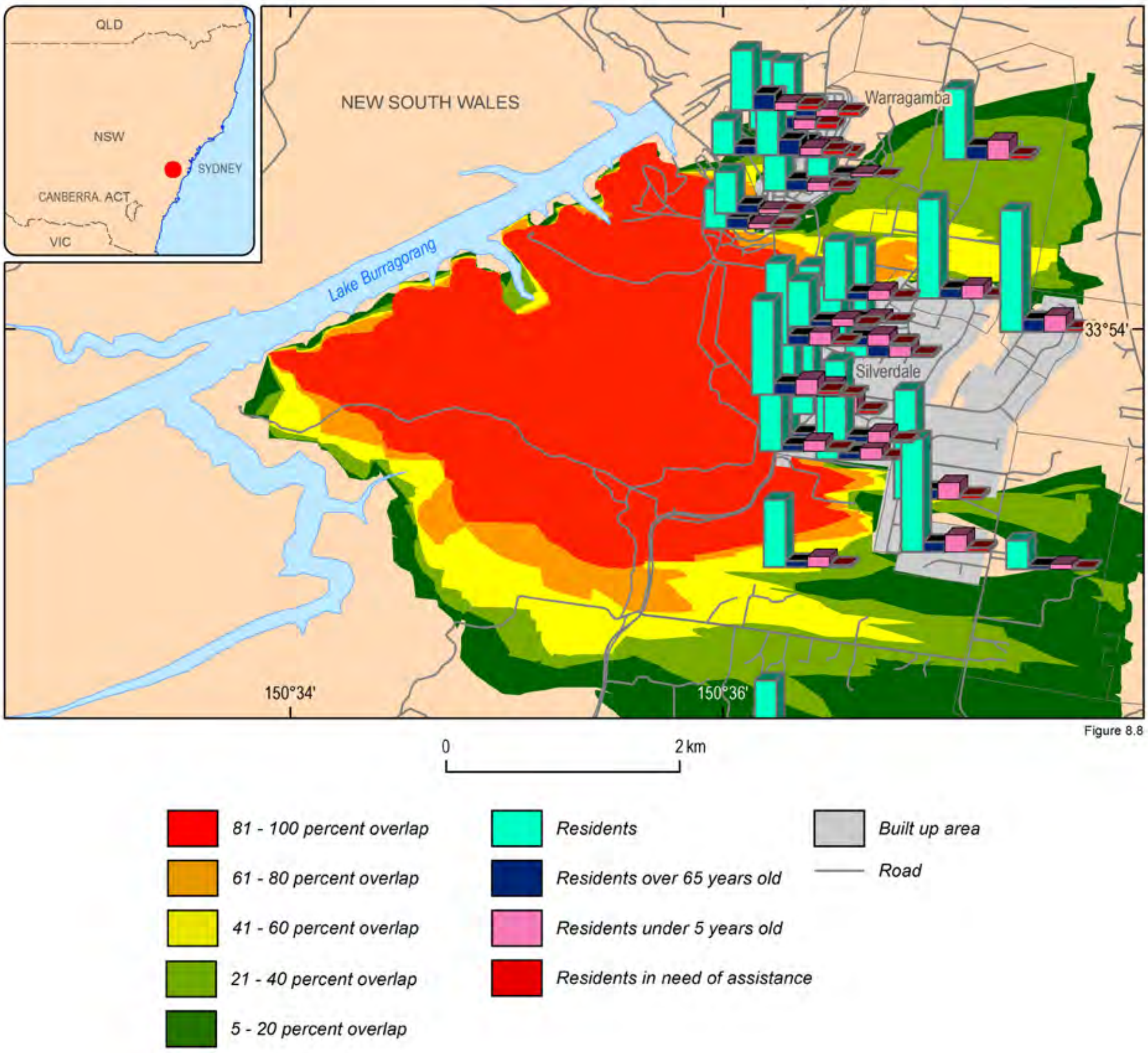



***Figure 8.8*** *Exposure graphs of the mesh block population for a Mt Hall ensemble fire spread.*

Tables 8.4 and 8.5 show the impact statistics for the ensemble fire spread in Figure 8.7. In this ensemble of 25 individual fires, if a building is simulated as destroyed in one or more individual simulations then it is counted as having been impacted by the fire in the ensemble spread. These impact statistics are calculated using the generic set of vulnerabilities (Section 5.3.2) and do not include any results from using the BFIM (Section 5.3.3).

***Table 8.4*** *FireDST people-related impact statistics for the Mt Hall ensemble simulation shown in Figure 8.7.*

| Ensemble fire spread overlap % | Number of people impacted | Number of people over the age of 65 | Number of people under the age of five | Number of people who need assistance |
|---|---|---|---|---|
| 81-100 | 52 | 6 | 9 | 2 |
| 61-80 | 171 | 21 | 29 | 7 |
| 41-60 | 196 | 33 | 40 | 10 |
| 21-40 | 185 | 38 | 42 | 11 |
| 5-20 | 507 | 84 | 66 | 26 |

***Table 8.5*** *FireDST building-related impact statistics for the Mt Hall ensemble simulation shown in Figure 8.7*

| Ensemble fire spread overlap % | Number of houses impacted | Estimated house replacement cost $ | Estimated house contents value $ |
|---|---|---|---|
| 81-100 | 22 | 7,639,552 | 3,317,768 |
| 61-80 | 62 | 35,796,590 | 6,492,500 |
| 41-60 | 85 | 90,382,180 | 10,161,250 |
| 21-40 | 85 | 68,294,200 | 11,513,830 |
| 5-20 | 159 | 97,461,410 | 28,766,650 |

The Warragamba/Mt Hall case study highlights some important considerations around the use of the FireDST methodology. It was difficult to simulate the fire spread accurately and there are several possible reasons for this. Most importantly, it became evident that it is very difficult to model a small fire in isolation when it is in reality part of a larger fire event. It was thought that this was partly because the conditions of the surrounding (larger) fires were not adequately included in the fire modelling. Furthermore, the reconstructed 'historical' ignition location and time may have been inaccurate, with consequences for the accuracy of the modelled simulation. The final issue could be the simulated ACCESS weather. As stated is Section 3, significant aspects of the AWS observations were missed or otherwise inadequately represented in the ACCESS model. This could be due to the quality of the initial model conditions, the complex topography or because the synoptic forcing was weaker than for example in the Kilmore case study.

Possibly because of these factors, the fire spread footprint did not match the historical event well, with clear implications for the inaccurate modelling of the fire impact and exposure affected. The ensemble methodology applied in FireDST did generate scenarios that matched the historical fire spread to some extent by adjusting the ignition locations, wind direction and wind speed. Uncertainty around ignition time and location is typical for fire spread modelling, so this case study illustrates again the rationale for taking an ensemble approach rather than a single 'best estimate' to understand fire spread and impact

# 9 Case-study 4: Margaret River Fire (Nov. 2011) Overview: Meteorological study only

(Bureau of Meteorology)

## 9.1 Introduction

The Margaret River fire of 23 November 2011 was due to a prescribed burn that escaped, with the impact including the destruction of 39 homes, including nine tourist chalets and the historic Wallcliffe House, four sheds, and damage to 16 houses and one shop. All of the affected properties were located in the coastal communities of Prevelly and Gnarabup and further south at Redgate. The Margaret River fire burned through 3400 hectares which mainly consisted of coastal scrubland.

