Spark Evaluation – 0.9.7

Comparison of Wildfire Rate of Spread Models Implemented within the Spark Framework to Historical Reconstructions of Wildfire Events

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Version control

Report Revision	Date	Spark framework version	Spark batch release version	Difference log
Draft A	26/8/2016	0.7.1	38086	Original report
0.9.7	19/2/2018	0.9.7	44551	• General solver improvements • Time varying fuel moisture model used • Elliptical fire spread template used • Cut/grazed grass model used • Compared Pickering Brook fire to an earlier isochrone • Sourced higher resolution land classification layers for WA fires

Citation

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Acknowledgments

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1 Introduction

1.1 Overview

The aim of this project is to create, maintain and grow a standard data set of historical fire events which can be used in an ongoing effort to improve fire prediction through the Spark framework. This 'standard input stack' of fire simulations can be used to validate fire models, test new rate of spread models and check the Spark framework for systematic errors before new versions are publically released. Furthermore, the standard input stack is intended to be publically available, allowing researchers using the Spark framework a starting point for full scale fire simulations. The stack is intended to grow as new historical events are added, and the results from the comparison are intended to improve over time as new rate of spread models, behaviour models and computational methods are developed.

The project is *not* intended to give a best fit to historical fire models, or to detail a set of tweaks required to match a simulation with a particular fire event. Rather, the project is intended as a snapshot of the model performance for using the newest research and best current modelling techniques. As these are improved and updated the results will be updated accordingly. Similarly, as better input data becomes available (such as fuel and meteorological conditions) the results will be updated using the newer data. The report provides a comparison of model performance, as well as highlighting shortcomings in the current state of the art to identify areas for future improvement.

1.2 Spark

The Spark framework is a fully configurable fire propagation system allowing rate-of-spread models for any fuel type to be easily implemented. The system includes a range of plug-in packages including generation of wind fields, topographic correction of wind fields, spot fire models and road/transmission line crossing.

The system is based on a level set propagation model, allowing simulation of any number of distinct fire perimeters, multi-front interaction and coalescence as the fire evolves. The method is parallelised on GPU architecture, enabling simulations to run much faster than real time.

The framework is based on the CSIRO developed Workspace, a computational workflow tool. Each element of wildfire simulation, such as reading input data, running the simulation and outputting data can be fully customised within this workflow environment. The system has integrated geospatial support, image analysis, scripting, database, and provenance reporting, making Spark compatible with any standard data types.

Spark allows any number of input data layers to be used and combined in any way within rate-of-spread calculations. The model is raster-based, where each cell can be classified by fuel type and use a different rate-of-spread model. The system handles all temporal and spatial interpolation of input data, allowing the user to define rate-of-spread models in a clear and straightforward manner.

1.3 Comparison Wildfires

Seven wildfires are currently used for comparison. These were picked based on data availability, location and size of the fire. For each of these cases the best available input data sets were used. The input data sets included land classification, fuel conditions and metrological data. The input data used in each case is detailed in the following sections. For situations where no input data was available the methodology used to construct required inputs is detailed. Each of the cases were simulated for time periods between 4 to 25 hours.

The wildfires used for comparison are listed below:

#	Name	State	Year	Comparison
1.	State Mine Fire	NSW	2013	Observed / reconstructed fire front at 21:15 on 17 October 2013
2.	Kilmore East Fire	VIC	2009	Observed / reconstructed fire fronts at 14:00, 15:00, 16:00 and 17:00 on 7 February 2009
3.	Giblin River Fire	TAS	2013	Observed / reconstructed fire front at 16:15 on 4 January 2013
4.	Forcett-Dunalley Fire	TAS	2013	Observed / reconstructed fire front at 14:30 on 4 January 2013
5.	Wangary Fire	SA	2005	Observed / reconstructed fire front at 00:00 on 12 January 2005
6.	Mount Cooke Fire	WA	2003	Satellite imagery of the burn scar, Landsat 7 image LE71120822003036EDC00, digitised for area matching comparison.
7.	Pickering Brook Fire	WA	2005	Reconstructed fire perimeter isochrones from Cheney (2010)

Table 1 - Wildfires used in evaluation

2 Model Inputs

The simulations require metrological inputs, starting locations of the fire, geospatial inputs (such as topography and land classification) as well as rate-of-spread models for different fuel types and the geospatial data associated with each rate-of-spread model. This section describes this input data and the spread rate models used for each of the comparisons.

2.1 Meteorological Input Data

Wind and weather data is the most important information required for a bushfire simulation. For several of these cases only point source metrological data was available from an automated weather station (AWS). For others, however, gridded reconstructed metrological data is available. This data was available in the following forms:

- Time series values from Bureau of Meteorology (BoM) AWS. This data is a point source time series that is usually recorded at intervals of 30 minutes or one hour. Wind speed and direction, surface temperature, relative humidity and dew point temperature (among others) are available from the supplied comma separated variable (CSV) files. This data is quite accurate, however, it is recorded at a fixed point, often in different topography many kilometres from the fire.
- Gridded NetCDF datasets. This data is three dimensional (2D space and varies with time). This is generated as a prediction or as a reconstruction. Predicted data may not be what was observed as it is a forecast from a model. Hindcast reconstructions calibrated to AWS data are the most accurate gridded datasets available.

The framework contains a sub-module for down sampling and correcting wind flow over topography. This is currently undergoing testing and validation, and was not used in the current version of this study.

2.2 Initial Fire Conditions

The initial position and size of the fire front as the start of the simulation can either be defined as a set of circular point sources (specifying locations, radii and start times), or using a geo-referenced raster or shape file dataset. The simulation resolution is set when specifying the initial fire conditions.

2.3 Geospatial Input Data

The two main geospatial input groups are fuel data and terrain data. Different rate-of-spread models require different fuel data layers. Terrain data is common to all rate of spread models and consisted of:

1. Topographic digital elevation model (meters above a datum such as AHD). This was sourced from Geoscience Australia Digital Elevation Data[1].

2. Land classification data for defining the cover type and hence rate-of-spread model to be used. This data was sourced from Catchment Scale Land Use of Australia[2] (classifications from Australian Land Use and Management Classification[3]) or the TasVeg data set[4].

Internal classifications were assigned as:

Class	Land type	Rate of spread model
0	Unburnable (water/rock)	None
1	Grassland	CSIRO grassland
2	Dry Eucalypt Forest	Vesta - Dry Eucalypt
3	Urban	Proportional to wind
4	Moorland	Buttongrass moorland
5	Wet Eucalypt Forest	VESTA - Wet Eucalypt adjusted

Table 2 – Fuel models used in study

The methods and initialisation models used to convert various land use maps into classification layers are reported in Appendix A . Results from the simulations were projected onto a base satellite map image (Bing Aerial with labels) in QGIS.

Geospatial data layers can be specified in a number of ways:

- A constant value specified over the entire simulation domain,
- A two dimensional map with spatially varying levels,
- A three dimensional map with spatially and temporally varying levels,
- A model defined in an initialisation stage specifying the two-dimensional values over the domain.

The layers in each of the test cases used one of the above, depending on data availability.

All of the input data layers are required to be converted into a Cartesian projection (for example, Mercator or conical) before being used in the solver. The conversion is carried out within the framework using the relevant EPSG codes of the projections.

[1] Digital Elevation Data: http://www.ga.gov.au/scientific-topics/national-location-information/digital-elevation-data

[2] Catchment Scale Land Use of Australia: https://www.data.gov.au/dataset/catchment-scale-land-use-of-australia-update-march-2014

[3] Australian Land Use and Management Classification: http://www.agriculture.gov.au/abares/aclump/land-use/alum-classification-version-7-may-2010

[4] TASVEG: http://dpipwe.tas.gov.au/conservation/flora-of-tasmania/monitoring-and-mapping-tasmanias-vegetation-(tasveg)/tasveg-the-digital-vegetation-map-of-tasmania

2.4 Fire Spread Rate Models

The fire spread rate models used in the comparison simulations are described in this section.

2.4.1 Grasslands

The CSIRO grassland model[5] (Cheney et al. 1998) was used for all grassland areas within the domain. The cut/grazed variant was generally implemented for all grassy regions in lieu of more specific vegetation classification (Cruz et al. 2015b). Dead fuel moisture content and curing level were required as inputs into this model.

Curing

The curing coefficient was calculated using the equation proposed by Cruz et al. (2015a).

Fuel moisture content

Fuel moisture content was estimated from McArthur (1966), using surface temperature and relative humidity as inputs.

2.4.2 Dry Eucalypt Forest

The fuel hazard score version of the Vesta dry eucalypt model[6] was used for all forest areas within the domain. Dead fuel moisture content and fuel hazard scores were required as inputs into this model.

Fuel hazard scores

The fuel hazard scores are surface fuel hazard (FHSs, 0-4), near surface fuel hazard (FHSns, 0-4) and near surface height (Hns, cm). Fuel Hazard Scores were generally defined in the simulations by estimating them from fuel ages.

For the calculation from fuel ages, Eq. (1) and Eq. (2) give exponential and hyperbolic relationships between the hazard score and the fuel age (Gould *et al.* 2011). These equations are assumed to be reasonable estimates up to a fuel age of approximately 25 years:

$$h_{exp} = a * (1 - \exp(-k * A)) \quad (1)$$

$$h_{hyp} = (a * A)/(b + A) \quad (2)$$

Where h is the hazard score and a, b and k are different fitting constants for FHSs, FHSns and Hns, and A is the fuel age. The fitting constants also depend on whether the under story layer is considered tall shrub or low shrub. These equations were implemented in the initialisation model of Spark to build a spatial map of the fuel parameters and were assumed for all forest types (not just the E. marginate they were developed for).

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[5] Available from: http://research.csiro.au/spark/resources/model-library/csiro-grassland-models/

[6] Available from: http://research.csiro.au/spark/resources/model-library/vesta/

Fuel moisture content

Fuel moisture content levels were estimated from surface temperature and relative humidity values using Gould et al. (2007) and Matthews et al. (2010).

2.4.3 Wet Eucalypt Forest

Wet Eucalypt Forest was modelled using the Vesta model in lieu of any specific rate of spread model developed for the vegetation type. The Vesta model was adapted for the denser under canopy vegetation by including wind reduction factors and by adapting fuel moisture models from Sneeuwjagt et al. (1985)[7] as per the Amicus fire knowledge database[8] (Plucinski et al. 2017).

2.4.4 Buttongrass Moorlands

The Marsden-Smedley and Catchpole (1995) model[9] was used for all moorland areas within the domain. Fuel moisture content and fuel age were required as inputs into this model.

Fuel age

Fuel age was defined either using a spatial map or a constant value over the domain.

