Case studies and preliminary WRF-fire simulations of two bushfires in sea breeze convergence zones

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Abstract

From time to time, bushfires exhibit fire behaviour that was never anticipated in the prevailing environmental conditions. The Layman burn, in scenic southwest Western Australia, and D'Estrees Bay fire, on pristine Kangaroo Island, were two such fires. Both developed intense crown fires, high flames and convection columns with a deep vertical circulation that extended through the lower part of the atmosphere. In both cases, the intense fire activity was driven by a combination of meteorological processes not routinely assessed in fire environments. Low level sea breeze convergence and vertical circulation on the sea breeze front, combined with potentially unstable vertical temperature and moisture profiles conducive to convective parcel motion as measured by FireCAPE, as well as entrainment of dry air from aloft desiccating already climatologically dry fuels, were all present. It is believed that these co-located elements produced the intense conflagrations.

Improved understanding of how the processes described above impact fire behaviour may mitigate against such events in the future - or at least better anticipate their potential in advance. Coupled fire-atmosphere simulation models have the potential to further our understanding of fire and atmosphere interactions. Simulation results with the coupled fire-atmosphere model WRF-fire provides insight into current ability to reproduce the feedback processes observed in the case studies.

Contents

1 Introduction

The initial phase of our research has been two case studies investigating the interactions between local meteorology and unexpected fire behaviour at the D'Estrees Bay and Layman fires (Peace and Mills [2011] and Peace (in preparation)). Both fires were located in local sea breeze front convergence zones and produced spectacular convection columns that developed in an atmosphere where potential instability was present. Subsequent to the case studies, our focus has been on simulating the fires using the coupled atmospheric-fire behaviour model WRF-fire.

The Kangaroo Island and Layman events, in concert with other (published) case studies, unpublished events and anecdotal evidence, shows that vertical atmospheric dynamics and feedback processes frequently and significantly impact bushfires and prescribed burns in Australia (see, for example Mills [2005], Mills [2008b] Mills [2008a] Fromm et al. [2006] as well as the Black Saturday fires of 2009). This repeatedly manifests as fire behaviour that would not be anticipated by consideration of the surface weather elements temperature, relative humidity and wind alone. In order to anticipate fire behaviour; vertical, temporal and spatial structure of the atmosphere must all be considered.

The circumstances leading to unusual fire behaviour highlights limitations in the current Australian approach to forecasting fire weather conditions, which are based on the McArthur indicies [McArthur, 1962][McArthur, 1966]. The point forecasts of meteorological parameters considered in the McArthur system provide an incomplete picture, as they neglect to describe temporal and spatial variations that may have an important influence on fire behaviour. Additionally, current forecast ratings are contingent on precise predictions of near surface wind, temperature and humidity, omitting detail on three dimensional atmospheric evolution. It is clear that Australian fire weather forecasting should place greater emphasis on vertical atmospheric profiles, convergence zones, dry air entrainment and low level stability (as well as non-meteorological factors such as topography and fuel).

A factor that further complicates understanding of fire weather processes is fire atmosphere coupling. Numerous studies (most notably Clark et al. [1996]) describe feedback processes between the fire and the atmosphere. Most recently in Australia, fire atmosphere feedback during the 2009 Black Saturday fires was clearly apparent and is a topic of current research. The evidence is convincing also that fire atmosphere interaction occurred in the Kangaroo Island and Layman fires. Fire behaviour and fire spread models such as WRF-fire [Mandel et al., 2011] have the potential to contribute to contemporary fire science in understanding these feedback processes.

To extend our findings from the case studies, WRF-fire has been run (in real, as distinct from idealised mode) on two days of unusual fire behaviour during the 2007 Kangaroo Island bushfire event. One day was the D'Estrees

Bay fire, which will be described in this paper and the second the Rocky River fire, when topographic channelling, dry air entrainment and heavy fuels are believed to have caused the observed fire behaviour [Peace and Mills, 2011]. The results so far demonstrate the model can be successfully run using Australian data and our provide useful insights into the current state of coupled modelling and its ability to reproduce phenomena hypothesised from the case studies. A number of avenues for future research have been identified in the course of these simulations. The Layman and D'Estrees Bay fire case studies will be described in the next two sections, followed by a description of the WRF-fire simulations.

