# Applications of very high resolution atmospheric modelling for bushfires

Jeffrey D. Kepert, Robert J.B. Fawcett, Kevin J. Tory and William Thurston
Centre for Australian Weather and Climate Research, Melbourne, Australia
J.Kepert@bom.gov.au

## Introduction

Bushfire behaviour is well known to be sensitive to the weather. What is 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 strength and direction). 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 two 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 events including Black Saturday of 2009, the Eyre Peninsula fire of 2005, the Margaret River fires of 2011, the Blue Mountains fires of 2001, and the Dunalley fire of 2013. 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 will summarise some of these phenomena, and indicate the prospects for predicting them in the future, thereby improving fire-fighter effectiveness and safety. However, while our focus is on meteorology, we note that other factors, including fuels and topography, also strongly influence fire behaviour.

This paper is an interim review and summary of our research, and aims for breadth at the expense of depth. 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.

## 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, 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 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 the previous analysis with all available satellite and *in situ* meteorological observations. The boundary conditions include data on topography, sea-surface temperatures, vegetation type, and soil moisture, as well as lateral boundary conditions from the nesting process described in the next paragraph.

Models may be run at a variety of resolutions, depending upon the spacing between grid cells[1]. 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 domain – this allows weather systems to migrate into the limited-area domain. Very fine resolution can be achieved by successive nesting steps. In this project, grid spacings of down to 400 m 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 Fig. 1.

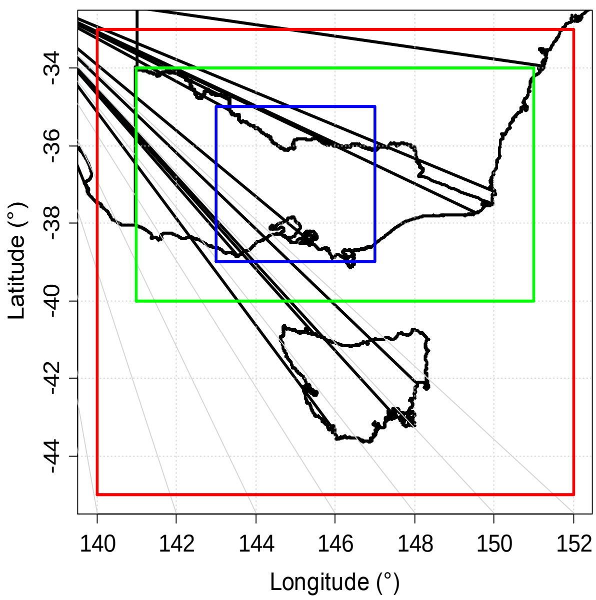


**Fig. 1:** Boundaries of the third (0.036°, red), fourth (0.012°, green) and fifth (0.004°, blue) nesting levels for the Black Saturday model runs. Model boundaries are chosen, as far as is possible, to avoid areas of elevated topography. The 0.036°-resolution model run is nested in a large regional model 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.

The NWP system used in this study is the Australian Bureau of Meteorology's ACCESS (Australian Community Climate and Earth Simulation System). It is a substantial improvement over the former LAPS system in the model dynamical core, the representation

[1] 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.

of physical processes, and the data assimilation system. Full details may be found in Puri et al. (2013).

## 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 resolution used and some physical processes, such as turbulence or convection, have to be approximated. Another source is that the initial condition and boundary conditions (both lateral and surface) are not exact. A third is that the atmosphere is chaotic, which means that small initial errors grow exponentially and eventually swamp useful information in the forecast. Therefore, it is necessary to verify forecasts.

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 object-oriented verification is our verification of the timing of the wind change on Black Saturday, in which Fig. 2 shows the difference in timing of the wind change between the model and AWS sites with a measurement frequency of 1 minute, and Fig. 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. 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 Fig. 4, which shows the observed 1-minute data at Eildon Fire Tower, together with the modelled 5-minute data at the nearest gridpoint.