Fuel moisture content

Fuel moisture content levels were estimated from surface temperature and relative humidity values using Marsden-Smedley and Catchpole (2001), assuming that no rain had fallen in the previous 48 hour to the fire.

2.4.5 Urban

In lieu of any existing empirical models, a linear rate-of-spread was used in urban areas. The fire spread rate (m/s) was assumed to be 0.8% of the wind speed (in km/h). Due to the uncertain fuel loads and continuity in urban areas, future sensitivity analyses could be conducted with varying spread rates. Depending on the simulation region, this may or may not be considered to be critical as the urban areas are often outweighed by the grass and forest areas in the simulated regions. The wildfires sometimes occur, however, on the urban fringe or near major infrastructure such as highways.

2.4.6 Fire Shaping

The rate of spread models presented in the previous sections were developed as one-dimensional steady-state rates of spread for a fully developed head fire. Adapting these one dimensional rate of

[7] Available from: https://research.csiro.au/spark/resources/model-library/wet-eucalypt/

[8] Available from: https://research.csiro.au/amicus/

[9] Available from: http://research.csiro.au/spark/resources/model-library/buttongrass-moorlands/

spread models into two dimensional perimeter propagation models (including flanking and backing spread) is an ongoing area of research. There are several approaches which can be used.

One approach is to use the dot product of the wind vector and the unit normal to the fire perimeter to calculate the reduced wind speed (capped at zero) at areas of the fire perimeter not normal to the wind vector. This has advantages of being easy to implement, however they may not be appropriate for models where the rate of spread is zero when the wind speed is zero as no flanking or backing spread is predicted.

Another approach is to define the rate of spread around the fire perimeter as a fraction of the head fire rate of spread. These can be defined using geometric templates. An elliptical fire shape has been observed in many experimental and wildfires. In this study, all rate of spread models (except for urban) were implemented using an elliptical template where the length to breadth ratio depends on the wind speed and the fuel type as per Cruz et al. (2015b) adapted from Taylor et al. (1997).

2.4.7 Slope Effects

The effect of slope on fire spread rate was included using McArthur's rule of thumb (McArthur 1967). This rule states that the head fire spread rate doubles for every 10° of parallel incline for a slope range from 0° to 20°. For slopes above 20°, a speed gain for 20° is assumed. For negative slopes, the CSIRO Kataburn model (Sullivan et al. 2014) is applied. For slopes below -20°, a speed reduction factor of approximately one half is applied. As this is a one dimensional model it is necessary to extrapolate it to two dimensions within the framework. For the analyses in this report a scalar method from Sharples (2008) was used.

The slope model was applied to all vegetation types. Slope effects have not been applied to urban classifications as these regions can be a combination of variable, discontinuous or un-burnable fuels.

2.5 Resolution

Spark simulations can be run at different resolutions or grid sizes. A grid size of 30 metres was used for the simulations in this report. Increasing the grid size would decrease the computational time for the simulation to be conducted, however smaller scale features in topography and land cover may not be captured as accurately. Decreasing the grid size captures smaller scale details, but increases the computational time for the simulation to be conducted. A grid size of 30 m was chosen as it matched the highest resolution national topography data available (one arc second from Geoscience Australia) as well as the common Landsat 8 remote sensing data sets.

3 Comparisons

In order to test whether new models perform better or worse than previous models, it is important quantitatively measure how well a simulation matches the actual fire (a detailed reconstruction from observations in most cases). The measure currently used in this study is the threat score defined in the BoM evaluation report (Faggian et al. 2017), which is identical to the Jaccard similarity coefficient (Filippi et al. 2014). The score is based on a rasterised map where each cell represents one of three states. These are true positive (*TP*), where the simulation and observations overlap, false positive (*FP*), where the simulation predicts fire spread but this is not within the observed fire footprint and false negative (*FN*), where the observed fire footprint falls outside the prediction. These are combined into a threat score using the formula:

$$threat\ score = \frac{TP}{TP + FP + FN} \tag{3}$$

where a perfect match has a threat score of 1 while non-overlapping fires will have a threat score of 0. Figures are presented in this report which highlight the comparison of the simulations and the observations, where true positive regions are shown in green, false positives are shown in red and false negatives are shown in blue as shown in Figure 1.

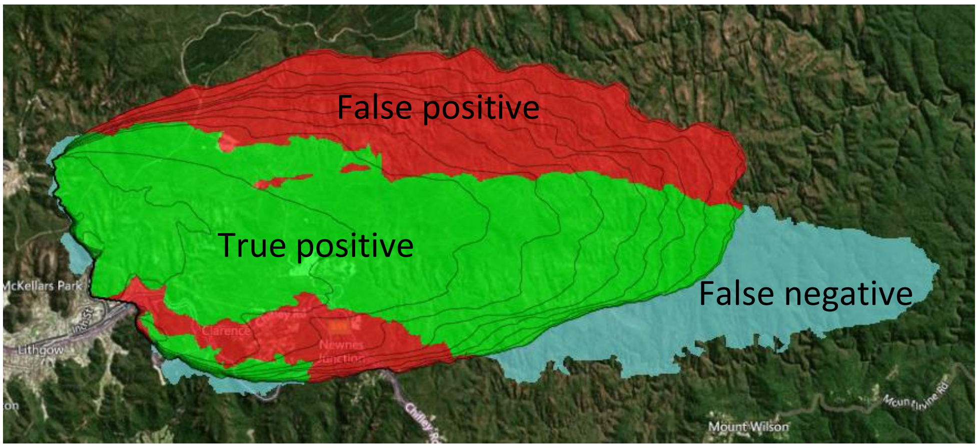

Figure 1 – Threat score example showing different score regions.

The threat score is not a perfect measure of how well a simulation matches an actual fire and does not necessarily distinguish or rank all scenarios of simulations well for all cases. Non-overlapping fires and comparing fires with mid to long range spotting are two examples where the threat score is not ideal. Furthermore, the threat score only compares the final fire extents, not the progression of the fire, and is unable to distinguish between potential sources of error such as bearing and rate of spread. This being said, the threat score is considered appropriate for the cases presented in this study due to having knowledge of the ignition fire positions as well as a lack of long range spot fires being present in the final fire isochrones.

4 State Mine Fire

4.1 Background

The Lithgow State Mine bushfire started on 16 October 2013 and burned in New South Wales until 25 October 2013. The fire was caused by a training exercise being carried out by the Australian Defence Force. The fire travelled the furthest distance and the fastest speed on 17 October 2013, burning through a large area of dry eucalypt forest.

The fire was simulated for a period of just over 9 hours on 17 October 2013.

4.2 Model Parameters

DATA TYPE	DATA SOURCE
Meteorological Data	1. Mount Boyce AWS, ID: 063292, Lat/Long: -33.62, 150.27, Elevation: 1080 m 2. BoM gridded data
Other Available Meteorological Data	Bathurst Airport AWS
Land Use Classification	CLUM for data, initialisation model in Appendix A.1 was used for classification grid mapping
Topography	GA 30m raster (AHD)
Curing Level	Constant value of 60% was assumed based on time of year
Fuel Loads	A constant fuel age of 18 years was assumed for the simulation. Fuel hazard scores were then estimated from growth curves.
Initial Fire for Simulation	Shapefile of reconstructed fire fronts starting at 11:59 on 17 October 2013
Simulation End Time	21:15 on 17 October 2013
Output Comparison	Observed / reconstructed fire front at 21:15 on 17 October 2013

4.3 Results and Discussion

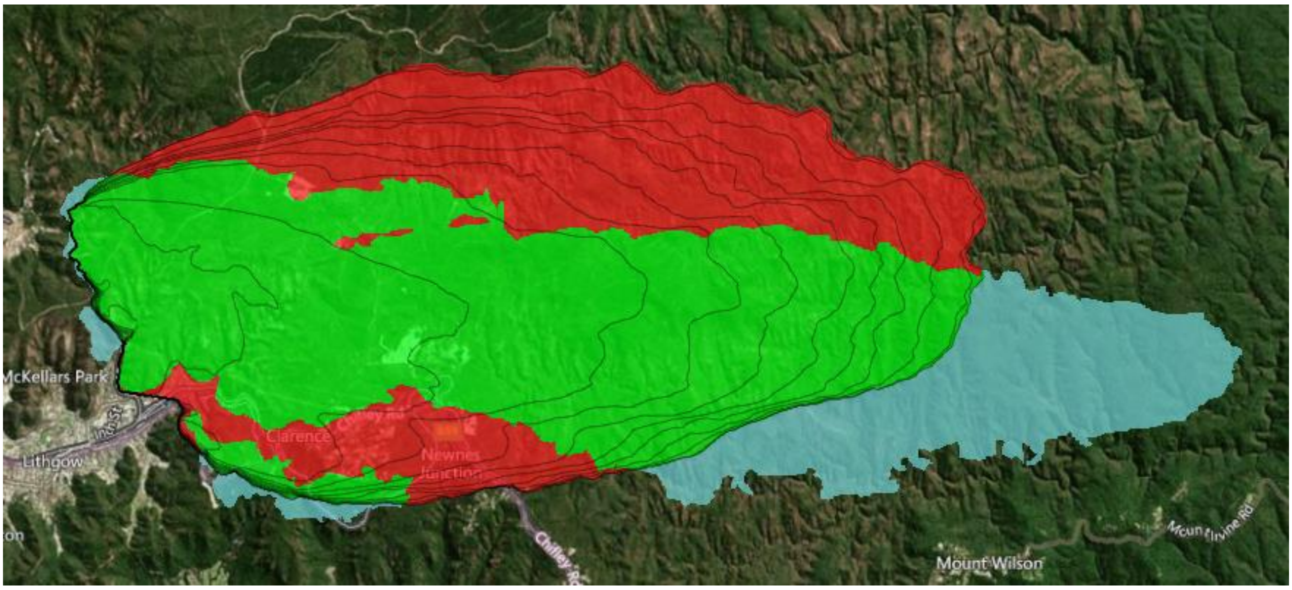

Figure 2 – Hourly isochrones of Lithgow State Mine simulation shown in black. Initial fire shown as first isochrone. Isochrones are superimposed over threat score visualisation.