This case study was added in 2012 (during the execution of the project science plan) following limitation expressed with the utility of the fire weather modelled for the Warragamba/Mt Hall case study. It was agreed that this fire weather case study would be explored in significant detail as this case was of scientific and operational interest because the fire, which had been reluctant to burn the previous day, intensified during the night and crossed the containment lines shortly after sunrise, before burning southwards during the day under the influence of hot, gusty northerly winds. The crucial re-intensification of the fire occurred during the night when fire behaviour is usually at a minimum, and fire crews had departed the scene after observing the fire's decline the previous afternoon and expecting further decline, following the normal diurnal trend.

## 9.2 Margaret River Weather Results

This case study stands in contrast to the Bureau of Meteorology's work on the Black Saturday event: while there they were seeking to understand the details of what was already clearly extreme fire weather, here they are attempting to understand why unexpectedly extreme fire behaviour occurred under what were expected to be benign conditions. Modelling of the meteorology of the Margaret River fire revealed the following features, all of which would have contributed to increased fire behaviour.

- A mass of dry air was advected from the interior of Western Australia to the Margaret River region during the early morning prior to the escape, replacing the moister maritime air mass previously over the fire ground. Evidence from observations and the model suggests that the fuels experienced the drying effect of this air for about six hours before the escape.
- Beginning in the early evening, strong downslope winds developed in the lee of the hill that occupied the northeastern portion of the prescribed area, due to a gradual strengthening of the pressure gradient and the formation of a nocturnal inversion. These winds would have reinvigorated the fire, pushing it towards the west (i.e. towards the coast) and then southwest, from whence it escaped. The modelling suggests that the winds over the southwest portion of the prescribed area were the strongest land winds in the region. Figure 9.1 shows a plan view of the 10-m wind speed and direction at 0800 WST, showing the strongest winds in the lee of the hill, while Figure 9.2 displays cross-sections of potential temperature, vertical velocity and wind speed showing the strong descent in the lee of the hill associated with the strong surface winds. While the dynamics of such flows are reasonably well understood, this case was unusual for the

modest size and height of the hill on which they occurred. This case-study is one of the first to show a strong connection between nocturnal downslope winds and enhanced fire activity.

- A strong low-level wind maximum developed over southwest WA during the night, apparent in the model and the upper air observations from Perth, and apparent in Figure 9.2. This maximum likely contributed to stronger winds during the early morning and afterwards, since the downslope winds would have transported this momentum to the surface. During the day, turbulent mixing would also have intermittently transported this momentum downwards, contributing to the marked gustiness noted by the fire crews.
- Hills to the north of the fire ground developed a strong linear wake which passed across the fire ground around midday. This may have contributed stronger winds and dryer air to the fire, at about the time of its observed peak intensity due to increased vertical transport, although other evidence for the wake is lacking due to the sparse observational network.

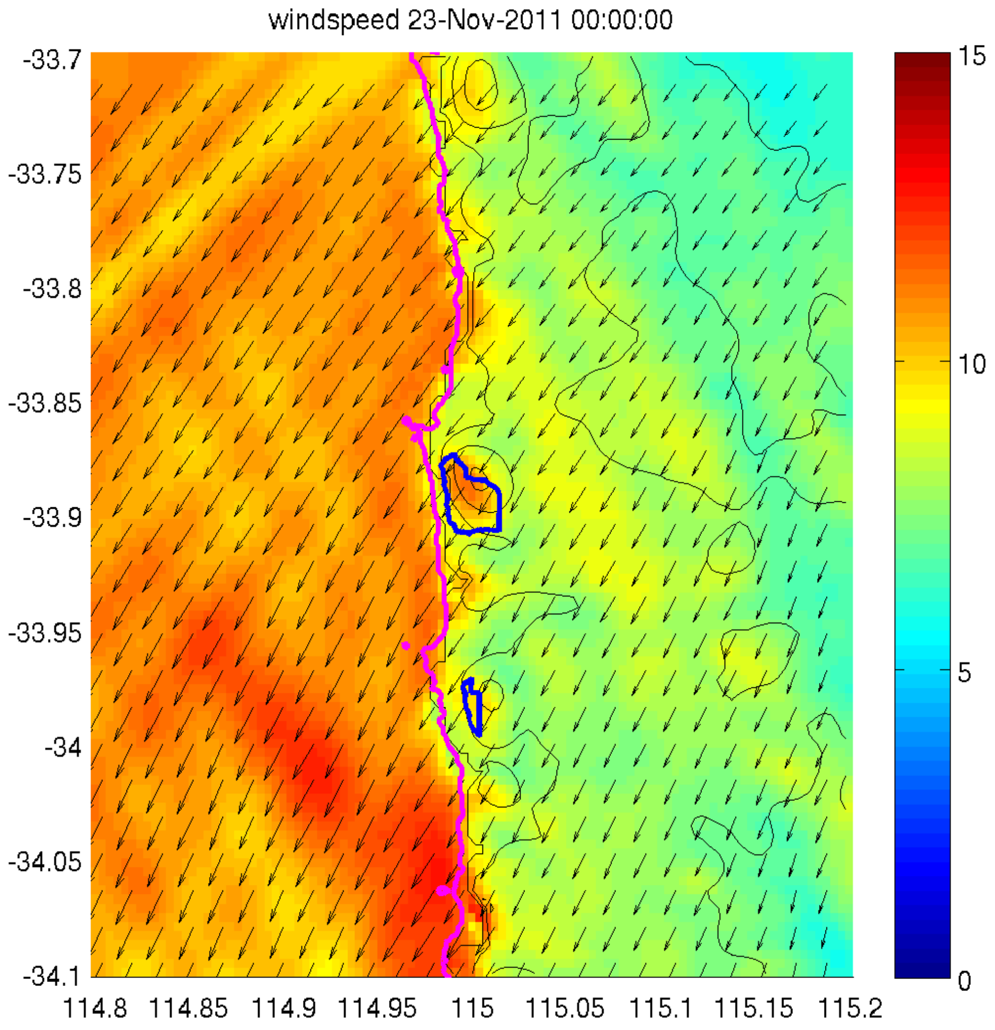



***Figure 9.1*** *Surface wind speed (shading, m s$^{-1}$) and direction (arrows) at (0000 UTC) 0800 WST on 23 November 2011 in the 440-m ACCESS simulation. The topography is shown by the black contours at 50-m intervals, the coastline by the magenta line, and the two prescribed burn areas are outlined in blue, with Ellenbrook being the northern one. The coincidence of the strongest winds with the burn area is clear.*