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).

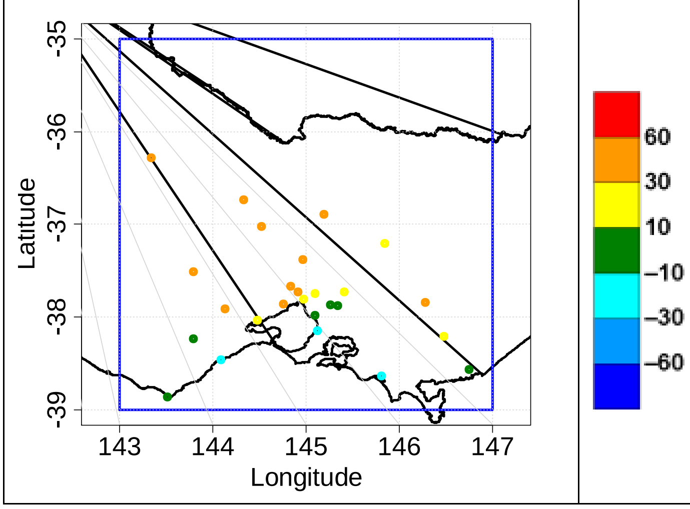


**Fig. 2:** Approximate timing errors in minutes for the location of the primary wind change on Black Saturday. Positive (*negative*) values imply that the primary wind change in the 0.004°-resolution simulation is late (*early*) relative to the change at the indicated AWS locations. The blue box denotes the model domain.

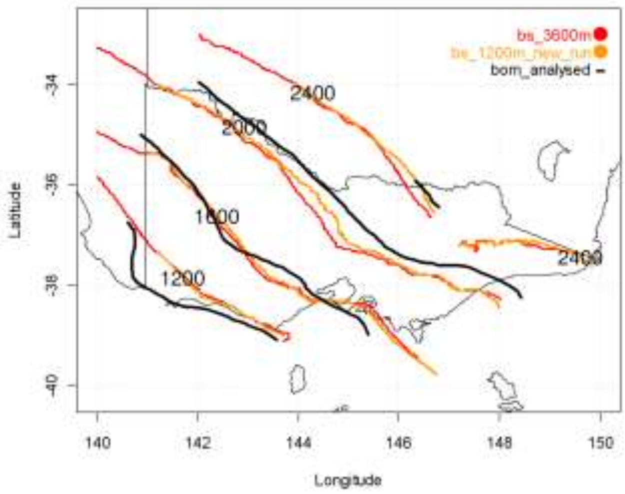


**Fig. 3:** Comparison of analysed primary wind-change positions (black lines) with model wind-change positions from the 0.036°-resolution (red lines) and 0.012°-resolution (orange lines) simulations, for 1200, 1600, 2000 and 2400 EDT (0100, 0500, 0900 and 1300 UTC) on Black Saturday. Analysed wind-change positions are from VBRC (2010). Modelled wind-change positions are determined semi-objectively from the 10-metre wind-direction field.