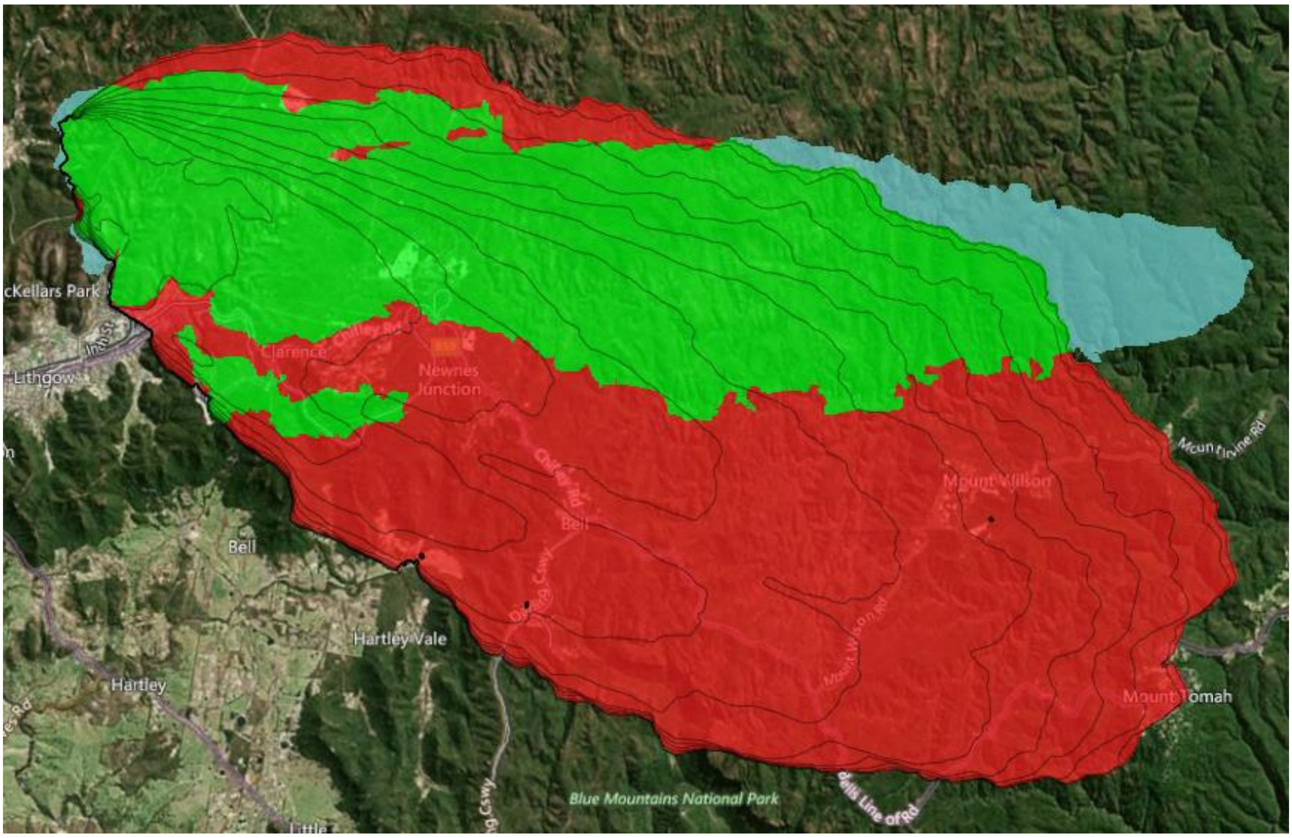

Figure 3 – Hourly isochrones of Lithgow State Mine simulation shown in black. Initial fire shown as first isochrone. Isochrones are superimposed over threat score visualisation. Gridded NetCDF data used for weather inputs.

The Lithgow case provides a reasonable match over a long simulation duration but highlights the sensitivity of the predictions to the meteorological data used. Figure 2 shows the simulated fire using the Mount Boyce AWS meteorological data while Figure 3 shows the simulated fire using the gridded data.

4.3.1 Mount Boyce meteorological data

The simulation based on AWS data values predicts a similar burn area to the reconstructed fire. However, the simulation over predicts to the north and under predicts to the east. The simulation also over predicts the burned area to the south of the main fire near the start of the simulation. Possible reasons for these differences include:

1. Unmodified weather data from the Mount Boyce AWS was used, which was approximately 20 km away from the fire. This potentially resulted in higher relative humidity, and hence lower spread rates than were actually achieved. The wind direction from the AWS appears to be south-westerly during later times in the simulation compared to the westerly wind direction indicated by the fire scar.
2. A spotting model was not included in the simulation. Spotting was present during the actual fire as evidenced by the two initial burn areas. Including such a model could increase the easterly rate of spread.
3. The fire being actively supressed at the Southern edge of the fire near the start of this simulation (which was not simulated) to protect the urban population and urban fringe.

4.3.2 Gridded meteorological data

The simulation based on BoM gridded data predicts a larger burn area compared to the reconstructed fire. The simulation predicts a much greater southern extent than the reconstruction. Possible reasons for these differences include:

1. Unmodified NetCDF weather model data was used. This data may not have matched the ground conditions during the fire. The gridded wind direction appears to north-westerly, rather than the westerly wind direction from the fire scar near the middle and the end of the simulation.
2. A spotting model was not included in the simulation. Spotting was present during the actual fire as evidenced by the two initial burn areas. This could increase the easterly rate of spread.
3. The fire being actively supressed at the Southern edge of the fire near the start of this simulation (which was not simulated).

Future work could investigate inclusion of a spotting model, accounting for suppression at the urban fringe and modifying weather input based on topography to improve the model predictions.

5 Kilmore East Fire

5.1 Background

The Kilmore East bushfire started on 7 February 2009 and burned in Victoria until it was contained in early March. It was the largest fire out of the Black Saturday bushfires. The fire was started by a power line and burned the fastest and most intensely on 7 February 2009. Further background information is contained in Cruz et al. (2012).

The fire was simulated for a period of 4 hours on 7 February 2009.

5.2 Model Parameters

DATA TYPE	DATA SOURCE
Meteorological Data Used	Wallan (Kilmore Gap) AWS, ID: 088162, Lat/Long: -37.38, 144.97, Elevation: 528 m
Other Available Meteorological Data	None identified
Land Use Classification	CLUM for data, initialisation model in Appendix A.1 was used for classification grid mapping
Topography	GA 30m raster (AHD)
Curing Level	Constant value of 100% was assumed based on time of year
Fuel Loads	A constant fuel age of 15 years was assumed for the simulation. Fuel hazard scores were then estimated from growth curves.
Initial Fire for Simulation	Shapefile at 13:00 on 7 February 2009 based on Cruz et al (2012)
Simulation End Time	17:00 on 7 February 2009
Output Comparison	Observed / reconstructed fire fronts at 14:00, 15:00, 16:00 and 17:00 on 7 February 2009

5.3 Results and Discussion

The Kilmore case shows over prediction in the extent of the predicted fire for the first few hours of the simulation, however the simulation results significantly under predict the burned area at 17:00 (see Figure 4, area 'A'). This is most likely due to the following factors:

1. A spotting model was not included in the simulation. It was reported that significant long range spotting of several kilometres occurred during the afternoon of the fire. Some of these break outs can be seen on the southern flanks of reconstruction (arrows in Figure 3).
2. Unmodified weather data from the Kilmore Gap AWS was used. As the fire propagated to the south east the head of the fire moved further from the weather station used. This may have resulted in different wind speeds at the head of the fire to that used in the model.
3. To attempt to better correlate with actual fire observations, adjustments could be made to the input weather data including increasing the wind speed. A detailed fuel age or fuel load map may also be able to explain the changes in the observed spread rates. Future modelling could also include long range spot fires ignited from recorded breakout positions.

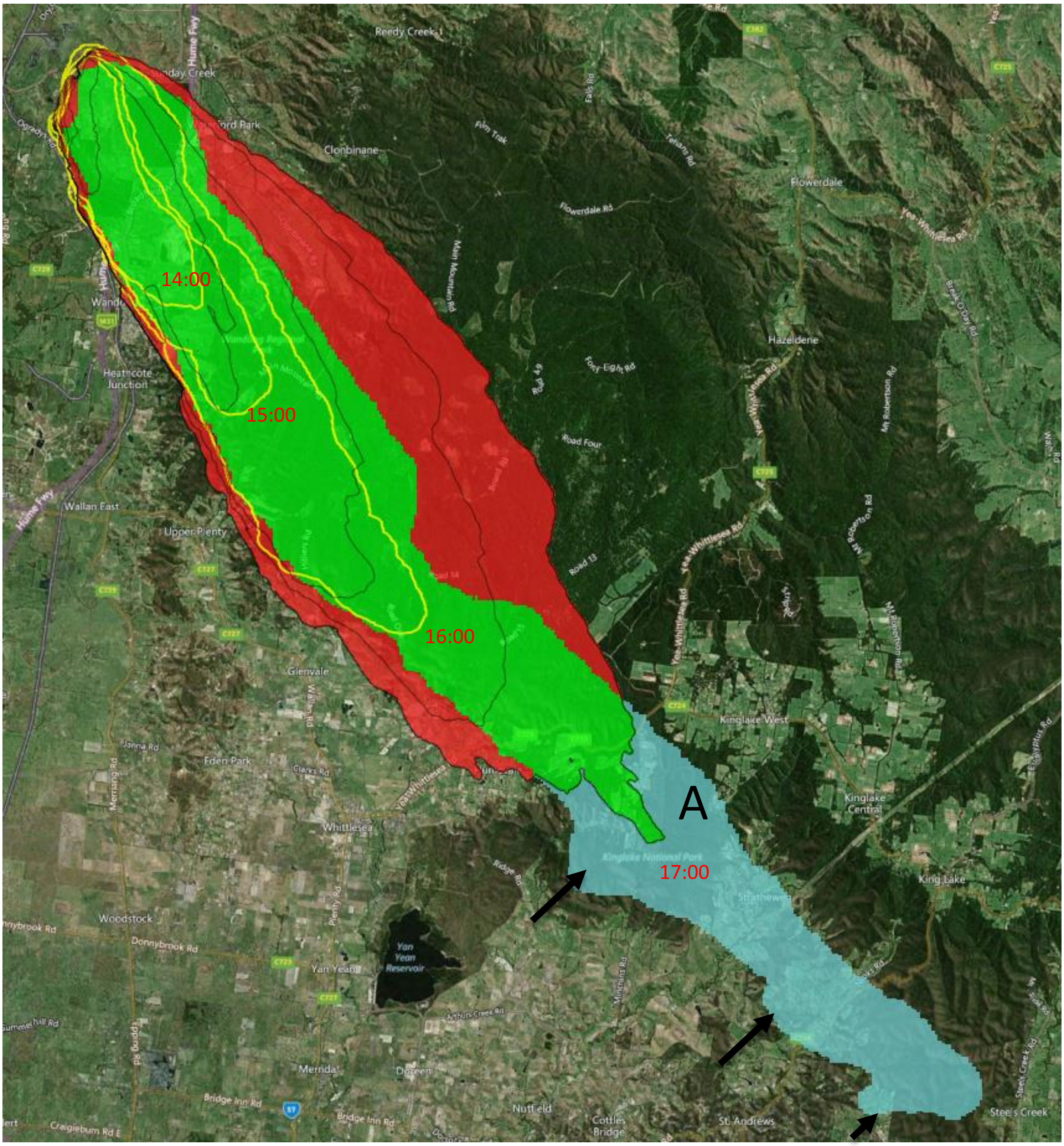

Figure 4 – Hourly isochrones of Kilmore East simulation shown in black, first isochrones at 14:00. Initial fire shown as first isochrone. Reconstructed fires at 14:00, 15:00 and 16:00 are shown in yellow for comparison to early isochrones. Isochrones are superimposed over threat score visualisation.