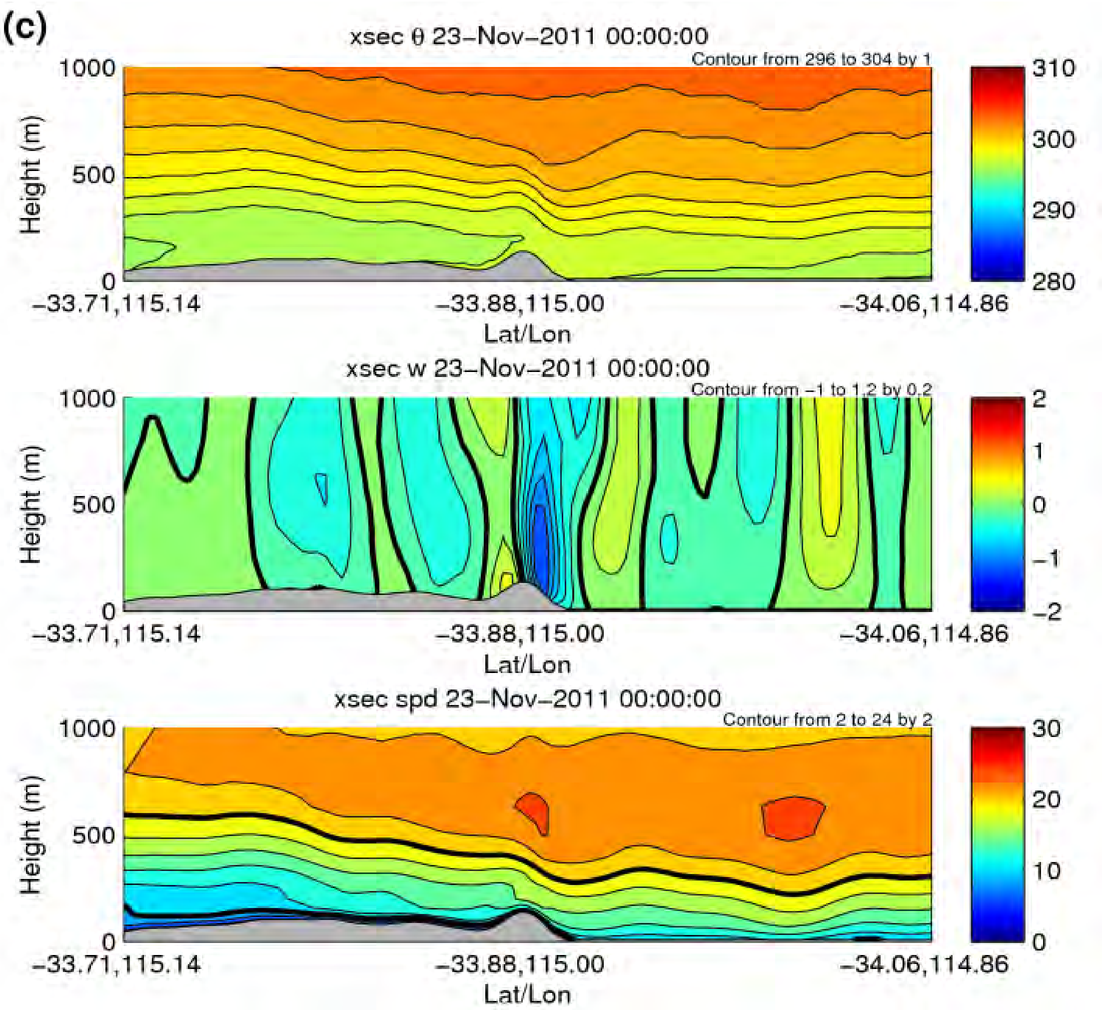



***Figure 9.2*** *Cross-sections through the Ellenbrook fire ground at 0000 UTC (0800 WST) on 23 November 2011 from the 440-m ACCESS simulation. Top: potential temperature (K). Middle: Vertical velocity (m $s^{-1}$). Bottom: Wind speed (m $s^{-1}$). The cross-sections are aligned with the wind direction at 200-m height, approximately north-east to south-west, and are 50 km long. Contour intervals are indicated at the top right of each panel.*

Given the small size of the region affected, it will be difficult to predict similar cases in the future. The relevant atmospheric dynamics, however, are reasonably well understood and are not uncommon. We therefore recommend that due caution be exercised with fires on lee slopes overnight; such caution should take account of expected wind direction changes. A full report of this research is available in Kepert *et al.* (2012a) and Kepert and Fawcett (2013a,b).

# 10 Discussion

The FireDST tool successfully enabled the research team to investigate the respective research questions that were the focus of this project. The learnings from the project should support an improved capability for fire spread and impact modelling, as well as the ability to make robust decisions based on the outputs from the modelling. This chapter summarises the key lessons learnt from this project, and Chapter 11 reviews how these might be considered for further implementation by both end-users and researchers. While most end-users on this project had an operational fire management focus, other potential applications for the FireDST approach have been identified, and these are also discussed in Chapter 11.

The FireDST project delivered a range of outputs within its component sub-projects and also collectively as the FireDST 'proof of concept' simulation system. Here, considering each of these areas in turn, we briefly discuss the research program over the last three years, the major outcomes, and the 'where to next'. This goes towards discussing Research Question 8, *How will the tool address the needs of* end-user*s and researchers.*

## 10.1 Lessons learned and the path forward

### 10.1.1 The FireDST 'proof of concept'

At the commencement of this project, fire spread simulation was being trialled for operational application with fire agencies (Victoria and Western Australia). The science of fire spread modelling was empirical in nature and had been validated on few case studies. Rigorous evaluation over a range of event types and severities was required.

The collective challenge for the FireDST team was to integrate fire spread modelling with three-dimensional high-resolution fire weather to inform fire impact assessment; specifically, likely building damage and health impacts on people from smoke. Furthermore, the project aimed to capture the impact of uncertainty in such complex modelling through presenting the outputs in pseudo-probabilistic ensemble terms. Uncertainty in fire spread and impact modelling is significant, particularly for extreme fire conditions. Incident management requires an improved understanding of this uncertainty to better inform decision making.

The FireDST system represents the integration of a set of modules, each individually building on significant scientific development in fire spread and impact modelling. The design of this complex integrated system was underpinned by a data model (detailed in French *et al.,* 2014a), which implemented a computational risk framework that itself was developed as part of the project (Jones *et al.,* 2012). The system was used to model fire exposure of people and houses, as well as ensembles consisting of scenarios that explore uncertainty in the 'best estimate' of the modelled fire.

As preliminary outputs became available, the research team discussed their utility with the end-user advisory committee. The case studies were selected by the FireDST end-user advisory committee and covered a range of terrain, topography and severity. These case studies enabled the utility of FireDST to be evaluated. The results of the project confirm that a deterministic (single) scenario has a very high likelihood of being inadequate to reflect the likely outcome of an event. A range of possible scenarios can further qualify the understanding of the potential outcome of an event. Furthermore, impact information for a range of possible scenarios also looked to add useful information to the fire spread modelling. However, further work needs to be done to consider how to use the information presented by a system like FireDST to support decisions, e.g. on allocating resources.

Although FireDST development was focused on simulating active bushfires for an operational context, the use of FireDST for a number of other applications (i.e. relating to land use management/planning, education, etc.) was also discussed with the FireDST end-user advisory committee. Some applications are briefly discussed in Section 10.2. More would need to be done to explore these and other applications and understand their particular development requirements.

FireDST is a prototype for a unique ensemble fire spread and impact system. FireDST proved that the scope of information available for fire event decision support can be significantly expanded. It has demonstrated a proof of concept for a pseudo-probabilistic ensemble simulation system as an alternative to 'best guess' or 'most likely' simulations. Furthermore, FireDST has demonstrated that the impact of a fire can be quantified and summarised while the event is in progress. The FireDST simulation quantifies the impacts from discrete events as well as ensemble impact considering a range of possible scenarios. Finally, the FireDST project has helped to identify and prioritise a number of remaining challenges in fire spread and impact modelling. In short, the FireDST project has provided fire agencies with concrete examples of feasible directions for the development of decision support information and tools.

### 10.1.2 Fire Weather (Bureau of Meteorology)

Numerical weather prediction is a mature field of science with remarkable skill improvements in the last decade, due to a steady increase in model grid resolution, significant improvements in model initialization, and a very large increase in satellite observations. Currently the highest horizontal resolution in the Australian operational forecast system (a state-of-the-art numerical weather prediction system, called ACCESS) is about 4 km, which is still too coarse to resolve many atmospheric features believed to be important for understanding fire behaviour. The research challenge was to build the capacity to conduct very-high-resolution (grid spacing < 1 km) hindcasts (i.e., retrospective forecasts) of the meteorology of significant fire weather events that have occurred in the recent past, using the grid spacings currently possible. The challenge was to push the limits of the ACCESS numerical weather prediction system, and in particular to analyse and verify the fine-scale wind structures that were developed in the model.