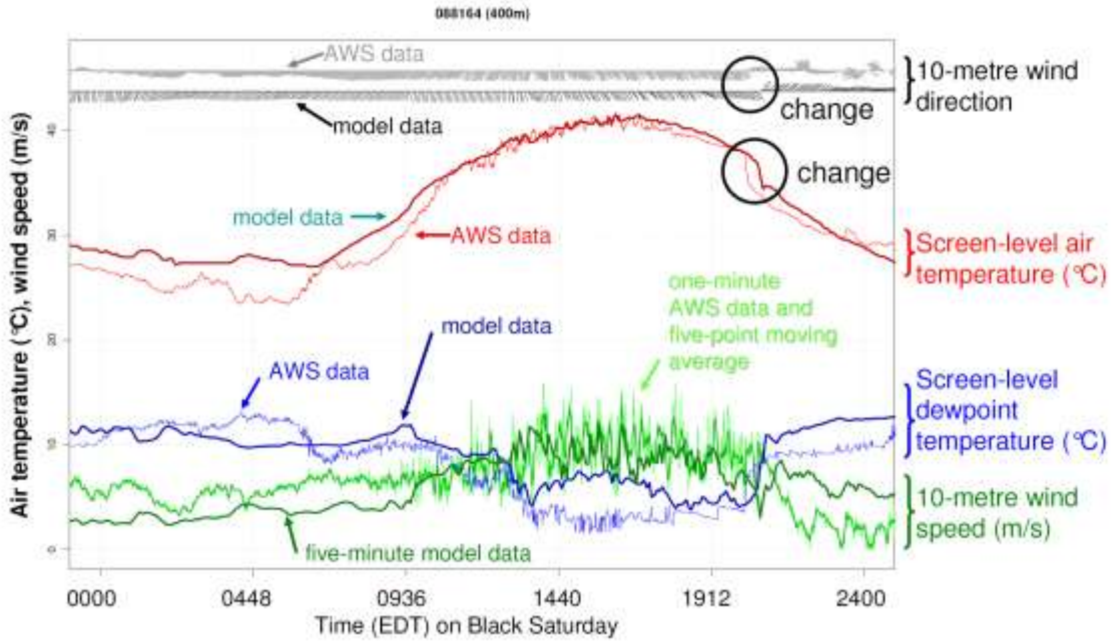


**Fig. 4:** Verification of the 400-m resolution simulation of Black Saturday against 1-minute observations from the Eildon Fire Tower. Model data is shown by thick curves and observations by thin. Meteorological variables are as annotated on the diagram. The timing of the change is indicated in the wind direction and temperature data.

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

Black Saturday, February 7 2009, was the worst fire disaster in Australia's recorded history, with 173 deaths over 2100 houses and many other buildings destroyed, and major environmental damage (VBRC 2010). The fires followed a decade-long drought, and an extreme heatwave the preceding week, which combined to cause extremely dry fuels. The fires spread exceptionally quickly, exceeding the upper limit of the expectations of experienced professionals. The spread mechanism was both direct, and due to spotting over distances exceeding 30 km, and the fires were extremely intense. The weather on the day itself was broadly similar to earlier major disasters 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 weather simulations was high. Maximum temperatures were very accurately predicted, humidity somewhat less so, while the wind speeds showed a consistent negative bias of 10 to 20 %. 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 different times. The spread of timing of the 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 06 UTC (1700 EDT) shown in Fig. 5. The simulated 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 (Fig. 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 m 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 Bushfire 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 (Fig. 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 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.

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).

.

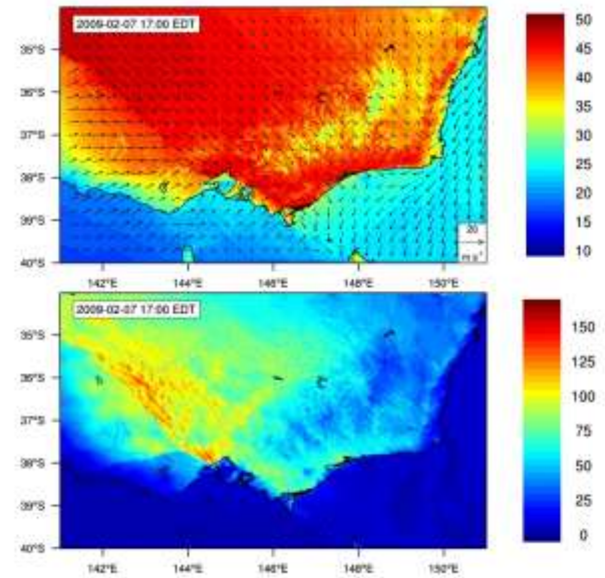


**Fig. 5:** Simulation of the surface meteorology over Victoria at 1700 EDT (0800 UTC) on Feb 7 2009. Top: 2-m air temperature (colour) and wind (vectors). Bottom: Notional instantaneous forest-fire danger index (FFDI). The dual structure of the wind change to the west is clearly apparent. The variations 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.