6 Giblin River Fire

6.1 Background

The Giblin River bushfire started from a lightning strike on 3 January 2013 and burned in Tasmania until 22 January 2013. The fire burned through many different types of vegetation and resulted in a final burn area of 45,124 ha. Further background information is contained in Marsden-Smedley (2014).

The fire was simulated for a period of just over 25 hours starting on 3 January 2013.

6.2 Model Parameters

DATA TYPE	DATA SOURCE
Meteorological Data Used	Scotts Peak Dam AWS, ID: 097083, Lat/Long: -43.04, 146.27, Elevation: 408 m
Other Available Meteorological Data	Low Rocky Point AWS
Land Use Classification	TASVEG for data, initialisation model presented in Appendix A.2 for classification grid mapping
Topography	GA 30m raster (AHD)
Curing Level	Constant value of 80% was assumed based on time of year
Fuel Loads	A constant fuel age of 15 years was assumed for the simulation. Fuel hazard scores were then estimated from growth curves.
Initial Fire for Simulation	Assumed to be at 145.796 E, 43.009 S (within 2km from 401950, 5237070 (GDA94/55)) with a radius of 200 m at 15:00 on 3 January 2013 based on Marsden-Smedley (2014)
Simulation End Time	16:15 on 4 January 2013
Output Comparison	Observed / reconstructed fire front at 16:15 on 4 January 2013

6.3 Results and Discussion

The Giblin river case resulted in good overall size and extent agreement with the reconstructed fire at the south east head fire. However, there was an over prediction of the burned area on the south west flank (see Figure 5, area 'A'). Differences may be due to the following factors:

1. The TASVEG dataset contained many different vegetation types, even in the relatively small area of the fire. For the simulation these were classified to known rate of spread models: dry eucalypt forest, grass land, moorlands, wet eucalypt forest, or un-burnable. These assumptions are likely to have introduced errors into the overall rate of spread.
2. A constant fuel age was assumed for the simulation. A detailed fuel age or fuel load map may improve the simulation through more accurate fuel load values.
3. The ignition of the fire is only known to be within an area of 2km radius. Due to the multiple land classifications within the ignition region the simulation is quite sensitive to the start location.

The inclusion of calibrated and published spread rate models for more of the vegetation types present, such as rain forest, scrub and highlands, as well as a fuel load or fuel age map may provide a better match to the reconstructed fire extent. An initialisation model could also be developed which estimates or adjusts fuel loads based on the elevation, slope and aspect of the terrain.

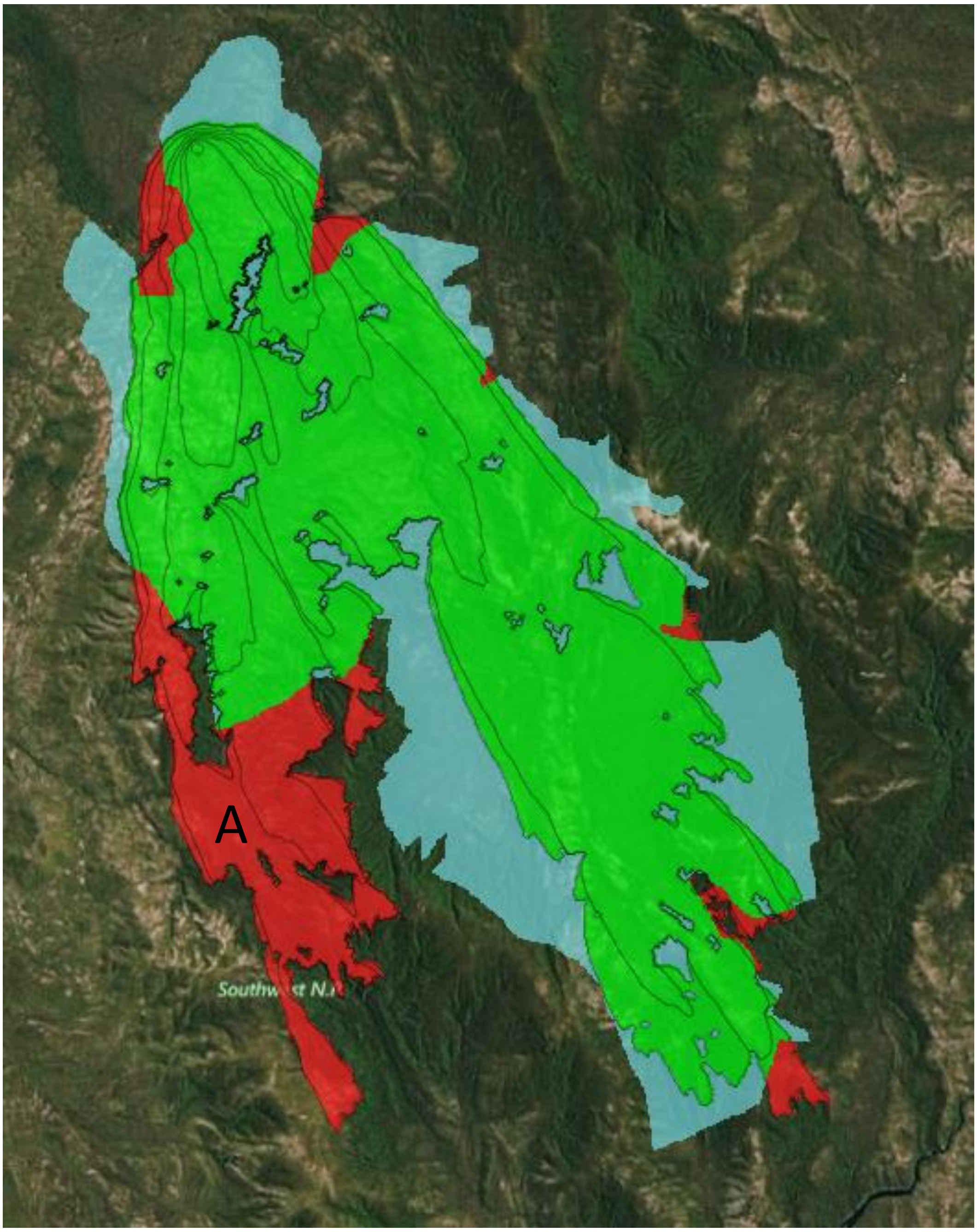

Figure 5 – Four-hourly isochrones of Giblin River simulation shown in black, first isochrone at 19:00 on January 3. Isochrones are superimposed over threat score visualisation.

7 Forcett-Dunalley Fire

7.1 Background

The Forcett-Dunalley bushfire started east of Hobart on 3 January 2013 and burned until contained on 18 January 2013. The fire burned through several different vegetation types and significant spotting was observed at times. The final burn area of the fire was 23,960 ha. Further background information is contained in Marsden-Smedley (2014).

The fire was simulated for a period of just over 24 hours starting on 3 January 2013.

7.2 Model Parameters

DATA TYPE	DATA SOURCE
Meteorological Data Used	Dunalley (Stroud Point) AWS, ID: 094254, Lat/Long: -42.90, 147.79, Elevation: 12.4 m
Other Available Meteorological Data	Hobart Airport AWS
Land Use Classification	TASVEG for data, initialisation model presented in Appendix A.2 for classification grid mapping
Topography	GA 30m raster (AHD)
Curing Level	Constant value of 80% was assumed based on time of year
Fuel Loads	A constant fuel age of 8 years was assumed for the simulation. Fuel hazard scores were then estimated from growth curves.
Initial Fire for Simulation	Assumed to be at 147.6751 E, 42.8065 S (within 25m from 555195, 5260448 (GDA94/55)) with a radius of 100 m at 14:00 on 3 January 2013 based on Marsden-Smedley (2014)
Simulation End Time	14:30 on 4 January 2013
Output Comparison	Observed / reconstructed fire front at 14:30 on 4 January 2013

7.3 Results and Discussion

The Forcett-Dunalley simulation had reasonable overall agreement between the extent and size of the reconstructed burn area and the simulation. The simulation resulted in an over prediction of the burned area of the south west and north east flanks and an under prediction of the burned area at the south east of the fire (see Figure 6). This may be due to the following factors:

1. The TASVEG dataset contained many different vegetation types, even in the relatively small area of the fire. For our simulation, these were all classified into known rate-of-spread models: dry eucalypt forest, grass land, moorlands, wet eucalypt forest, or un-burnable. Mappings were based on 11 vegetation groups (given in Appendix A.2).
2. A constant fuel age was assumed for the simulation. A detailed fuel age or fuel load map may improve the simulation through more accurate fuel load values.

3. Unmodified weather data from the Dunalley AWS was used, which was some distance from the initial fire. This is likely to have resulted in slightly different wind speeds and directions that at the head of the fire.
4. The reconstructions show the fire may have been controlled along the western flank (Arthur Highway and Sugarloaf Rd). This was not included in the simulation and may have resulted in a significant reduction in the burn area 'A'.
5. Farmland area towards the north east (area 'B') appeared to be bare earth in satellite images. This was not included in the simulation and would have resulted in a reduction of burned area to the east.

The inclusion of calibrated and published spread rate models for more of the vegetation types present, such as agricultural lands, plantations and scrub, as well as a fuel load or fuel age map may improve match between the simulation and reconstruction. Modifying weather inputs may also improve the simulation through more accurate wind conditions.