In the early part of the project the majority of the effort went into experimenting with the high-resolution ACCESS model to identify the practical limits of very high resolutions. For example, due to computing limitations there is a trade-off between grid-spacing and domain size. Furthermore, there are different ways to represent physical processes in the model depending on grid resolution, which led to the necessity to test a variety of physical processes at the various grid resolutions. Once a workable system was established and tested, the weather for the first case study (Black Saturday) was modelled at a number of grid spacings (approximately 4 km, 1.3 km and 440 m). The output was distributed to project partners, and in subsequent years these outputs were refined and a number of additional case studies were modelled and analysed and distributed to project partners.

Numerical weather hindcasting methods are well established and have been used for decades throughout the world. However, very few studies have been performed using an operational system like ACCESS at such high resolution, and all but one of the fire weather events studied in this project have not been modelled in such detail before now. Consequently, results from this project contain unprecedented levels of detail in the examination of the meteorological phenomena specific to the events of the day.

One important finding was the development of a range of small-scale weather phenomena in the very-high-resolution modelling that would have very likely impacted the fire behaviour. This includes wind field phenomena such as boundary-layer rolls, undular bores and solitary waves, small-scale vortices on wind changes, a broad spectrum of wind-change types, wind changes that transition from one type to another, and strong down-slope winds on relatively small hills. Most of these phenomena were verifiable in observations. Few of these features are well resolved in contemporary operational forecast models, and many came as a surprise to the team and to others in the research, forecasting and fire communities. A lot can be learned from analysing these simulations.

All of the above weather phenomena have been previously studied in some way (e.g., theoretically, observationally or modelled in idealized scenarios), but perhaps one of the more surprising results was just how common some of these features are in the case studies considered. For example, the morning glory is an undular bore that is observed in northern Australia at certain times of the year. It becomes visible when the humidity is just right for clouds to form at the crests of the wave. It is occasionally observed in other parts of the world. However, the modelling results from this study suggest that undular bores could perhaps accompany most or almost all strong wind change events across southern Australia. The undular bore that appeared in the Black Saturday simulation was observed by satellite and radar, and is very likely to have been responsible for a surge in nocturnal fire activity as it passed over the Beechworth-Mudgegonga fire ground. This project makes it very clear that a wind change can be a very complex feature that perhaps should never be reduced to a line on a map. A remaining challenge is to find a way to identify these features in real time. At present computing resources do not allow for such high resolution modelling in real time (i.e., it takes longer than 24 hours to run a 24-hour hindcast at the smallest grid spacings adopted here), which means most of these interesting and important features are not resolved in contemporary high-resolution operational forecast models. Instead forecasters need to know under what conditions these phenomena occur, before they can issue warnings. Future research into developing automated tools that flag such conditions would be of great value to forecasters, and ultimately to people on the fireground.

The first two intended case studies (the Black Saturday and Eyre Peninsula case studies) proved to be very successful as numerical weather hindcasts, while the third (and chronologically earliest) case study (the Warragamba/Mt Hall fire in the Blue Mountains) did not. A significant event (Margaret River) occurred soon after our work on the project started (in the second half of 2011), and it was decided to make use of our developing capabilities to study that event as well. That case study was also very successful. Increasing automation of the hindcast process enabled us to investigate a number of additional high-interest cases (as listed in Section 3.2). Further case-study research may shed some light on the limitations of the modelling approach (particularly in complex terrain).

This project has increased our capacity to perform very-high-resolution hindcasts of significant weather events. This capacity is now being applied to other types of severe weather, such as dust storms and tropical cyclones. The knowledge gained will also guide future operational development of high resolution forecast modelling within the Bureau of Meteorology, including the development of an on-demand relocatable very-high-resolution system to be applied to any impending high impact weather event. The revelation of the myriad of complex small-scale weather features and their surprising frequency will be of great value to forecasters, and an understanding of these features will be important for communicating associated threats to fire fighters.

Continued study of important high impact weather events, using the very-high-resolution hindcast methodology developed in this project will be important for identifying and improving understanding of important small-scale weather phenomena. As noted above the very high resolutions used in our contribution to this study will not be available operationally for some years because of the very high computational costs, and it will be important to develop forecast tools or techniques to identify the afore-mentioned small-scale weather phenomena. With sufficient funding small-scale weather identification tools or techniques could be further developed into operational forecast products. As mentioned above, much of the knowledge gained from pushing ACCESS to the limit (with respect to grid resolution) will be inherited by the operational team as they continue to increase resolution with future computing upgrades.

### 10.1.3 Fire spread modelling (University of Melbourne)

PHOENIX RapidFire was originally developed as part of the original Bushfire CRC. It was developed as a ‘proof of concept’ application, but subsequently was applied operationally without formal development and validation. PHOENIX RapidFire is the only bushfire simulator worldwide that incorporates the spotting process as a fundamental component of fire behaviour. The challenge we had set out to address basically involved:

- How to validate and assess the simulations from PHOENIX RapidFire?
- Would we see significant improvement in fire behaviour predictions if higher spatial and temporal resolution weather data was utilised?
- Could forecast upper winds be used to predict the spotting pattern?

We have developed and published practical mathematical methods that objectively assess the accuracy of fire spread predictions. A range of spatial and temporal resolution weather data was used in PHOENIX RapidFire and the effect on fire spread prediction was quantified. PHOENIX RapidFire was modified to incorporate upper level winds in the ember transport and spotting process. Three case-studies were used to test PHOENIX RapidFire under different conditions. The sensitivity of PHOENIX RapidFire to a range of inputs was tested and quantified using the ‘Area Difference Index’ which we developed as part of this project. This is a novel method as before the project commenced there were no methods or statistics suitable for this purpose in existence.

We found that PHOENIX RapidFire required accurate inputs to provide accurate predictions. We found that the forecast weather was the main source of inaccuracies in fire spread prediction, specifically the systematic bias associated with the wind speed predictions (i.e., ACCESS wind speed information had a systematic low bias of up to 20% and this had to be corrected by post-processing; corrections were derived through comparison with observations). We were unable to determine whether these systematic biases were also associated with upper level wind speeds (due to lack of AWS observational data). We have implemented a rudimentary treatment of upper winds within PHOENIX RapidFire (i.e., averaging over a shallow vertical column), and this single averaged upper wind speed is utilised in the ember transport used in the fire spread modelling. The validation indicated that we could also use PHOENIX RapidFire to model fire travel times across the landscape, and we therefore developed a travel-cost model for fire suppression resources (i.e., important for fire suppression modelling).

No systematic sensitivity of PHOENIX RapidFire had previously been undertaken. Results from this work gave some important insights to the workings of the PHOENIX RapidFire model. No previous practical application of the ember spotting modelling was available for comparison. The three case-studies indicated that PHOENIX RapidFire could provide a close estimate of fire behaviour providing the input data was accurate (i.e., wind speed bias removed by validation against observations where available). Predicting the wind fields for the Warragamba/Mt Hall fire in NSW was most difficult due to the complex terrain and the somewhat poor correlation between the synoptic weather and the valley weather in this region. The modelling of this fire was the most difficult, however, reasonable fire spread simulation which could provide some guidance for fire fighting was still possible.