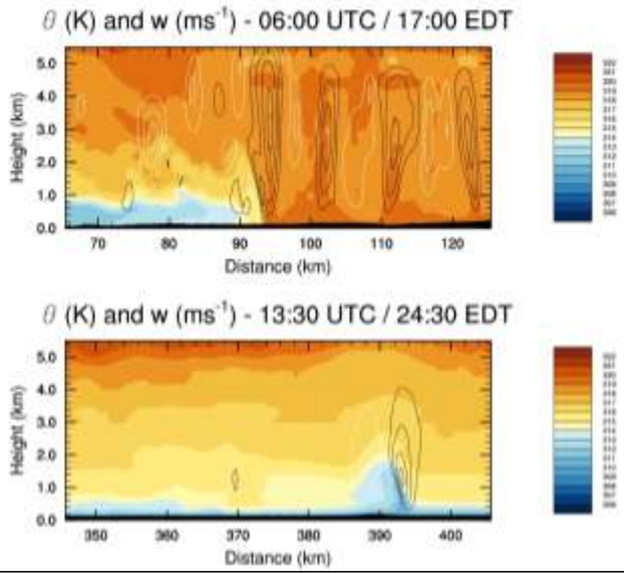


**Fig. 6:** Cross-sections of potential temperature (colour) and vertical velocity (contours, interval 1.5 m s$^{-1}$, black is upwards and white downwards motion) oriented approximately perpendicularly to the wind change at 1700 Feb 7 EDT (top) and 0030 Feb 8 EDT (bottom) on Black Saturday. During the 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.

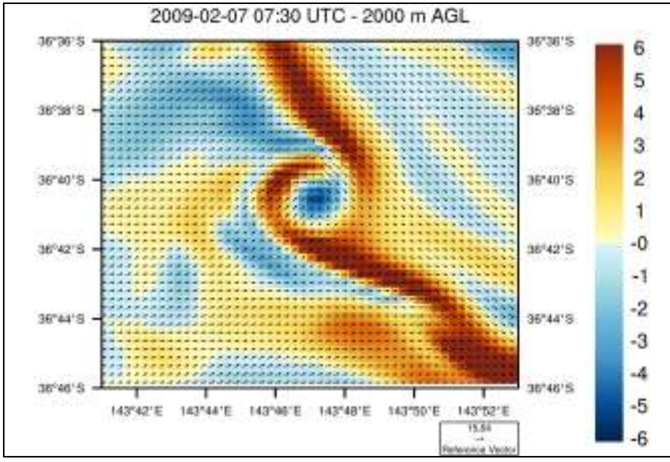


**Fig. 7**: Vertical velocity at 2000 m above ground level (shading, m $s^{-1}$) and horizontal wind at 10 m above ground level (vectors) in one of the vortices along the wind change at 1830 EDT Black Saturday.