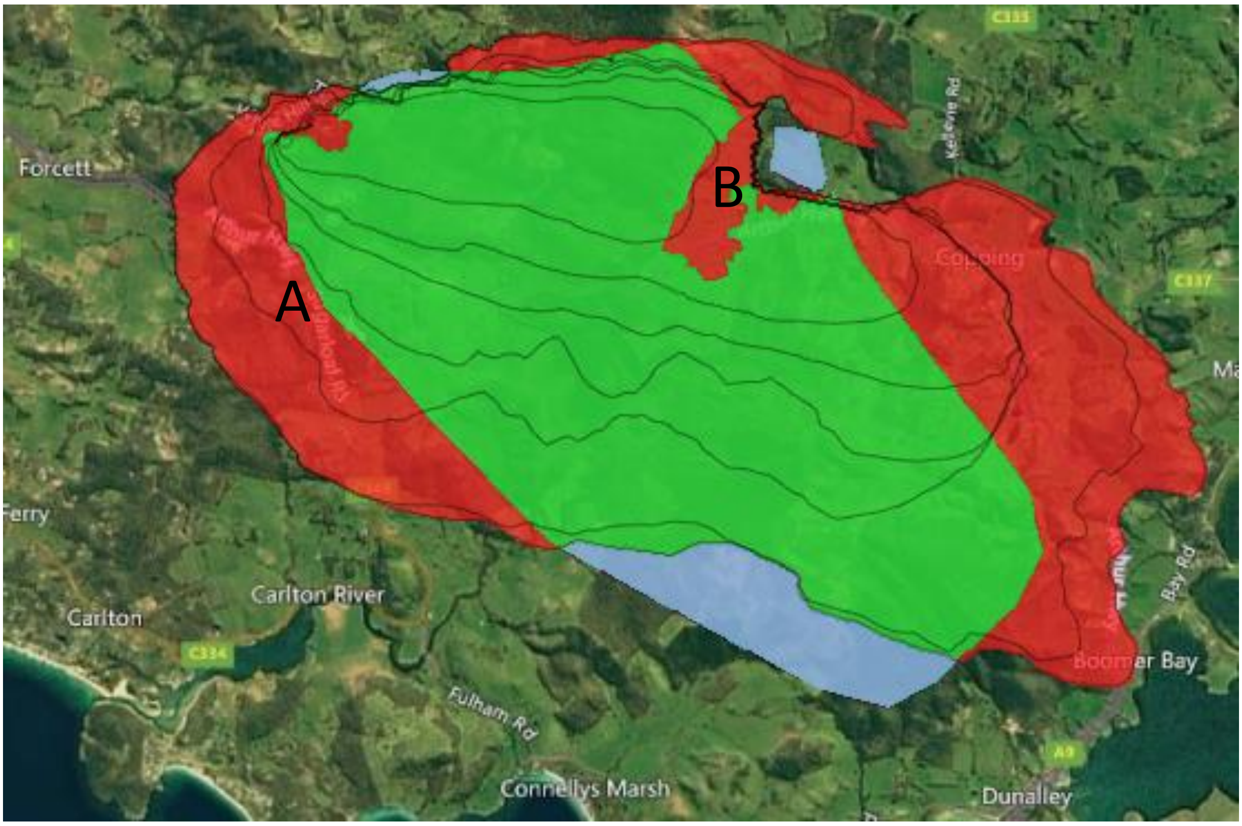

Figure 6 – Four-hourly isochrones of Forcett-Dunalley simulation shown in black. Isochrones are superimposed over threat score visualisation.

8 Wangary Fire

8.1 Background

The Wangary bushfire started on 10 January 2005 and burned in South Australia until 12 January 2003. The fire broke out from swamplands on 11 January 2005 and spread the fastest and burned the largest area on that day. Further background information is contained in Gould (2005).

The fire was simulated for a period of just over 14 hours starting on 11 January 2005.

8.2 Model Parameters

DATA TYPE	DATA SOURCE
Meteorological Data Used	1. North Shields (Port Lincoln) AWS*, ID: 018192, Lat/Long: -34.60, 135.88, Elevation: 28 m 2. Coulta (Coles Point) AWS, ID: 018191, Lat/Long: -34.37, 135.37, Elevation: 28 m 3. BoM ACCESS gridded data from Fawcett et al. (2013)
Other Available Meteorological Data	None identified
Land Use Classification	CLUM for data, initialisation model in Appendix A.1 was used for classification grid mapping
Topography	GA 30m raster (AHD)
Curing Level	Constant value of 100% was assumed based on time of year
Fuel Loads	A constant fuel age of 6 years was assumed for the simulation. Fuel hazard scores were then estimated from growth curves.
Initial Fire for Simulation	A shapefile of the reconstructed fire at the end of 10 January 2005 was defined as un-burnable (already burned) while several breakout fires were modelled, the first starting at 09:51 on 11 January 2005 (Gould 2005).
Simulation End Time	00:00 on 12 January 2005 based on Gould (2005)
Output Comparison	Observed / reconstructed fire front at 00:00 on 12 January 2005 (Gould 2005)

* It should be noted that there is no publically available data from the North Shields AWS for a large portion of the fire duration. This data was, however, captured by BoM and has been privately supplied to us in a raw format with a 10 minute data capture period. The raw data was different to the publically available AWS data.

- Raw wind speed was recorded in knots. This was converted into km/h for the simulations.
- Percentage relative humidity was not recorded. This was calculated from the raw surface temperature t and dew point d in degrees Celsius using Eq. (4) [10].
- Wind direction was recorded to the nearest degree, not the nearest 10 degrees.

$$rh = 100 * 10^{7.591386\left(\frac{d}{d+240.7263} - \frac{t}{t+240.7263}\right)} \tag{4}$$

[10] Equation provided by Andrew Sullivan and was validated against complete data sets.

8.3 Results and Discussion

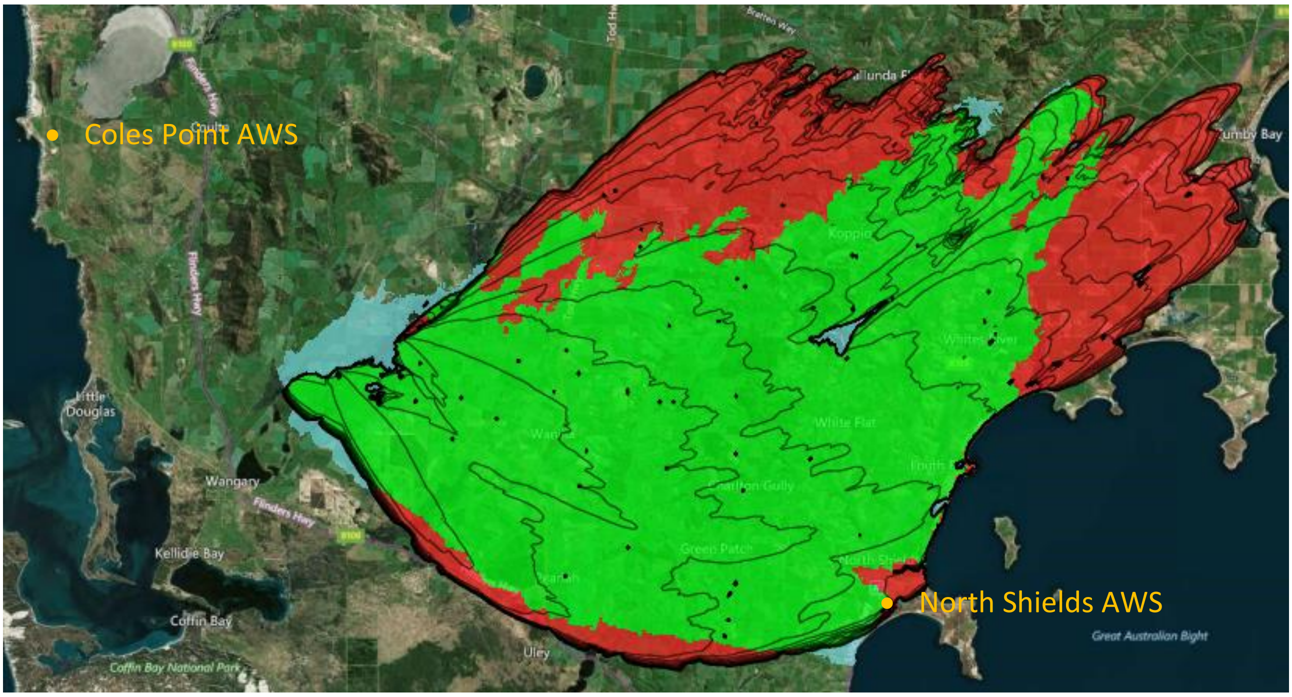

Figure 7 – Hourly isochrones of Wangary simulation shown in black. North Shields AWS data used for weather inputs. Overnight burn area shown in blue at North West of burn area. Isochrones are superimposed over threat score visualisation. Weather stations shown as orange circles.

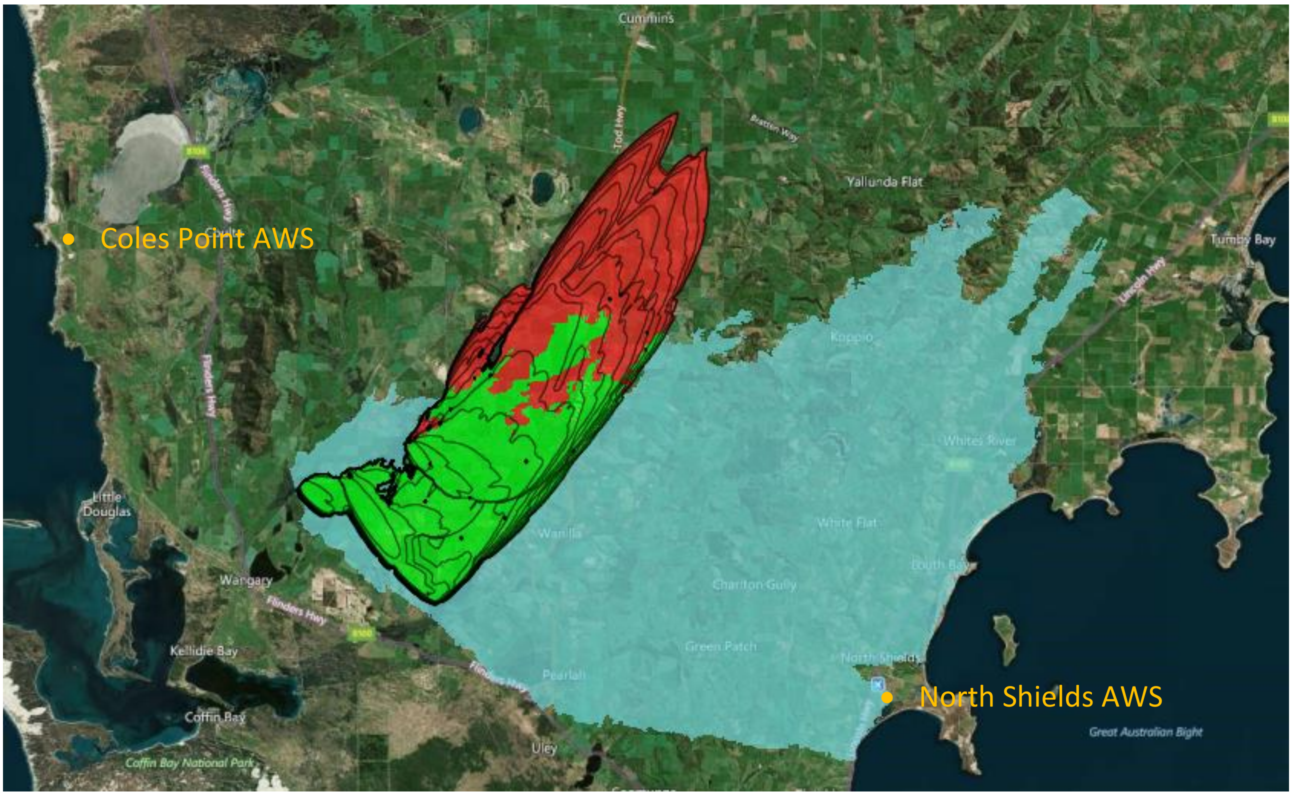

Figure 8 – Hourly isochrones of Wangary simulation shown in black. Coles Point AWS data used for weather inputs. Overnight burn area shown in blue at North West of burn area. Isochrones are superimposed over threat score visualisation. Weather stations shown as orange circles.