The University of Melbourne researchers had originally intended to do more work on defining interface fuels and linking these definitions to house vulnerability models. Here we were reliant on information from the CSIRO Ecosystem Science (i.e., LiDAR determination of vegetation character/structure), which was not provided in a timely manner. We found that we could not get AWS upper level wind data that had sufficient accuracy for prediction or verification. This resulted in only a rudimentary application of upper winds with regards to fire spotting. Significant future research work needs to be undertaken to improve this parameterisation.

Our research has firmly shown the importance of spotting in fire behaviour and how important it is to include it in the modelling process. We have shown that it is possible to objectively quantify the accuracy of a fire spread prediction and identify aspects of the prediction that are most in error such as orientation or extent. We were surprised that higher resolution weather input did not necessarily improve the fire spread prediction even though it provided an improved explanation of weather phenomena. We were happy to find that PHOENIX RapidFire still provided a good prediction of fires in terrain and situations not previously tested.

There is still a need for a more comprehensive fire suppression model to link with the fire propagation model. There is the need to have a well-documented set of case-studies for further testing of fire spread models and other fire related research. It is clear that three case studies are not sufficient for thorough testing and validation of PHOENIX RapidFire. With regards to impact and risk, we believe that better links between fire characteristics and the vulnerability of a range of assets and values need to be made.

FireDST has been useful in starting the discussion with fire agencies about dealing with uncertainty. Ensemble weather prediction and the lessons learnt in the past have direct relevance to ensemble fire prediction. This is a complementary area of further research. PHOENIX RapidFire is already being used operationally and also for planning applications. There is a need is to train users and provide better output information that shows the level of uncertainty in predictions.

### 10.1.4 Regional and local impacts from bushfire smoke dispersion (CSIRO Marine & Atmospheric Research)

Prior to the project there was little information of the risk to populations from transport of smoke from prescribed fires and wildfires or how this impact compared with other risks to health from wildfires. The questions addressed were, through the analysis of three contrasting fire scenarios (case studies):

- development of accurate models as well as verification of plume rise;
- improved emissions models which accurately account for emissions from coarse woody debris;
- measurement and validation of emissions from wildfires;
  The current view is that the emission actors are similar to those from prescribed burning, but that the fuel loads differ. This needs further testing.
- development of methods for quantification of uncertainty in estimated dispersion.

The research involved:

- reviewing extant emissions and transport models for relevance and ease of application for the scenarios;
- testing and validating the implemented modelling system;
- applying the procedures to two additional scenarios: the Kilmore East fire of Black Saturday 2009 and the 2010 high-intensity prescribed burning event in April 2010 in the Huon valley; and
- developing an inverse method for assessing the relative impact of source regions of specified receptor regions within a defined spatial domain.

The project involved applying and testing extant modelling procedures on previously unanalysed bushfires and prescribed fires, as well as implementing new procedures for sampling and analysing smoke composition for determining emission factors for application in emissions models.

We determined that the CSIRO Models (TAPM, CCAM and CTM) were suitable for transport modelling. In addition, variants of the methods developed by Meyer *et al.* (2008) were suitable for emissions estimates. Plume rise models were less effective than prescribing plume injection height. Large fire events of long duration carried the greatest risk of smoke impact on population, with major potential health impacts. This contrasted with extreme, but short-lived events such as the Kilmore East fire (Black Saturday) where high plume rise dispersed smoke into the free troposphere and stratosphere with relatively small surface impact and relatively small impacts in health. It also contrasted with prescribed burning scenarios in which the impacts were largely localised, close to the point of emission and dependent on prevailing wind patterns and topography. Procedures developed for inverse dispersion analysis show promise for development of smoke dispersion climatologies for application in seasonal planning of prescribed burning.

The experimental results for emission factors are consistent with measurements in the Australia savanna and rangelands, and with international studies. This is an important finding that confirms that it is valid to apply internationally agreed algorithms for emission accounting within Australia. The work on impacts of smoke on regional and urban populations from a range of contrasting fire events in Australia is new knowledge, which has mostly confirmed previous expert judgement.

The study has established that the impact on rural and urban population from wildfires can be large, but is highly event specific. We have determined that the capacitance of the atmosphere acts to smooth out small uncertainties in emission location and rates, however uncertainties currently occurring in quantifying fire progression have significant effects on predicted smoke dispersion.

Therefore, as is the case for fire spread, ensembles of smoke spread scenarios are also required for assessing likely smoke dispersion and impacts.

We have demonstrated that an inverse application of dispersion models is useful for seasonal planning of prescribed burning for lowering the risk of smoke impact on sensitive receptor locations. We have quantified the progression of greenhouse gas and particulate emissions from a progressing fire front, and have confirmed that the greenhouse and particulate emission factors in Southern Eucalypt forests are consistent with northern Australian woodlands and with biomes in Europe and North America.

The project was aimed at assessing the smoke spread tools available for implantation in a decision support tool (DST), as well as testing the feasibility and limits for development of the DST. The outcome of this study is that the tools exist and implementing a system for applying them for operational fire management and forecasting is entirely feasible. Some of the data sets utilised in the case studies were expanded by direct measurements of emission factors, which largely agreed with the current knowledge. The big advance was in reducing the uncertainties in the emission estimates.

For emissions dispersion issues remaining to be addressed are

- development of accurate models as well as verification of plume rise;
- improved emissions models which accurately account for emissions from coarse woody debris;
- measurement and validation of emissions from wildfires;
- The current view is that the emission actors are similar to those from prescribed burning, but that the fuel loads differ. This needs further testing.
- Development of methods for quantification of uncertainty in estimated dispersion.

The challenge is to take this project from ‘proof of concept’ to a fully functional operational system. This is entirely feasible but unlikely to occur without the continued participation of the current team in which the detailed knowledge is vested. Some components are in development under projects commissioned directly by DEPI, Victoria.

### 10.1.5 Impact and Risk Assessment (Geoscience Australia)

Geoscience Australia developed and implemented the architecture for the FireDST system, linking all the components provided by the team to visualise and quantify integrated fire spread and impact modelling outputs. Geoscience Australia also provided many of the underpinning datasets, and undertook the computational system sensitivity analysis.

An impact/risk assessment framework and a supporting computational platform for a simulation system that brought together the elements of weather, fuel, exposure and vulnerability were not in existence at the start of the project. All of the elements (weather, fuel, exposure and vulnerability) were examined in separate projects within the first 7-year round of the Bushfire CRC (2002-09). Within this project these elements were brought together to build and demonstrate a ‘proof of concept’ simulation system.

We developed an impact/risk assessment framework, and worked with collaborators to coordinate the design/structure and data model for the computational simulation system. This entailed integrating fuels information with three-dimensional high-resolution fire weather, fire spread modelling, spatial building/people exposure assessment, building vulnerability and quantity surveying costing methods. The system was designed to compute fire spread and impact for discrete fire events, and produce output in terms of event-based statistics. FireDST summarised impact output as the number of houses damaged/destroyed, visibility and people affected by smoke, either across the lifetime of the event or in 30-minute interval time-steps. In parallel to FireDST, a Wildland Fire Decision Support System (WFDSS; US Fire Service, Missoula) as well as the Wildfire Analyst simulation system is being developed in North America. However, neither of these systems models impacts in terms of costs.

Another key outcome of the FireDST project is that it addresses uncertainty in the system components described above through the use of multi-scenario ‘ensemble’ techniques. Ensemble-based outputs could support the emergency management sector to manage uncertainty in fire spread modelling. One of the important lessons that this project yielded is that we don’t have a good knowledge of the actual uncertainty in the various components. Such knowledge is essential to be able use the FireDST ensemble output to define the probability of projected fire spread. At this point, the FireDST output indicates sensitivity of the model outputs, but does not reflect the true range of likely outcomes, because we cannot weight or constrain the scenarios in an ensemble in terms of their likelihood.