2 The Layman fire

The Layman fire started as a fuel reduction burn on the 16th October 2010. Weather conditions were benign, with similar conditions forecast to continue for the next few days. Late morning on the day following ignition, fire activity escalated rapidly, transitioning from a controlled surface litter and understorey burn to a fire with a well developed convection column and a deep vertical circulation that extended through the lower part of the atmosphere. Low level sea breeze convergence in the wind field combined with potential instability by the process of FireCAPE, entrainment of dry air from aloft desiccating already climatologically dry fuels and vertical circulation on the sea breeze front were all present in the environment. It is believed that these co-located elements produced the intense conflagration.

The transformation in fire behaviour is most clearly seen in the two MODIS images (Figures 1 and 2) taken just $4\frac{1}{2}$ hours apart, showing the dramatic change in fire size and fire behaviour.

Figure 1: NASA Terra satellite Moderate-Resolution Imaging Spectroradiometer (MODIS) image 0200UTC (10am local time) Sunday 17th October

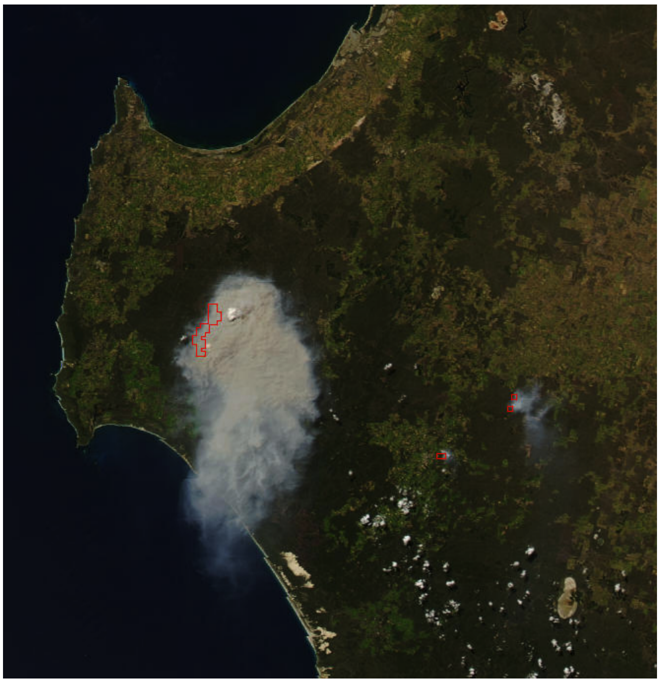

Figure 2: NASA Aqua satellite Moderate-Resolution Imaging Spectroradiometer (MODIS) image 0620UTC (2:20pm local time) Sunday 17th October

Figure 3 shows the convection column over the fire. There are three features to note in this image. The first is the vertical extent of the convection column. The second, the apparent near-surface convergent inflow from all directions and third, the smoke shield spreading out in the top left of the picture. Some of these features are worth cross referencing with Figure 2. One is the extensive area of smoke seen from above in Figure 2, which is likely to be at the same level as the smoke shield seen from below in Figure 3. Another is the white circular "lump" embedded in grey smoke near the active (red outlined) fire area in Figure 2. This is likely to be cloud which has developed by convection "punching through" the level of the smoke shield. The shadow on the southern edge suggests the cloud is significantly higher than the surrounding smoke. The final point to note from Figure 2 is the presence of two (smaller) fires further east, burning in comparable fuels. These fires show dissimilar fire behaviour to the Layman fire, suggesting that although the dryness of local fuels was likely to have been a contributing factor, it was not the dominant factor in the development over the Layman site.

Figure 3: Aerial image of the convection column above the Layman fire. Taken on the northern boundary of the burn, looking towards the south, between 1:20pm and 1:30pm. Picture provided by Department of Environment and Conservation WA.