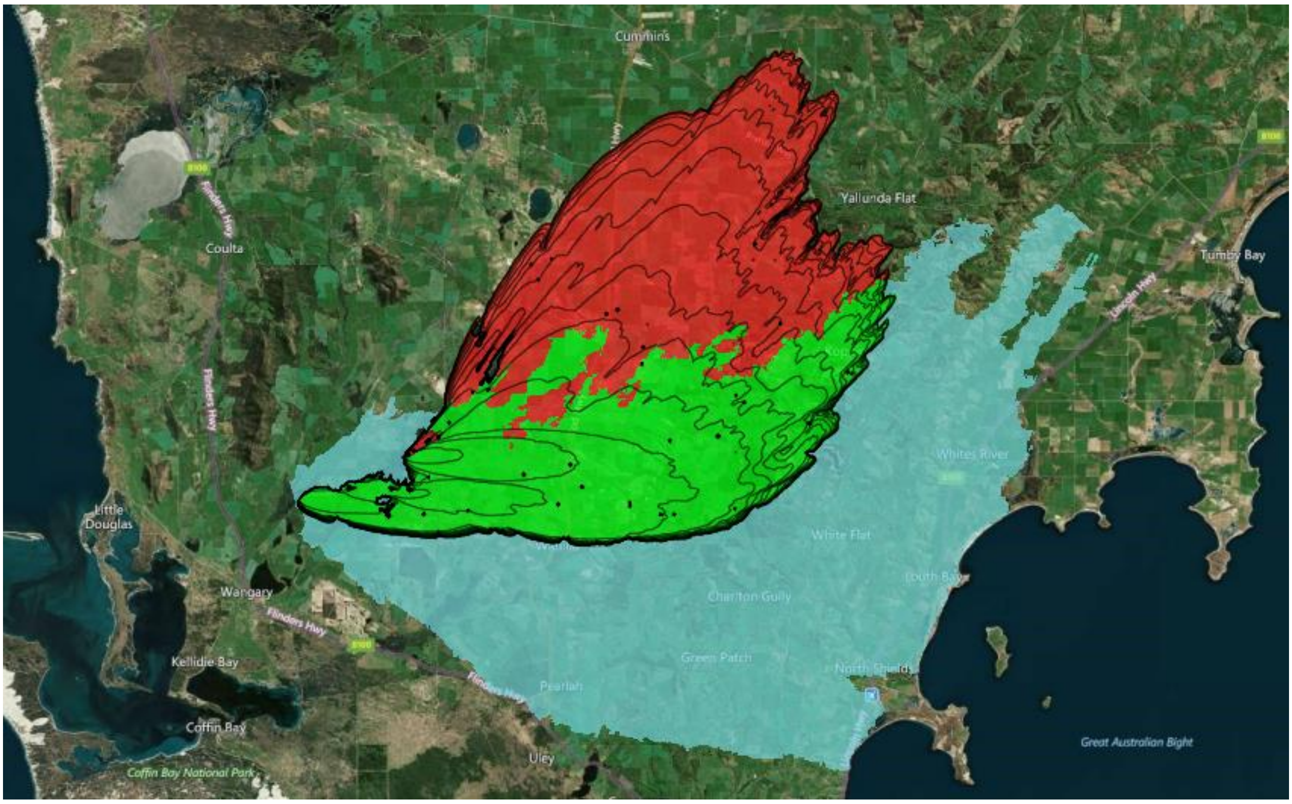

Figure 9 – Hourly isochrones of Wangary simulation shown in black. BoM raw gridded data used for weather. Overnight burn area shown in blue at North West of burn area. Isochrones are superimposed over threat score visualisation.

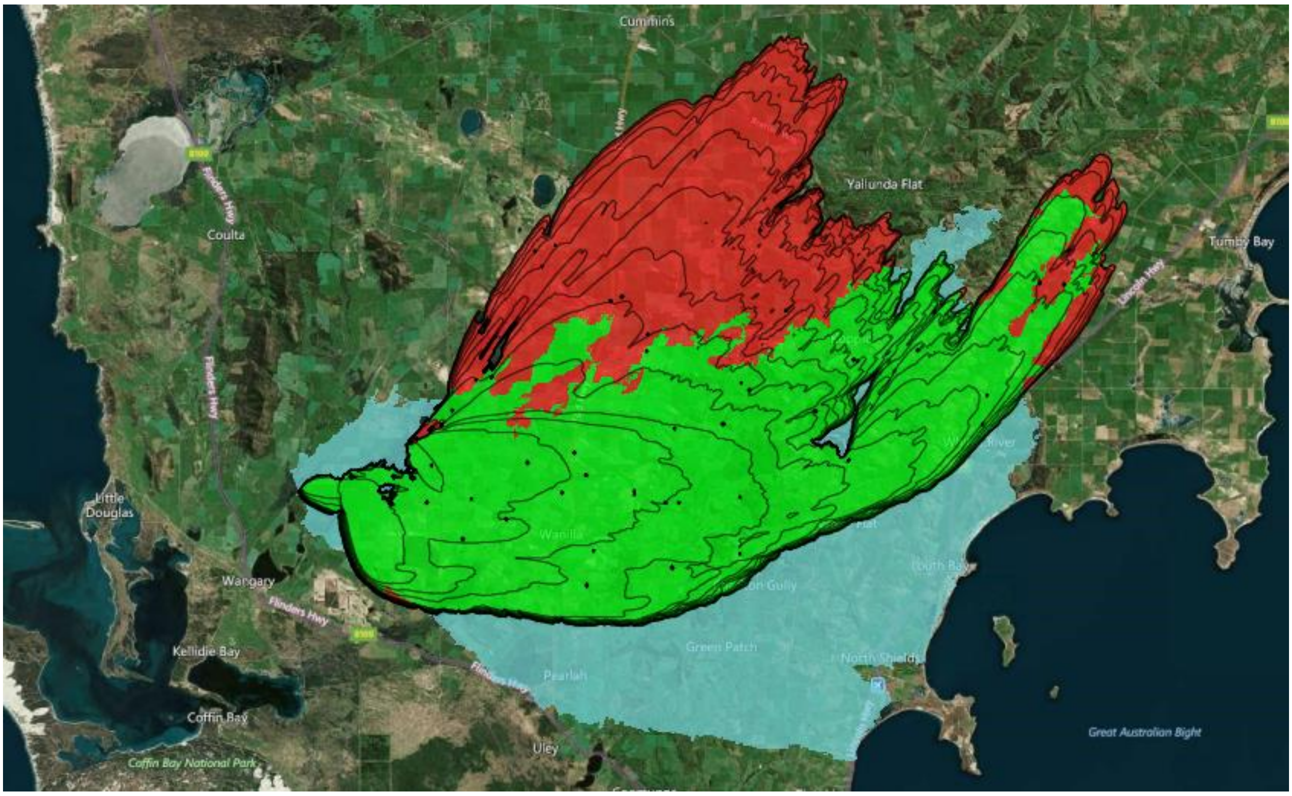

Figure 10 – Hourly isochrones of Wangary simulation shown in black. One hour adjusted BoM gridded data used for weather. Overnight burn area shown in blue at North West of burn area. Isochrones are superimposed over threat score visualisation.

The Wangary test case showed the greatest sensitivity to meteorological conditions of all the cases considered. While the rate of spread appeared to agree well with the observations, small differences in the timings of the wind change made great differences to the predicted fire perimeter. Figure 7 shows the simulation using North Shields AWS data, Figure 8 shows the simulation using Coles Point AWS data and Figure 9 and Figure 10 shows the simulation using gridded weather model data (raw and one hour adjusted).

8.3.1 North Shields meteorological data

The simulation using North Shields AWS data shows that the simulated fire generally matches the burn extent quite well, while slightly over predicting the burned regions in the North-East and North-West. Use of a curing map and local topographic wind corrections may improve this match further.

8.3.2 Coles Point meteorological data

The simulation using Coles Point AWS data shows that the simulated fire does not spread far enough to the East before the wind change propagates the fire to the North-East. This is most likely due to the following reasons:

1. Unmodified weather data from the Coles Point AWS was used.
   a) This possibly resulted in higher relative humidity, lower temperatures, and hence lower spread rates than were actually achieved, especially during the mid-afternoon when the wind was coming from the West.
   b) Another issue is the wind direction and the timing of when the change comes through. Representing this with a single data point, many kilometres away from the active fire front, introduces significant error to when the fire changes direction.

8.3.3 Gridded meteorological data

The gridded meteorological data was kindly supplied by Robert Fawcett from the Bureau of Metrology and has been previously published as a case study (Fawcett et al., 2013). The simulation using gridded model data (Figure 9) shows that the simulated fire does not spread far enough to the South-East before the wind change propagates the fire to the East and then North-East. This is most likely due to the following reasons:

1. Unmodified model weather data was used.
   a) Figure 4 from Fawcett (2013) shows that the model weather data when the wind change occurs at the fire front is nearly an hour different from analysed data. This effectively removes the portion of the simulation which would propagate the fire to the South-East.

To attempt to better correlate with actual fire observations, adjustments can be made to the input weather data including modifying the start time by up to an hour in order to better match the analysed data of when the change hits the fire ground. This results in a better match (but not perfect) to the burn area as shown by the isochrones in Figure 10. The inclusion of a topographic local wind corrector may also improve results.