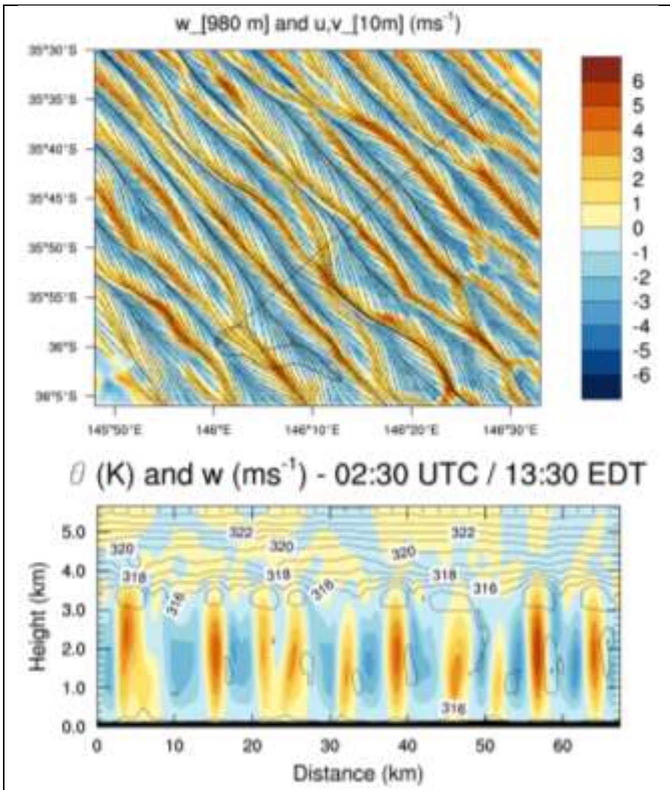


**Fig. 8:** Boundary-layer rolls at 1330 EDT (0230 UTC) on the afternoon of Black Saturday. Top: 10-m wind (streamlines) and vertical velocity at 980 m (shading). Bottom: Cross-section along the line indicated in the top panel, of vertical velocity (shading) and potential temperature (contours, K). The top of the boundary layer is where the significant potential temperature gradient begins, near 3-km height.

## The meteorology of the Margaret River fires of November 2011.

The Margaret River fire was due to a prescribed burn that escaped, with the impact including the destruction of some 30 houses and damage to others. The case is 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 as per the normal diurnal trend. This case thus stands in contrast to our work on Black Saturday: while there we were seeking to understand the details of what was already clearly extreme fire weather, here we were trying to understand why unexpectedly strong fire behaviour occurred under what were expected to be benign conditions.

Modelling of the meteorology 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 over-land winds in the region. Figure 9 shows a plan view of the 10-m wind speed and direction at 8 am LST, showing the strongest winds in the lee of the hill, while Fig. 10 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 Fig. 10. 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.

Given the very 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).

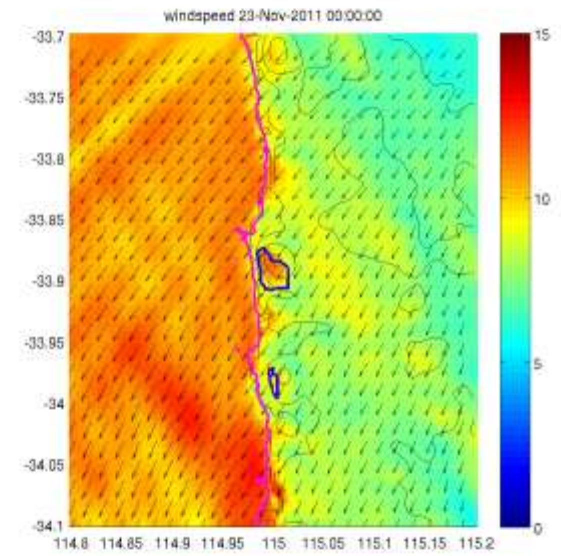


**Fig. 9**: Surface wind speed (shading, m $s^{-1}$) and direction (arrows) at 0800 WST (0000 UTC) on November 23 in the 400-m ACCESS simulation. The topography is shown by the black contours at 50-m intervals, the coastline by the magenta line, and the two prescribed burn areas are outlined in blue, with Ellenbrook being the northern one. The coincidence of the strongest winds with the burn area is clear.