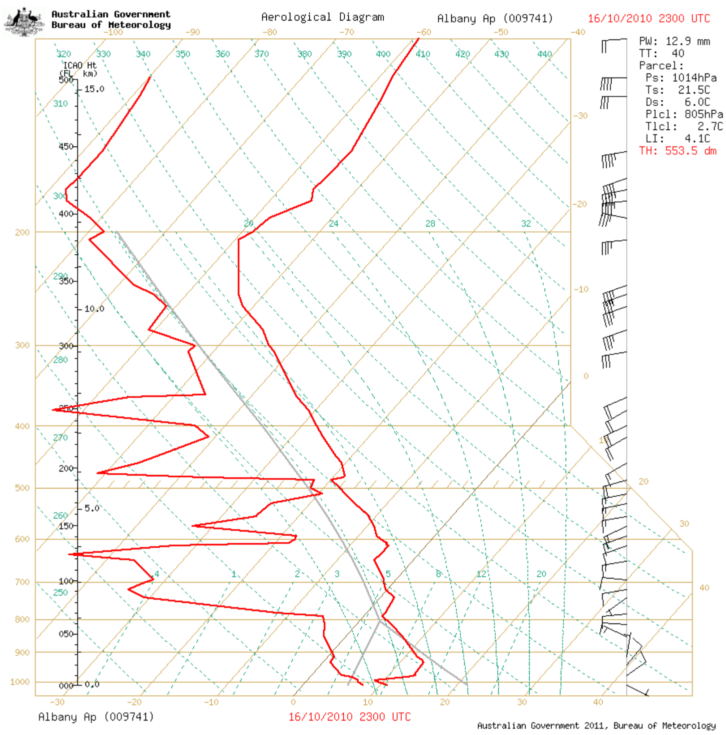

Figure 4: Albany vertical profile of temperature and dewpoint temperature 2300UTC 16th October. Albany is approximately 245km southeast of the fire site.

The temperature profile from Albany (Figure 4) provides insights as to the mechanism for convective development, however, in order to describe the processes that occurred, the concept of fire modified CAPE [Potter, 2005] or FireCAPE must be introduced.

Combustion of cellulose (wood) creates carbon dioxide and water. Approximately half a tonne of water vapour is released for each tonne of fuel consumed. The released water vapour is mixed through the low levels of the atmosphere over the fire site (to an uncertain depth). Consequently, the mixing ratio above the fire is elevated from background environmental levels. Additionally, the heat generated increases temperature in the vicinity of the fire. Potter [2005] proposed that, at a fire site with a given vertical temperature profile, surface dewpoint and surface temperature may be incremented to account for the moisture and heat released by the fire. Conceptually, this is similar to modifying surface conditions to account for diurnal heating and calculating convective available potential energy in a thunderstorm environment, hence the alias “FireCAPE”. Research to date has not resolved the vertical and horizontal extent of the fire influence and appropriate values of temperature and water vapour remain uncertain, however 1-5°C and 1-3g/kg may be considered approximate starting values.

Application of the FireCAPE concept to the Albany profile (Figure 4) produces the following insights. Surface values of 6-7g/kg and 26-28°C produce free convection from 800hPa to the inversion just below 600 hPa. This suggests development of a vertical circulation to 4000m, which is consistent with the vertical column extent seen in Figure 3. Also seen in Figure 3 is the smoke shield spreading at a constrained height. The presence (and height) of this smoke shield agrees with the supposition that the convection is hitting the inversion from beneath and spreading horizontally (in much the same way as a thunderstorm may generate a cirrus shield at the troposphere).

Further insight into the vertical structure over the fire can be made by examining Figures 2 and 4 in combination. As noted earlier, the white circular "lump" embedded in the grey smoke shield is likely to be convective cloud that has "overshot" the surrounding smoke. This is again consistent with the Albany profile, which shows that (given sufficient surface heat and/or moisture) a vertically accelerating air parcel could convect past the inversion near 600hPa and continue unimpeded to $\approx$500hPa, with cloud forming due to the shallow layer of moisture near that level. A cloud height of 500hPa also correlates with the shadow seen on the southern edge of the cloud in Figure 2.

A history of dry air over the fire site provides another element to the development of unexpected fire behaviour. Figure 5 shows water vapour imagery 36 hours before the rapid fire development. Examination of observation and numerical weather prediction guidance from the Australian Bureau of Meteorology's operational model "ACCESS" indicates that in the intervening period the dry air subsided from near 200hPa to a layer between 800 and 600hPa.

By reference to the Albany profile (Figure 4), entrainment of the dry air by the fire's convection column was possible if the vertical circulation created by the fire extended from the surface to the inversion near 600hPa. Mixing of dry air from aloft has significant implications for fuel dryness and subsequent fire activity [Mills, 2005]. The moisture response time of fine fuels is of the order of 1 hour, well within the time frame for entrainment to impact fire behaviour. A decrease of fuel moisture of 1-2%, may, double or triple fire activity due to the near exponential effect of fuel moisture on fire behaviour (Catchpole et al. [2001] and pers. comm. Dr. L. McCaw, 2011).