The extent on the North-West flank for all simulations is greater than observed in the reconstruction. The cause appears to be the use of the ALUM classification for marshlands. In lieu of a known rate of spread model for these regions they would normally be treated as un-burnable. However, for this particular case, making these regions un-burnable prevents the observed initial breakouts from occurring. For these simulations the marshland regions were treated as urban areas, which allowed the observed breakouts and potentially gave increased spread rates through this regions, resulting in a larger final extent than observed. A general strategy for dealing with this issue is uncertain but could involve:

1. Manual modification of the classification data only within the area of the break out fires, keeping the other marshland areas defined as un-burnable. This is not a satisfactory solution as it would require manual tweaking of the classification layer for this particular case.
2. Development of a rate-of-spread model for marshlands. This could provide a balance between allowing the development of break out fires while reducing the spread through other marshlands. This would require further scientific investigation to develop the empirical rate of spread for marshlands.

9 Mount Cooke Fire

9.1 Background

The Mount Cooke bushfire started from a lightning strike on 9 January 2003 and burned in Western Australia until 11 January 2003. The fire burned quickly through dry eucalypt forest of varying ages, propagating the furthest on 10 January 2003. Further background information is contained in Johnston et al. (2008).

The fire was simulated for a period of 21 hours starting on 10 January 2003.

9.2 Model Parameters

DATA TYPE	DATA SOURCE
Meteorological Data Used	Bickley AWS, ID: 009240, Lat/Long: -32.01, 116.14, Elevation: 384 m
Other Available Meteorological Data	Karnet AWS, Jandakot AWS and Dwellingup AWS
Land Use Classification	CLUM for data, initialisation model in Appendix A.1 was used for classification grid mapping
Topography	GA 30m raster (AHD)
Curing Level	Constant value of 80% was assumed based on time of year
Fuel Loads	A map of fuel ages in the region of the fire was sourced from Johnston et al. (2008) which was extracted and implemented in the simulation. Growth curves were then used to estimate fuel hazard scores.
Initial Fire for Simulation	Assumed to be at 116.295 E, 32.375 S with a radius of 310 m at 08:00 on 10 January 2003, based on Johnston et al (2008)
Simulation End Time	05:00 on 11 January 2003, based on Johnston et al (2008)
Output Comparison	Satellite imagery of the burn scar, Landsat 7 image LE71120822003036EDC00, digitised for area matching comparison.

9.3 Results and Discussion

The Mount Cooke case provided the poorest match out of the test cases to the final observed fire extent, with a significant under prediction of the burned area (see Figure 11). This may be due to the following factors:

1. A spotting model was not included in the simulation. It was reported that significant spotting of 1-2km and even up to 5km occurred during the day of January 10 (Johnston et al. 2008). One such breakout from a spot fire can be seen on the satellite image (Figure 6, marked with an arrow).
2. Unmodified weather data from the Bickley AWS was used. This likely resulted in higher relative humidity, higher fuel moisture levels, and hence lower spread rates than were actually achieved. The wind direction in the first hour or so is also likely to have been south-westerly rather than south-easterly. Other simulations of this fire modified the weather

data, including increasing the applied wind speed in order to obtain a similar burn area (Johnston et al. 2008).

To attempt to better correlate with actual fire observations, adjustments could be made to the input weather data including increasing the wind speed, modifying the wind direction and decreasing the relative humidity. The inclusion of a calibrated and published spotting model for the fuel type would also improve the simulation to match the actual fire better.

There was a slight over prediction of fire spread into the one year old fuels (area 'A'). This is likely due to the following reasons:

1. The youngest fuels tested in Gould et al. (2011) to develop fuel growth curves for low and tall shrub were 16 and 23 months respectively, and that the effects of very young fuels on fire spread rate were not accurately captured.
2. A property of the VESTA dry eucalypt model is that a forest which has just been burned (with fuel hazard scores of zero) is still predicted to propagate fire at a minimum spread rate given by the fuel moisture coefficient. This is perhaps a limitation of the model which could be improved upon for very young fuels.

To attempt to better correlate with actual fire observations, adjustments could be made to the one year old fuel in various sensitivity analyses.

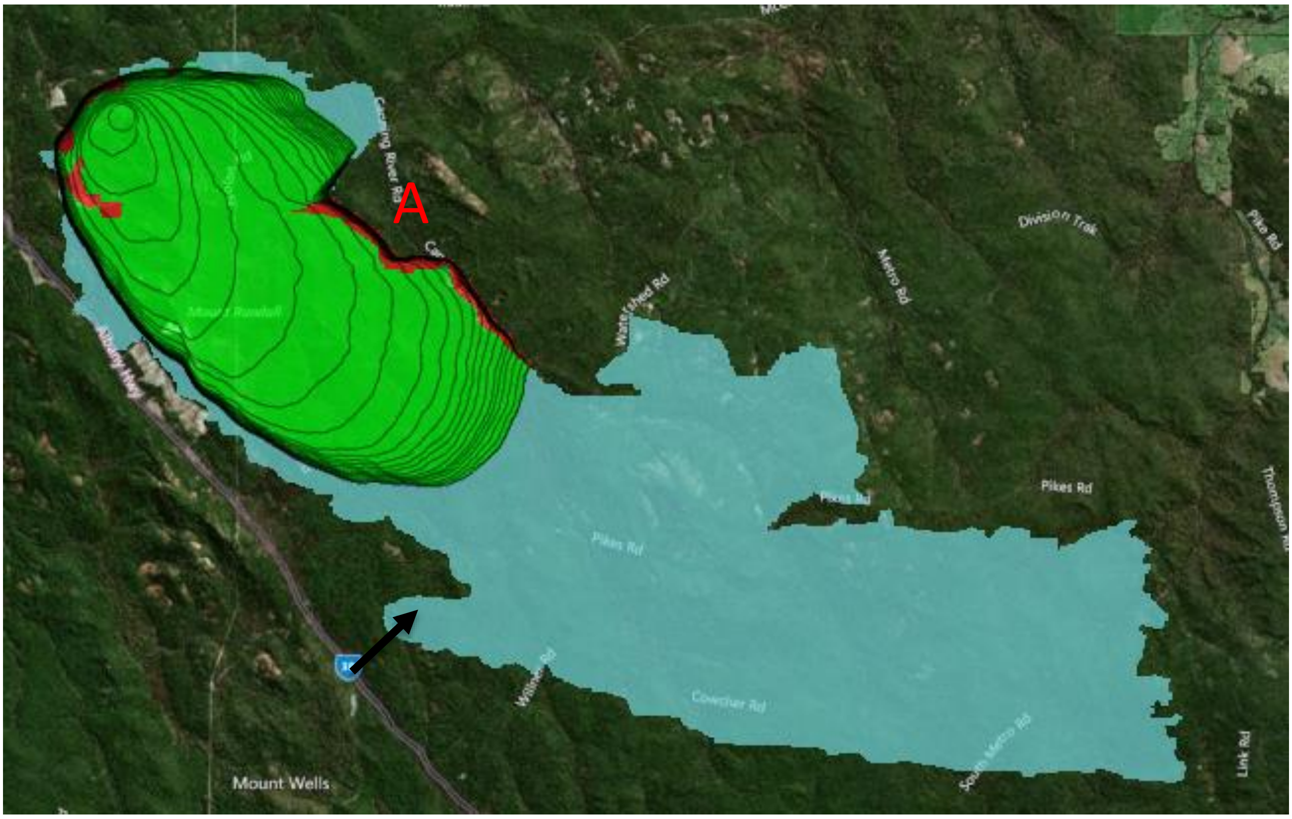

Figure 11 – Hourly isochrones of Mt Cooke simulation shown in black. Isochrones are superimposed over threat score visualisation.

10 Pickering Brook Fire

10.1 Background

The Pickering Brook bushfire started from several deliberate ignitions on 15 and 16 January 2005 and burned in Western Australia until 25 January 2005. The fire burned through dry eucalypt forest of varying ages. Further background information is contained in Cheney (2010).

The fire was simulated for a period of 25 hours starting on 15 January 2005.

10.2 Model Parameters

DATA TYPE	DATA SOURCE
Meteorological Data Used	1. Bickley AWS, ID: 009240, Lat/Long: -32.01, 116.14, Elevation: 384 m 2. Wandering AWS, ID: 010917, Lat/Long: -32.67, 116.67, Elevation: 275 m
Other Available Meteorological Data	Perth Airport and Dwellingup
Land Use Classification	CLUM for data, initialisation model in Appendix A.1 was used for classification grid mapping
Topography	GA 30m raster (AHD)
Curing Level	Constant value of 80% was assumed based on time of year
Fuel Loads	A map of fuel ages in the region of the fire was sourced from Cheney (2010) which was extracted and implemented in the simulation. Growth curves were then used to estimate fuel hazard scores.
Initial Fire for Simulation	Fires 75, 76 and 80 were started with radii of 120 m on 15 and 16 January 2005, based on Cheney (2010) (fires 78 and 79 were not modelled as they were controlled). The first fire was started at 18:00 on 15 January 2005.
Simulation End Time	19:00 on 16 January 2005, based on Cheney (2010)
Output Comparison	Reconstructed fire perimeter isochrones from Cheney (2010)

10.3 Results and Discussion

Figure 12 – Four-hourly isochrones of Pickering Brook simulation shown in black. Isochrones are superimposed over threat score visualisation. Bickley AWS data used for weather inputs. Simulated control lines shown in black.