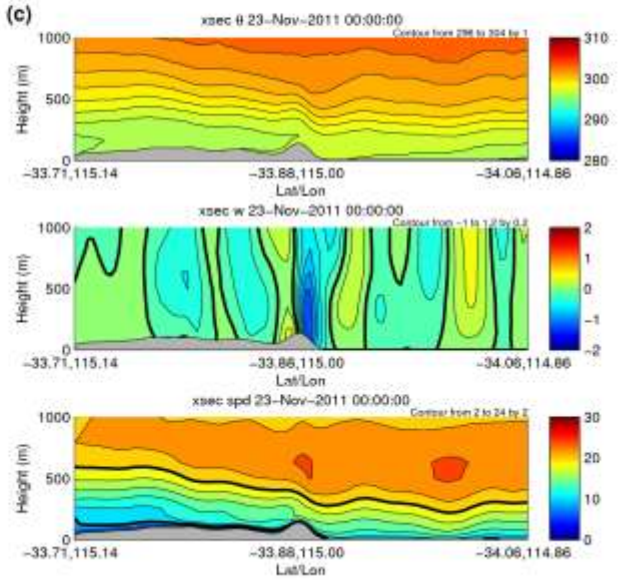


**Fig. 10**: Cross-sections through the Ellenbrook fire ground at 0800 WST (0000 UTC) on November 23 2011 from the 400-m ACCESS simulation. Top: potential temperature (K). Middle: Vertical velocity (m $s^{-1}$). Bottom: Wind speed (m $s^{-1}$). The cross-sections are aligned with the wind direction at 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.

## 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 southwesterly winds behind the wind change and reached North Shields, 35 km from the original fireground. The fire caused 9 deaths and 115 injuries. 77,964 hectares of land were burnt, with 47,000 in stock losses and around $100 million in total property damages

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 (Fig. 11). 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 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 northwesterlies 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 affect on fine-fuel dryness, and was attributed to a narrow band of subsidence followed by strong vertical mixing within the boundary layer (Mills 2008). An 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).

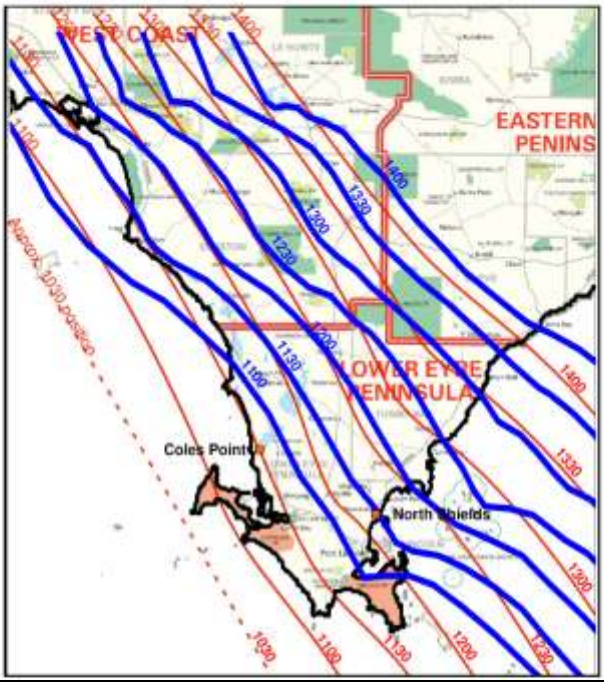


**Fig. 11:** Comparison of modelled (blue lines; 0.012°-resolution model run) and analysed (red lines) wind-change isochrones at half-hour intervals across the Lower Eyre Peninsula from 1100 to 1400 CDT (0030 to 0330 UTC) on 11 January 2005.

## The meteorology of the Warragamba / Mount Hall fire, 24 – 25 December 2001.

Of the fire weather cases investigated so far, this one is the earliest (December 2001), has the most orography, and is the least successful in terms of the accuracy with which the simulations reproduced observations. 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) (Fawcett et al. 2012c,d).

The relatively poor simulation is possibly due to the quality of the ERA-Interim (ECMWF Interim Reanalysis) initial condition, although we tried initialising from several different times without significant improvement from our original simulation. We note however that an ERA-Interim initial condition was also used in the later and more successful Eyre Peninsula simulation for January 2005, discussed in the previous section. The complex topography may be another factor, since the forecast wind direction in the Warragamba valley was not consistent with the reconstructed fire spread. 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 occurred 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. Rather, it illustrates the importance of thorough verification before the fields are used.