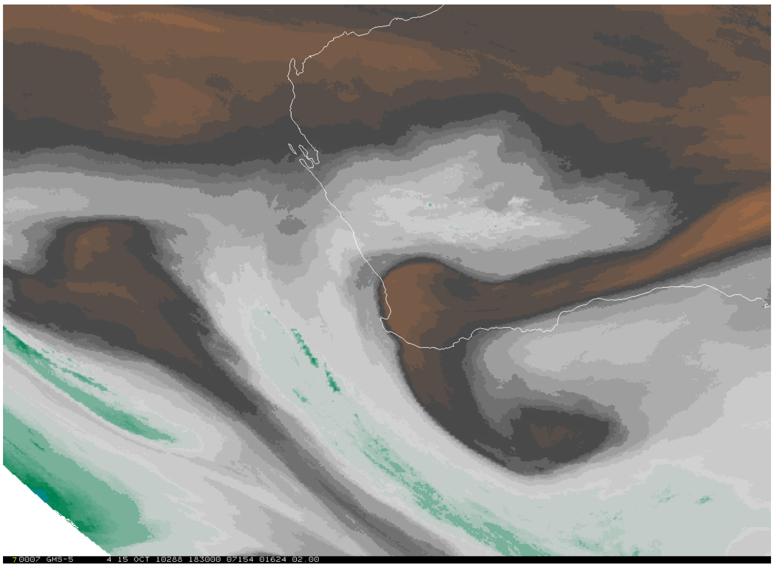

Figure 5: Water vapour image 1830UTC 15th October. Colour enhancement shows very dry air as brown and moist air as green

The operational forecast grids in figure 6 show convergence over the fire location at the intersection of three sea breeze boundaries from the south, west and north. The strongest sea breeze is from the south, due to the highest temperature gradient in the southerly direction, as well as enhancement of the sea breeze front by extension of a weak frontal change over the ocean. The aerial photograph (Figure 3) was taken at approximately the same time, when the fire was in the centre of broadscale convergence (see Figure 6), but still well ahead of the direct vertical circulation on the frontal line.

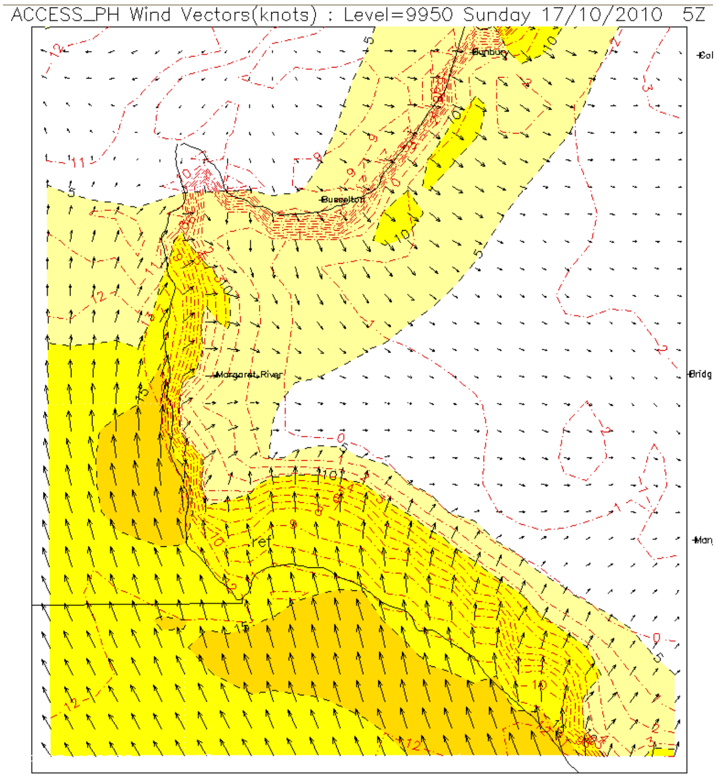

Figure 6: ACCESS-Perth sigma level .995 wind vectors (knots) (shaded yellow) and Td (red dashed contours) at 0500UTC (1pm)

The fire behaviour and observations from the Layman fire, by analysis of meteorological observations and NWP data, can be reconciled with mesoscale (or microscale) meteorological processes in the area and interaction between the fire and atmosphere. However, conventional approaches to predicting fire behaviour from prevailing weather conditions would be extremely unlikely to have anticipated the fire intensity that occurred.