The ‘proof of concept’ fire spread and impact simulation system has been demonstrated on three case studies, both as single scenarios and as ensemble outputs. A number of presentations of this material have given the FireDST end-user advisory committee and a number of State fire agencies the opportunity to consider the type of outputs the system produces. The ensemble information yielded by FireDST is new in fire spread modelling in Australia. A separate project is investigating the issue of dissemination of scientific information with regards to probabilistic fire spread mapping (Cheong *et al.,* 2013). In addition, further work should indicate how best to adopt and integrate probabilistic outputs into the information used for various emergency management practices and procedures. Furthermore, there has been significant discussion with end-users on the potential applications of a system such as the FireDST proof of concept. A brief summary is discussed below.

## 10.2 Summary of possible FireDST applications

Demonstrations, workshops and discussions with the FireDST end-user community have provided a list of potential applications that are listed here. Possible FireDST applications include:

- Operational applications:
  - Operational (ensemble) fire spread, smoke and impact assessment
  - Operational ‘worst case scenario’ fire spread, smoke and impact assessment
  - Operational vulnerability assessments, e.g. examining communities to determine vulnerable sections of the community that need extra resourcing during an event, or ‘safer regions’.
- Land management applications:
  - Fuel reduction burns, to understand fire spread and smoke
  - Urban land planning; land use, including greenfields development
  - Urban sustainability (i.e. examining current communities to determine those people/structures most at risk). This includes the use of FireDST to examine community/structure vulnerability and the change in impact resulting from undertaking mitigation exercises. The methodology could also be used to develop or validate building and planning standards.
- Vulnerability and risk assessments:
  - Cost/Benefit analysis for
    1. fuel reduction burns
    2. mitigation activities associated with household vulnerability

3. residential (greenfields) planning
4. critical infrastructure protection
5. Validating and developing building standards

- Training
    1. Firefighter: case studies of the impact of suppression on fire spread
    2. Community: understanding of possible consequences of fires in region
    3. Incident Management Team (IMT): realistic training scenarios for team training activities.

# 11 End user considerations for the adoption of the FireDST methodology

The FireDST (Fire Impact & Risk Evaluation Decision Support Tool) project has produced a 'proof of concept' study which has sought to provide an fire impact and event 'relative risk' assessment through a multi-agency collaboration. FireDST is essentially a scenario generator that explores the uncertainty in a wide range of input parameters required for impact assessment (meteorology, fuel, building vulnerability) and delivers a set of products that aggregate the possible range of event impact assessments into simple mapped outputs.

The FireDST research has been very much focused on operational applications in line with the interests of the end-user advisory committee and the project Science Plan. The research team in consultation with the broader end-user community has determined the potential for a wide-range of applications for the FireDST methodology. These are discussed in Section 10.2. They include a range of operational applications, such as managing an active fire regarding fire spread and smoke, be it a wild fire or fuel reduction burn. Secondly, there are a number of land use planning and management applications, where the outputs are interpreted to reduce or mitigate bushfire risk. For example, as part of planning a new residential development, the FireDST methodology could generate scenarios that assessed different planning options in terms of their relative exposure to hazard. Finally, there are applications supporting building and community vulnerability, for example through validating building standards.

The use of case studies for training applications was considered a valuable application that would merit further development. Training involving fire-fighters and also staff involved in an Incident Management Team (IMT) situation (visualising what may happen under a large range of scenarios) was considered a useful application of the current research. In addition, informing the general public through interactive scenario exploration of measures that can be taken (i.e. evacuation, fuel reduction, improving construction elements such as fitting shutters, etc) was considered another application that could be explored.

We have attempted (below) to define 'where FireDST sits' with regards to an operational application compared to PHOENIX RapidFire and Aurora-Australis[7]. Tables 11.1 and 11.2 show this comparison considering 'Functionality criteria' and 'Importance criteria' for PHOENIX RapidFire, Australis and FireDST.

[7] Note that this information was based on the state of the respective systems at the time that this report was compiled.

**Table 11.1** Comparison table for PHOENIX RapidFire, Aurora & FireDST – Functionality criteria.

| Functionality | PHOENIX RapidFire | Aurora | FireDST | Comments |
|---|---|---|---|---|
| Grass Fire Spread Model | Yes | Yes | Yes | |
| Forest Fire spread Model | Yes | Yes | Yes | |
| BoM GFE forecast (operational) | Yes | No | Yes | Aurora operates currently using real-time BoM Access data on 12km grid nationally, forecasted for 48 hours. This is currently the only nationally consistent data. Will move to GFE for appropriate states soon. |
| Wind Ninja Wind Multipliers (100m) | Yes | No | Yes | |
| Fuel Load modelling by time since last burnt | Yes | Yes | Yes | |
| Suppression | Yes (Limited) | Yes<br><br>(Limited) | Yes (Limited) | Suppression is currently limited to back and flank of fire with equal resources |
| Animate stages (time steps in fire) | Yes – only in Google Earth | Yes – in Aurora – ArcGIS Desktop. | Yes – in ARCGIS and Google | |
| Automated start of simulations from detected/verified external source | Yes in Victoria's E-MAP software | Yes – triggered from multiple MODIS mapped fire hotspots | No | PHOENIX RapidFire has been built into E-Map and E-Map does initiate a single simulation. |
| KML (Google Earth output) | Yes | Yes – Direct KML / WMS link | Yes | |
| ARC-GIS Interactive | No (produces ARC files that can be read separately) | Yes – Aurora ArcGis Desktop Version.<br><br>Online Version supplies a WMS linjk and can download shape files for ArcGIS integration | Yes (ARC-GIS is fully controlled from FireDST) | |

| Functionality | PHOENIX RapidFire | Aurora | FireDST | Comments |
|---|---|---|---|---|
| Internet interface | No | Yes | No | |
| Open Source | No | Partial<br><br>Aurora is built using open source software. Australis is not open source. | Proof of concept research code only (IP Bushfire CRC) | Aurora is not open access to the system. It is limited to fire and emergency services agencies. |
| Fire spread model varies across vegetation types | Yes | Yes | Yes | This is a key benefit within Aurora / Australis. As a fire progresses across multiple fuel types, the appropriate fire spread model is run. |
| Can include multiple ignition points and lines | Yes | Yes | Yes | |
| Ignition points can be varied in time | Yes | Yes | Yes | |
| Can choose forecasted weather or custom weather or a combination of all. | Only at start | Yes | Only at start | For example a SPOT forecast is issued for 6 hours, but you would like to run a simulation for 12 hours – it is useful to integrate forecast and custom weather parameters. |
| Preserves users history of simulations and can modify any simulation parameters | Yes | Yes | Yes | Users can revisit any simulation and modify any parameters and re-run their simulation. |
| Simulations available as Interoperable Web Services | No | Yes | No | |
| FIREDST Project Extensions | | | | |
| BoM 12-km ACCESS (operational) | Yes (not automated) | Yes | Yes (not automated) | This is probably automated in the E-Map implementation at DPIE |
| BoM 4.0-km ACCESS (research) | Yes | No, but can be integrated | Yes | Not available in WA |
| BoM 1.3-km ACCESS (research) | Yes | No, but can be integrated | Yes | Not available in WA |
| BoM 440-m ACCESS (research) | Yes | No, but can be integrated | Yes | Not available in WA |
| BoM 4.0-km ACCESS Vertical Atmosphere (research) | Yes (single layer) | No, but can be integrated | Yes (single & average layers) | Not available in WA |
| Bias correction of ACCESS Wind strength | Yes (not automated) | No | Yes (not automated) | Not available in WA |
| ACCESS Weather Ensembles | No | No | Yes | Not available in WA |