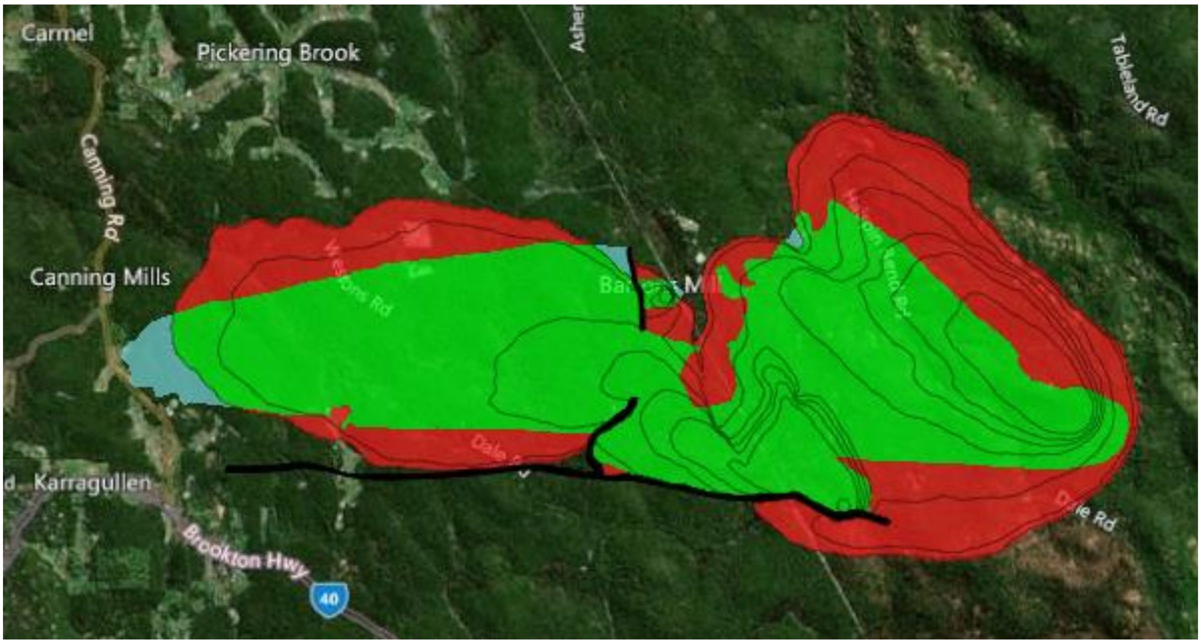

Figure 13 – Four-hourly isochrones of Pickering Brook simulation shown in black. Isochrones are superimposed over threat score visualisation. Wandering AWS data used for weather inputs. Simulated control lines shown in black.

The Pickering Brook case provides a reasonable match over a long simulation duration but shows sensitivity to the meteorological data used. Figure 12 shows the simulated fire using the Bickley AWS meteorological data while Figure 13 shows the simulated fire using the Wandering AWS meteorological data.

This test case was also simulated using temporary containment lines employed during the early stages of the fire (Figure 7 from Cheney, 2010). The containment lines were implemented by creating thin polygons which were treated as un-burnable for the entire simulation.

10.3.1 Bickley meteorological data

Using the Bickley AWS data (approximately 10 km north of the fire) resulted in reasonable overall size and extent agreement with the reconstructed fire (Figure 12). The northern flank of the simulated head fire was slightly under predicted while the head fire was over predicted in the south.

Due to the simulation having a higher than indicated flanking rate of spread, the east-west containment line was simulated to be breached around the eastern end. If the containment lines were not modelled then there would have been a much larger over prediction of burned area on the southern flank of the fire.

10.3.2 Wandering meteorological data

Using the Wandering AWS data (approximately 75 km South-East of the fire) resulted in reasonable overall size and extent agreement with the reconstructed fire (Figure 13). Flanking was over predicted in both the early and later stages of the fire, particularly at the east end of the fire which predicted a small breach around the containment line.

If the containment lines were not modelled then there would have been a much larger over prediction of burned area on the southern flank of the fire.

Differences between the simulations and recorded fire extents for both cases may be due to the following factors:

1. Several temporary control lines and suppression attempts were not modelled. These slowed and temporarily halted the progression of both the west travelling head fire and the southern flank of the fire.
2. A spotting model was not included in the simulation. It was reported that significant spotting of up to 1km occurred on January 15 and 16 (Cheney 2010).
3. Unmodified weather data was used. The wind data is likely to have not matched the actual conditions on the fire ground.

To attempt to better correlate with actual fire observations, adjustments could be made to the input weather data including modifying the wind direction, possibly combining the weather data from multiple weather stations. Modelling suppression attempts as well as temporary containment lines would improve the simulation further. The inclusion of a calibrated and published spotting model for the fuel type would also improve the simulation to match the actual fire better.

11 Discussion

11.1 Threat Scores

The threat scores were calculated for all of the simulations presented. The results are shown below.

#	Name	Conditions	Threat score
1.	State Mine	Time series weather	0.499
		Gridded weather	0.367
2.	Kilmore East	Time series weather	0.465
3.	Giblin River	Time series weather	0.608
4.	Forcett-Dunalley	Time series weather	0.569
5.	Wangary	North Shields AWS	0.664
		Coles Point AWS	0.138
		Raw gridded data	0.229
		Adjusted gridded data	0.462
6.	Mount Cooke	Time series weather	0.326
7.	Pickering Brook	Bickley AWS	0.593
		Wandering AWS	0.597

Table 3 - Threat scores for each comparison case

Interestingly, the time series simulations resulted in better matches (higher threat scores) than their gridded counterparts. In the Lithgow case, this is because the time series data better represents the wind direction experienced on the fire ground. In the Wangary case, this is because the North Shields AWS is the weather stream that best captures the wind direction and the timing of the wind change. These results further demonstrate the sensitivity of fire simulations to the input weather data, especially wind speed and direction.

11.2 Fire Shapes

Several of the cases presented in this report have larger simulated flanking fires than were actually achieved (Lithgow, Kilmore East, Forcett-Dunalley, Wangary and Pickering Brook). This could be attributed in part to the elliptical shaping that was implemented in this version of the study, described in Section 2.4.6. The length to breadth ratios used may have been too low for the conditions, resulting in wider simulated fires. This is perhaps an over correction to some particularly thin simulated fires in the previous version of this study which used the dot product method of calculating flanking spread rates. Future work will further investigate the two dimensional shaping of these fires.

The larger simulated flanking could also be due to the modelled effect of slope on flanking fires. The 2D scalar method implemented could be a cause of this and may have over predicted the rate of spread for flanking fires. Future work will investigate various methods of implementing wind and slope interactions.

12 Ongoing Development

12.1 Input Data Limitations

Input data limitations can be a large source of error in wildfire models and predictions. Limitations often come in the form of incomplete input data for fuel classification maps, curing maps, fuel age or fuel load maps. Furthermore, on site meteorological data may be unavailable, limited or inaccurate. The largest errors are introduced into fire simulations from incorrect fuel classifications and incorrect local wind data.

Fuel classifications for this study have been taken from CLUM and TASVEG datasets as described in Section 2.3. Effort was made in mapping fuel classifications to the most appropriate spread rate model, however mapping to only the handful of spread rates used can introduce error into the overall rate of spread. This limitation can be minimised in the following ways:

1. Sourcing the most up to date and highest resolution land classification data. State specific data may be more specific and applicable in some cases compared to national data sets.
2. Regularly review the mapping from land classification to spread rate model especially as new spread rate models are developed and validated for new vegetation types.
3. Meteorological data for this study was taken from weather station data as well as gridded NetCDF model data. Using a single value for the wind speed and direction for the entire fire can introduce significant error, especially if this data is taken from a weather station tens of kilometres away. This limitation can be minimised in the following ways:
4. Sourcing and using validated high resolution weather data when available.
5. Using a model for down sampling and correcting wind flow over topography. This model in the Spark framework is currently undergoing testing and validation, and was not used in the current version of this study.
6. Using a model to adjust weather data based on the location of the fire relative to the weather station, and the wind speed and direction. This is currently undergoing development.
7. Ensemble simulations could be utilised within the framework with error estimations for weather variables such as wind direction and speed could be used in order to predict a probability map of where the fire will spread, rather than just a single prediction.

12.2 Fire spread modelling

Future developments of the spread model currently under active research may improve the predictive ability of the model in some areas. Some of these developments include:

1. Including a process-based fuel moisture content model.
    1.1. Possibly adding solar radiation model as an input to the fuel moisture content models. The system allows slope and aspect to be calculated.
2. Lapse rate of varying temperature with elevation – this can be implemented in the current framework but was not included in this study.

3. A published and calibrated spotting model – research is required.
4. A greater understanding of wind and slope interaction – research is required.
5. New rate-of-spread models for different vegetation types – research is required. Any number of spread rate models can be implemented in the current framework.
6. Self-extinguishing of fires – this can be implemented in the current framework but was not included in this study as further research is required.
    6.1. Modelling how fires can be halted by discontinuities, and potentially breach them - this can be implemented in the current framework but was not included in this study as further research is required.
7. Fire suppression attempts – historical suppression data is required. Further research is required into the best way to model various suppression attempts as well.
8. Topographic fuel load adjustment (in particular, in lieu of accurate fuel load mapping) – research is required.

Appendix A Classification Initialisation Models

This Appendix contains the initialisation models for generating vegetation classification layers.

A.1 ALUM Classifications

For the Mount Cooke, Kilmore East, Wangary, Pickering Brook and Lithgow simulations, the ALUM classifications were used to generate the classification layer from the CLUM data based on the following initialisation model:

```
// Convert ALUM classification values to fuel types
const int main_class = (int)floor((REAL)class/100.0);
const int sub_class = (int)floor((REAL)class/10.0);


if (sub_class == 65) {

  // Wetlands, mapped to urban
  class = 3;

} else if (main_class == 6) {

  // Water
  class = 0;

} else if (main_class == 1 || sub_class == 22 || sub_class == 31 || sub_class ==
41) {

  // Forest
  class = 2;

} else if (sub_class == 21 || main_class == 3) {

  // Grassland
  class = 1;

} else if (main_class == 5 || main_class == 4) {

  // Urban
  class = 3;

} else {

  // Default is un-burnable
  class = 0;

}
```

A.2 TASVEG

For the Giblin River and Forcett-Dunalley simulations, the TASVEG dataset was used to generate the classification layer. The following code was used in QGIS to convert the three letter vegetation codes into numbers:

```
CASE

WHEN regexp_match( VEGCODE,'^A') THEN 1
WHEN regexp_match( VEGCODE,'^D') THEN 2
WHEN regexp_match( VEGCODE,'^F') THEN 3
WHEN regexp_match( VEGCODE,'^G') THEN 4
WHEN regexp_match( VEGCODE,'^H') THEN 5
WHEN regexp_match( VEGCODE,'^M') THEN 6
WHEN regexp_match( VEGCODE,'^N') THEN 7
WHEN regexp_match( VEGCODE,'^O') THEN 8
WHEN regexp_match( VEGCODE,'^R') THEN 9
WHEN regexp_match( VEGCODE,'^S') THEN 10
WHEN regexp_match( VEGCODE,'^W') THEN 11

END
```

The classification grid was then generated using on the following initialisation model:

```
if (class == 1 || class == 5 || class == 8 || class == 9) {

  // Water (O), wetlands (A), highlands (H), rainforest (R)
  class = 0;

} else if (class == 2) {

  // Dry eucalypt (D)
  class = 2;

} else if (class == 4) {

  // Grassland (G)
  class = 1;

} else if (class == 3) {

  // Urban (F)
  class = 3;

} else if (class == 6 || class == 7 || class == 10) {

  // Moorland (M), non-eucalypt (N), scrub (S)
  class = 4;

} else if (class == 11) {

  // Wet eucalypt (W)
  class = 5;

} else {

  // Default is un-burnable
  class = 0;

}
```

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