3 Kangaroo Island D'Estrees fire

In early December 2007, dry lightning ignited a number of bushfires on Kangaroo Island, off the coast of South Australia. Four fires continued to burn for a two week period, one of these was near D'Estrees Bay on the southeast corner of the island. On the 8th December, in weak synoptic flow, the D'Estrees fire developed a spectacular convection column, signalling fire behaviour distinct from the other active fires on the island. As with the Layman event, the fire was located in a sea breeze convergence zone, with a vertical atmospheric profile showing potential instability through the low to mid-troposphere.

Figure 7 shows the smoke plumes at 3:35pm on the 8th December. Comparison of the four active fires shows dramatic development at the D'Estrees fire (on the southeastern side of the island). The D'Estrees plume is the largest in extent and densest in opacity of the plumes from the (four) active fires, indicating greater energy release and a more intense fire. Analysis of the plume direction and wind regime shows that the plume was significantly higher than the other fires.

Figure 7: NASA Terra satellite Moderate-Resolution Imaging Spectroradiometer (MODIS) image 3:35pm 8th December 2007. Red indicates active fire area, where fire is not obscured by cloud.

The Adelaide radiosonde plot (figure 8) shows the evolution of atmospheric stability between 1200UTC on the 7th and 1200UTC on the 8th. Cooling and destabilisation occurred above 850hPa associated with an approaching front. The subsidence inversion evident on the 7th near 780hPa had broken down 24 hours later. Potential for vertical convective development was thus enhanced on the 8th due to the decreasing stability.

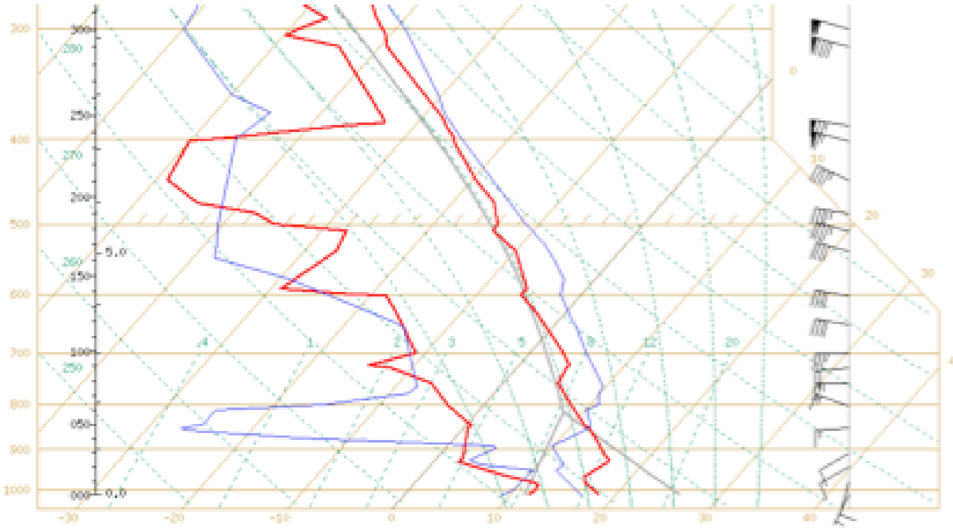

Figure 8: Adelaide airport vertical temperature and dewpoint temperature profile for 1200UTC 7th December in blue and 1200UTC 8th December in red. Wind barbs for 1200UTC 8th December.