| Functionality | PHOENIX RapidFire | Aurora | FireDST | Comments |
|---|---|---|---|---|
| Automated Weather perturbations | No | No | Yes | Not available in WA |
| Automated Ignition perturbations | Yes (grid only) | No | Yes (anywhere) | Aurora can input multiple ignition points as entered by users. MODIS derived ignition points are automated. |
| Automated Vegetation perturbations | No | No | Yes | |
| Automated management of perturbations | No | No | Yes | |
| Improved suppression planning | basic flank suppressio n | No | Basic flank suppressio n | Movement of teams to the fire.<br><br>Aurora calculates rates of spread and intensities and guides suppression options to meet objectives |
| High resolution Wind Multipliers | No | No | Yes | |
| New field to store the total ember density landing on a cell | Yes research version only | No | Yes research version only | |
| Vertical Ember Transport Model | Yes research version only | No | Yes – research version only | |
| User interactive control of simulations combination s used in an ensemble fire spread | No | No | Yes | |
| Ensemble view of potential fire spreads | No | No | Yes | |
| Inclusion of spatially explicit building information (NEXIS) | No (PHOENIX RapidFire - cells with buildings) | No | Yes | |
| Inclusion of spatially explicit Demographic info (i.e. NEXIS/ABS) | No | No | Yes | |
| Inclusion of specific building vulnerability | No | No | Yes | Currently vulnerability curves for 8 directions from a house and vulnerability to radiation & embers (for 3 different RH) |
| Exposure to fire (people and infrastructure statistics) | No | No | Yes | ABS Census information included |
| Interaction of fire with an individual building (impact) | No – only within cell | No – only within cell | Yes | Part of the Building Fire Impact Model |

| Functionality | PHOENIX RapidFire | Aurora | FireDST | Comments |
|---|---|---|---|---|
| Building to building fire spread | No | No | Yes research version only | Part of the Building Fire Impact Model |
| Ability to auto compare two simulated fire shapes | Yes | No | Yes | Using Area Difference Index (ADI) |
| Ability to visually compare simulated (or actual) differences in buildings damaged /destroyed | No | No | Yes | |
| Research Gaps | | | | |
| Physical ‘Ember Transport Model’ | | | | Nothing is known about the size, altitude and dwell time of differing embers in the atmosphere. There is no validated model. |
| Ember density on a cell over time | | | | Required to assist in defining for BFIM when the maximum ember density is so that a better human interaction can occur. |
| Radiation received in a cell over time | | | | Required to assist in defining for BFIM when the maximum radiation level is reached (2kW unprotected). |
| Coupled Atmosphere-fire model | | | | Atmospheric winds change when a fire is introduced. |
| More detailed interactive suppression modelling | | | | No system has a realistic suppression modelling system that can reflect resources and back burn operation. |
| Vegetation structure, typing and mapping – consistency across Australia | | | | Aurora uses standard NVIS data and applies the appropriate national fire spread model to that vegetation type. There some vegetation types that have had to have the fire spread model estimated. |
| Near ‘real time’ validation (and automated bias correction) of modelled output for weather (time series of modelled output vs. time series of actual observations) | | | | This is a tool development (or core capability) that is essential in fire managers and analysts understanding the ACCESS weather forecasts. |
| Spatially explicit Ignition Model (Lightning & anthropogenic) | | | | For anywhere in Australia based on actual information. |

**Table 11.2** Comparison table for PHOENIX RapidFire, Aurora & FireDST – Possible Importance to Fire Managers.

| | PHOENIX RapidFire | Aurora | FireDST | Comments |
|---|---|---|---|---|
| Accurate | Single deterministic simulation. Ember transport model is only available in theFireDST research version and requires further validation. | Single deterministic simulation | Ensemble output that is aimed at including the 'real' fire | |
| Timely - Operational | Yes in Victoria's E-MAP | Yes, available nationally | Not yet operational: proof of concept | |
| Timely – Land Management | Yes, can run multiple independent simulations | Yes, can run multiple independent simulations | Yes, can run multiple overlapping simulations | |
| Timely – Land Planning | Yes, but manual change to fuel and house layers | Yes, can manually change fuel loads | Yes, GIS areas of new land uses can be introduced | |
| Timely – Training system | Yes | Yes | Yes | |
| Fire Spread | Grid based | Irregular point grid based – dynamic grid | Grid based | |
| Calculate Impacts to buildings and people | Manual | Yes | Automatic | |
| Calculate Risk | No | No | Yes | |
| Integrated Interactive Sophisticated Graphics | No, GIS and Google separate | Yes, Aurora Online is fully interactive and interoperable. Aurora Desktop is fully integrated into ArcGIS | Yes, GIS is directly controlled. | |
| Integrated into Incident Management system | Yes, E-Map in Victoria | Yes | No, proof of concept only. | |

| | PHOENIX RapidFire | Aurora | FireDST | Comments |
|---|---|---|---|---|
| Research Support | No more ongoing research – maintenance only | Yes, until June 2013 with a possibility of extension | Yes, until December 2013. | All systems are currently dependant on future funding to provide the research support. |
| Operational (24x7) Support | No, PHOENIX RapidFire is a research tool and has a single disclaimer. | Yes, Aurora online available 24 / 7 with full disaster recovery offsite system near completion | Not operational, proof of concept only | |
| Ongoing Improvements | No, only if an issue arises. | No, seeking additional funding | Proof of concept only | Aurora team indicated that funding has been provided until 30/6/2013 |
| Open Source | No | No | Research grade code only. IP Bushfire CRC. | |
| Community of support ranging from Universities to Agencies – for research | No | No | No | The ‘user base’ for the system actively involved in developing and sustaining the software and the science. |
| User Forum | No | No | No | A ‘user group’ focused on training, system use, maintenance and management and ongoing development. |
| Compliance and Validation | No | Yes - used operational by DFES and DFES regularly assess Aurora outputs against manual fire spread calculations, aerial intelligence and remote sensing fire scars. | No | All systems must pass a set of standards for use; requirement to have a team → ensures system is validated meets compliance standards |

| | PHOENIX RapidFire | Aurora | FireDST | Comments |
|---|---|---|---|---|
| National data store for fire information and for the information related to prescribed burns.(fire scars/ severity , iso, weather, fuel) | No – State archives only | Fire information and simulation outputs are stored at Landgate | No – Research project only | To be used for research and validation |

## 11.2 Future of FireDST research

We believe that the future of the FireDST research can be summarised into two separate modes:

(1) Research;
Further research is required to allow development of the methodology for a range of applications, including those listed in Section 10.2. Research topics and priorities would depend on the particular application.

(2) Operational;
Development of a computationally efficient and robust operational/tactical implementation based on the learnings from the FireDST project has been suggested. At the very least, this requires business analysis to determine what the requirements are, and what components of the system could be used as a basis for development to meet these requirements. This would enable the development of a business case to support a bid for long-term operational funding (i.e. not research funding). This needs to be led and undertaken by a team experienced with developing/implementing operational systems.

### 11.2.1 Research future

The outcomes of the FireDST project suggest the following priorities for research work in fire spread and impact modelling.

(a) Development of a capability or ‘tool’ to monitor (near real time) of performance of weather forecasts vs. observations. This is considered crucial in the use of FireDST in operational response for quantifying weather uncertainty.

(b) Further development and validation of fire spread models in Australia.

(c) Integration of validated vulnerability functions (radiant heat and ember attack) for Australian archetypical house types and their near environment.