On the afternoons of 24 and 25 December 2001, the 0.004°-resolution simulation shows winds from the westerly quadrant crossing the simulation domain from west to east (see Fig. 12). There is an impression of the orography of the Blue Mountains causing “streamers” (coherent patterns of variation in 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).

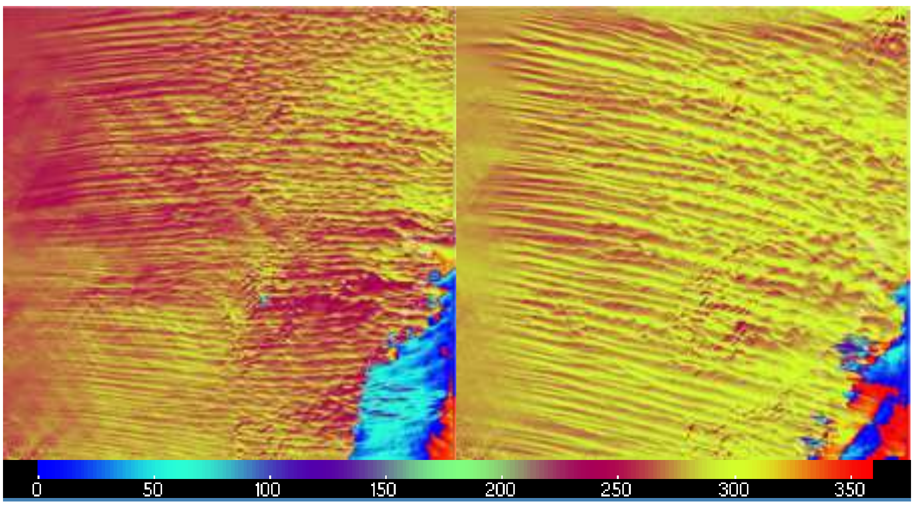


**Fig. 12:** Wind direction at 1400 EDT (0300 UTC) on 24 December (left) and 25 December (right), from the 0.004°-resolution simulations.

## 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 these extra simulations follows.

- *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 of the simulation for this event 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 for this fire event in central Victoria that destroyed at least 16 homes. Verification showed that the simulations were of good quality. Figure 13 shows a model verification plot for Hopetoun Airport in western Victoria from these simulations.
- *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. 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.

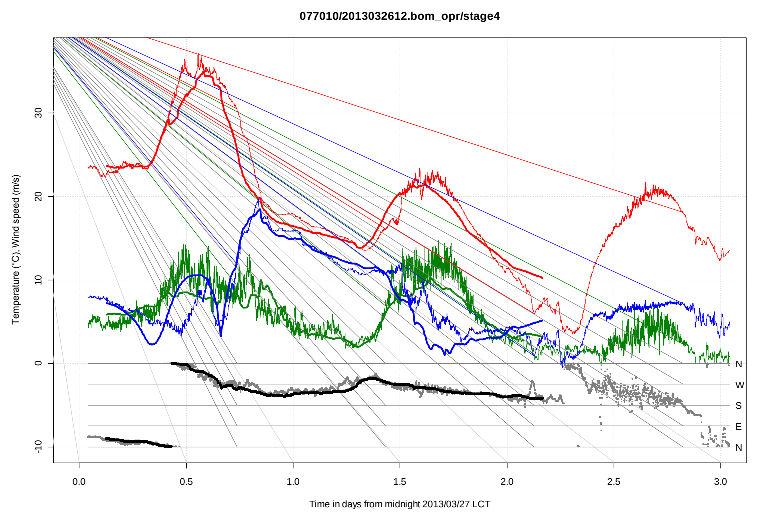


**Fig. 13:** Comparison of modelled (thick lines, black dots 0.012°-resolution model run) and observed (thin lines, grey dots) air temperature (red lines), dewpoint temperature (blue lines), wind speed (green lines) and wind direction (dots) for Hopetoun Airport in the Dereel fire case study. At this site, there is a high degree of consistency between the model and observations

## 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 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 three of the cases, Black Saturday, Eyre Peninsula 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.