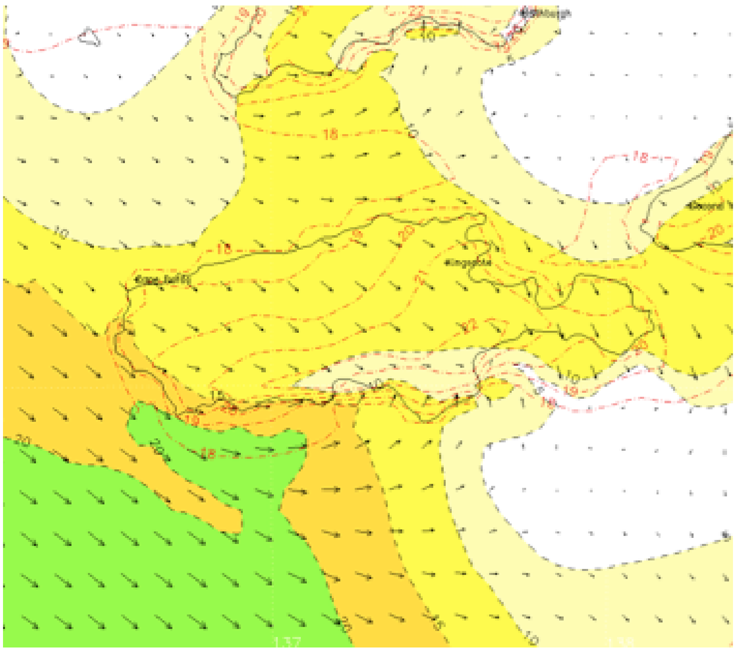

Figure 9: Meso-LAPS winds (knots) centred on Kangaroo Island at 04z 8th December 00z model run, 9943 sigma level (approx 45m above sea level). White 0-5knots, beige 5-10knots, yellow 10-15knots, pale brown 15-20knots, green 20-25knots. Red dashed lines temperature deg C.

At the time of plume development, the smoke from the other fires is directed towards the east (see figure 7), consistent with a plume height to around 800-900hPa (refer wind barbs of figure 8), whereas the plume from the D'Estrees fire has spread to the southeast, indicating a plume height to 750hPa or above. The plume spread direction, opacity and extent indicate that fire activity at the other active fires was not significantly affected by the decrease in stability. By comparison, the D'Estrees fire was able to realise the weak convective instability aloft to produce a deeper, stronger smoke plume that may be better described as a convection column.

Examination of the Meso-LAPS[1] low-level wind field (figure 9) provides insight as to how the D'Estrees fire interacted with the potential instability. Figure 9 shows convergence over the southeast corner of the island, (coincident with the fire site) between the northwesterly synoptic flow and the sea breeze. Elevated dewpoint temperatures in the onshore, moist sea breeze airstream would also contribute to moist convective potential in the vicinity. In addition, temperatures in the southwest corner are the highest on the island (shown in figure 9 as red dashed contours), due to the land trajectory to the northwest.

The discussion and figures above provide evidence the local temperatures and enhanced sea breeze convergence over the D'Estrees fire produced mesoscale (or even microscale) meteorological conditions that were significantly different to those over the other fires on the island. Examination of the atmospheric vertical profile shows that potential instability existed in the area and it is likely that the local meteorological conditions at the D'Estrees fire enabled the potential instability to be released, producing a deeper, denser plume than at the adjacent active fires.

4 Discussion

The case studies of the D'Estrees Bay and Layman fires describe two occurrences of unexpected fire behaviour when fires located in sea breeze front convergence zones produced spectacular convection columns in atmospheres that were potentially unstable in the low to mid levels. Little research exists on the impacts of convergent winds and flame residence time, as most experimental fires emphasise the wind effects of fire spread rather than fire intensity. However, evidence (particularly from the Layman fire observations) indicates fires in convergent zones produce greater intensity fires due to longer flame residence time and increased likelihood of crown fires, resulting in more efficient combustion and the burning of heavier fuels.

There is strong evidence that a fire-atmosphere feedback loops were generated in the D'Estrees and Layman fires. The case studies illustrate how three dimensional information as well as temporal evolution can be impor-

[1]Meso-LAPS was the Bureau of Meteorology's operational forecast model in 2007

tant in driving fire behaviour and the fires described developed unexpectedly due to a combination of meteorological factors not routinely assessed in the fire environments. So far, examination of meteorological processes such as those described here has been qualitative. How to transition current qualitative knowledge into a to quantitative assessment is an unclear pathway due to the non-linear nature of these processes and their interactions. However, convincing evidence shows these (non-linear) processes impact fire behaviour and should therefore be considered.

Subsequent to the meteorological case studies, our interest turned to whether the phenomenon we observed could be captured in a fire behaviour model. We took this approach because we believe that fire behaviour models have an important contribution to make in improving fire forecasting techniques. For this study, our aims were to determine whether we could run WRF-fire on an Australian event, and then to examine whether the coupled model was successful in capturing the vertical atmospheric structure and fire behaviour seen in the case study.