(d) Further research to support operationalisation of components of the FireDST product (see Section 11.2.2); potential topics are indicated in the respective chapters in this report. This includes characterisation of uncertainty in critical input parameters for fire spread modelling to support ‘true’ probabilistic fire spread modelling.

(e) Further knowledge of bushfire impact and risk by investigating i) meteorological ‘events’, i.e. a set of days with very-high to extreme fire danger; and fire ignition probability mapping (both lightning and anthropogenic). This would enable the full development of a ‘long-term’ risk model for communities that would mainly address the planning (environmental & land use) and extreme event applications of FireDST. Education applications could also be developed from this work.

### 11.2.2 Operational Future

An operational product based on the FireDST proof of concept requires a thorough business analysis effort. This would consider the following points, among others.

1. Potential multi uses of the product and the associated requirements for each use. This could include an assessment of potential conflicts between applications and requirements;
2. Further development and validation required (see research);
3. Potential integration of products based on FireDST within existing decision support tools;
4. Governance of a product,
5. Testing and deployment planning;
6. Ongoing software maintenance and systems support.

The business analysis and building/testing/training for an operational application:

- should be a separate undertaking. This requires skills that are completely different to those required for research, and should be undertaken by experienced resources. This requires considerable funding;
- should be undertaken by a professional systems oriented team (supported by the research team where required);
- should only be undertaken if an ongoing mandate to operate the system is in place with a governance/committee overseeing both the implementation and also ongoing performance testing and development (likely that further development/refinement is required).

# 12 Major Conclusions

The multi-agency and multi-disciplinary FireDST team has undertaken a three-year research project focused on collectively developing a 'proof of concept' simulation system to address the uncertainties and impacts associated with extreme fires. This was achieved through the exploration of three case-studies selected by the FireDST end-user advisory committee.

Some of the major outcomes from the project are:

(1) an improved understanding of severe weather associated with extreme fires
(2) ability to input a three-dimensional weather stream into a fire spread model
(3) ability to sample the uncertainty in the input parameters affecting fire spread and produce ensemble maps visualising the impact of this uncertainty in terms of possible fire spread information
(4) ability to assess 'exposure' for each simulated scenario of fire spread
(5) ability to assess 'impact' for each simulated scenario of fire spread
(6) ability to assess 'relative risk' from an ensemble of extreme fire impact events
(7) ability to assess 'smoke impact' on people for each simulated scenario of fire spread

The project has delivered over 25 peer-reviewed papers, over 35 agency peer-reviewed reports, as well as project information items such as 6 magazine-style articles and over 10 posters and two videos (durations of 4 and 10 minutes). The FireDST team has provided numerous presentations to other scientists, AFAC committees and end-users, as well as presentations at major emergency management and fire science conferences, supplemented by posters and information booths.

The project has also benefited from the direct involvement of fire and emergency agency (end-user) personnel, who not only provided guidance and encouragement, but were also active in providing information and data as well as reviewing material developed during the three-years of the project.

Major conclusions from the combined FireDST simulation system component of the project are:

- FireDST has shown that it is feasible to build an ensemble impact simulation system that has the potential to provide timely and informative advice about the predicted passage of a fire and the potential consequences on people, buildings and infrastructure.
- A distinguishing feature of the FireDST approach is the ensemble nature of the information provided, which supplies guidance on the range of expected impacts and their *likelihood* given the *uncertainties* in our knowledge and the input information. This guidance could better inform emergency management decisions and the general public in relation to the potential paths of fires and their impacts.
- FireDST is a *'proof of concept'* tool developed with the aim of providing critical fire planning information to emergency services, government and the public. FireDST has demonstrated the ability to predict the possibilities of both neighbourhood and house loss (and their $ value), the potential health impacts of bushfire smoke, and also both the area that is likely to be burnt as well as the area affected by the smoke generated.

- With further development, a system based on the FireDST approach could be run operationally under predicted weather and fuel conditions, and also be modified (in near real time) for a range of different scenarios that attempt to encompass the uncertainty in the weather and fuels (i.e. such as changing the fuel load and dryness, and also the wind strength/direction, and the time of a wind change; these are amongst a large number of variables to which the sensitivity of the fire extent, severity and location has been explored as part of this project).
- The methodologies built in FireDST could move to the next stage of development, and eventually through to operational implementation.
- The inclusion of the FireDST ensemble simulation approach within existing platforms such as Victoria's principal fire management application 'EMap' and/or the Western Australian fire monitoring and management application 'AURORA' is considered by the FireDST end-user advisory committee as an important pathway for the utilisation of this research (the development of an operational tool which has been beta tested and refined by trained end-users).
- An ensemble of high resolution (kilometre scale) weather modelling is required to adequately capture the uncertainty in synoptic and local scale atmospheric phenomena relevant to fire spread and fire behaviour. This facility is available in Europe and the United States, and the Bureau of Meteorology is planning a similar capability dependent on the upgrade of the existing supercomputing facility (i.e. consideration given to ensemble forecasting within the supercomputing upgrade cycle).
- Very high resolution weather modelling may be required to adequately capture atmospheric phenomena relevant to fire behaviour, particularly in the case of small-scale phenomena. Such small-scale phenomena may explain unexpectedly severe fire behaviour such as was seen in the Black Saturday and Margaret River case studies. There is the possibility that future research may be able to develop spatially specific parameterisations that will allow this small-scale information to be utilised within high resolution (km) weather modelling.

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| | |
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# Appendix A. Project Communication

Results of the F.I.R.E-D.S.T. project were communicated to stakeholders in the academic and end-user communities in various ways. Publications in Fire Australia (Cechet *et al.*, 2011b), Asia Pacific Fire (Cechet *et al.,* 2012), and also a Fire Note (Cechet *et al.*, 2013) have raised the profile of the FireDST project. In addition, presentations to a range of stakeholders throughout the course of the project as well as running an exhibition hall booth at the 2012 and 2013 AFAC/Bushfire CRC conferences assisted the FireDST collaborators to interface with industry stakeholders and end-users. A wide range of peer-reviewed publications and conference talks have discussed the project's scientific achievements in the academic community.

On the advice of David Youssef (lead end-user), the project team undertook the production of a 10 minute video describing the project and providing some early project outputs to raise interest within the broader stakeholder community. The video was scripted by Geoscience Australia with assistance from the Bushfire CRC Communications Manager. The production was managed by the Metropolitan Fire Brigade (MFB) in-house video production facility based in Fitzroy, Melbourne. The video is located on the Bushfire CRC website (http://www.bushfirecrc.com/projects/2-1/risk-assessment-decision-toolbox).

A further video was commissioned for the AFAC/Bushfire CRC 2013 conference where the FireDST team ran an exhibition stand. The video was scripted by Geoscience Australia with assistance from the Bushfire CRC, and the production was managed by an external consultant (on behalf of the Bushfire CRC).

The Bushfire CRC project webpages relevant to this project are listed below. They form the major project information dissemination points for the broader stakeholder group for each of the five sub-components of the project.

http://www.bushfirecrc.com/category/projectgroup/2-risk-assessment-and-decision-making

http://www.bushfirecrc.com/projects/2-1/risk-assessment-decision-toolbox

http://www.bushfirecrc.com/projects/2-2/enhancement-fire-behaviour-models

http://www.bushfirecrc.com/projects/2-3/enhancement-weather-predictions-under-extreme-conditions

http://www.bushfirecrc.com/projects/2-4/understanding-distribution-smoke-and-particulates

http://www.bushfirecrc.com/projects/2-5/enhancement-neighbourhood-impacts