We note also that errors in weather forecasts that may be small by meteorological standards may nevertheless have a significant impact on the course of a fire. For example, meteorologists would generally regard a forecast of a wind change with a timing error of only

30 minutes as being very good. That error, however, leads to a substantial error of 7.5 – 10 km in predicting the spread of a grass fire moving at 15 – 20 km/hr. While weather forecasts will continue to improve, they will never be perfect. It is therefore incumbent upon fire agencies to join the growing body of forecast users who are actively and explicitly accounting for forecast uncertainty in their operations, through the use of technologies such as ensemble prediction.

This paper has focussed on the possible impact of meteorological phenomena on fire behaviour. We note that other factors are also important, including fuels and topography.

The research described here was undertaken as part of the FIRE-DST project and was partially supported by the Bushfire CRC. All publications resulting from this project are available at http:/www.bushfirecrc.com/category/projectgroup/2-risk-assessment-and-decision-making.

## References

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, August 28 to 30.*

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, August 28 to 30.*

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, 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, September 2 to 5.* In preparation.

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, September 2 to 5.* In preparation.

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

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. *Extended abstracts, 20th International Congress on Modelling and Simulation, Adelaide, December 1 to 6.* Submitted.

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. *Extended abstracts, 20th International Congress on Modelling and Simulation, Adelaide, December 1 to 6.* Submitted.

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. *Papers presented at the Science to Wervices Workshop, Bureau of Meteorology, Melbourne, August 15 - 16.* Submitted.

Gellie, N, J D Kepert, K Tolhurst, C Rudiger and S Harris, 2012: Conceptual Framework for Assessing Seasonal, Daily, and Hourly Landscape Moisture and Fuel Energy. *Poster, Annual Conference of the Australasian Fire and Emergency Services Council and the Bushfire Cooperative Research Centre, Perth, August 28 to 30.*

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, August 29 to 31.*

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, August 29 to 31.*

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, August 29 to 31.*

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, August 29 to 31.*

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, August 28 to 30.*

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, August 28 to 30.*

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, September 2 to 5.* 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, December 1 to 6.* Submitted.

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

Mills, G.A., 2008: Abrupt surface drying and fire weather. Part I: overview and case study of the South Australian fires of 11 January 2005. *Aust. Meteorol. Mag.,* **57**, 299-309.

Puri, K., G. Dietachmayer, P. Steinle, M. Dix, L. Rikus, L. Logan, M. Naughton, C. Tingwell, Y Xiao, V. Barras, I. Bermous, R. Bowen, L. Deschamps, C. Franklin, J. Fraser, T. Glowacki, B. Harris, J. Lee, T. Le, G. Roff, A. Sulaiman, H. Sims, X. Sun, Z. Sun, H. Zhu, M. Chattopadhyay, C. Engel, 2013: Implementation of the initial ACCESS numerical weather prediction system. *Aust. Meteorol. Ocean. J.,* **63,** 25-284.

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, August 28 to 30.*

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, August 28 to 30.*

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, 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. *Extended abstracts, 20th International Congress on Modelling and Simulation, Adelaide, December 1 to 6.* Submitted.

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.

Skamarock, W.C., 2004: Evaluating mesoscale NWP models using kinetic energy spectra. *Mon. Wea. Rev.,* **132**, 3019 – 3032.

Victorian Bushfires Royal Commission Report, 2010: *2009 Victorian Bushfires Royal Commission Final Report*. The State of Victoria. Government Printer for the State of Victoria, Melbourne, Australia.