5 WRF-fire simulations

WRF-fire comprises the Weather Research and Forecasting model coupled with a fire behaviour model Mandel et al. [2011]. The algorithms for fire spread and fuel combustion in WRF-fire are based on the model of Rothermel [1972] using the fuel descriptors of Anderson [1982]. A level-set method is employed for propagation of the fire front across the model terrain, again following Rothermel's parameterisation for fire spread.

WRF-fire is the successor to the CAWFE model, described in Clark et al. [1996], in which the role of coupling in fire-line dynamics was also shown. Mandel et al. [2011] provides a comprehensive and current description of the WRF-fire physical model, the numerical algorithms used, the software structure and future development plans for the model. WRF-fire has been has been used for several real simulations; however, as noted by Mandel et al. [2011], a larger set of case studies is required in order to validate the model.

The coupled atmospheric-fire behaviour model WRF-fire has been used to simulate two days of the Kangaroo Island fires when unusual fire behaviour occurred. Our aims have been to: (1) test the ability for WRF-fire to be run on a real event, using available Australian data; (2) explore the capabilities of WRF-fire, in particular by assessing the models' skill in capturing aspects of fire behaviour observed during the case study and; (3) provide evidence to contribute towards current discourse on advancing fire weather forecasting in Australia.

These aims have been addressed by (1) a successful (albeit with potential for improved verification) run of the Kangaroo Island bushfires. (2)

Verification shows that WRF-fire captures some, but not all, of the phenomenon observed (limitations include differences in inferred height of convection columns and accuracy of fire spread through terrain). (3) Simulations show that WRF-fire may be run in near-real time and, through available visualisation tools, produce output that may be interpreted by a range of users.

Our WRF-fire model domain, physics and dynamics options were determined by a combination of reference to Mandel et al. [2011], Dobrinkova and Jordanov [2010], Beezley et al. [2010] and Coen [2005], in addition to trial and error. Our model configuration is undergoing further testing and may be improved in future.

From the case studies, there were two main atmosphere-fire coupling phenomena we wanted to explore. The first was to examine the hypothesis that the convection column may have enabled dry-air entrainment from above a subsidence inversion. The second was to explore the interactions between potential instability, sea breeze convergence and subsequent convection column development. In order to do this WRF-fire has been run on two fires on Kangaroo Island - the D'Estrees Bay fire described above and a second fire at Rocky River fire. Figures 10 and 11 show output from the two simulations.

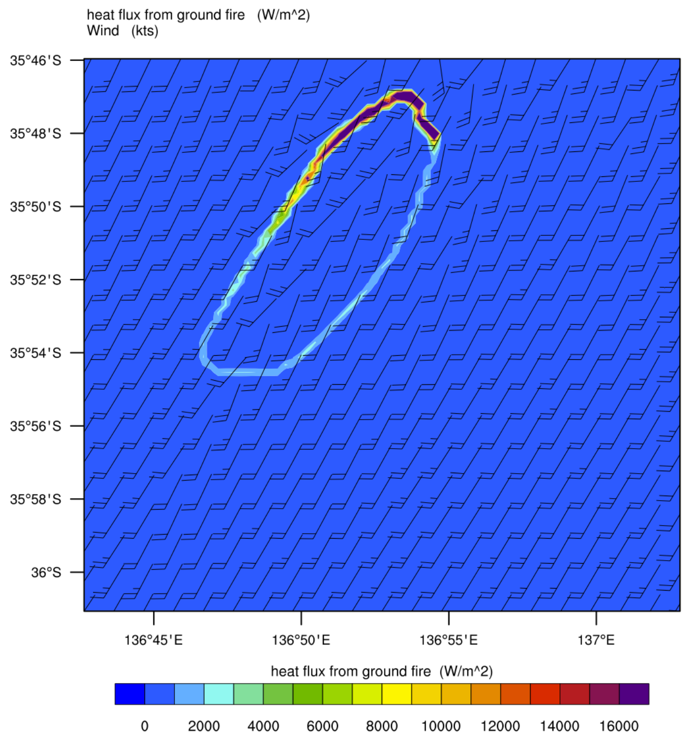

Figure 10: Ground heat flux from the Rocky River fire as a proxy for fire perimeter and 10m wind vectors

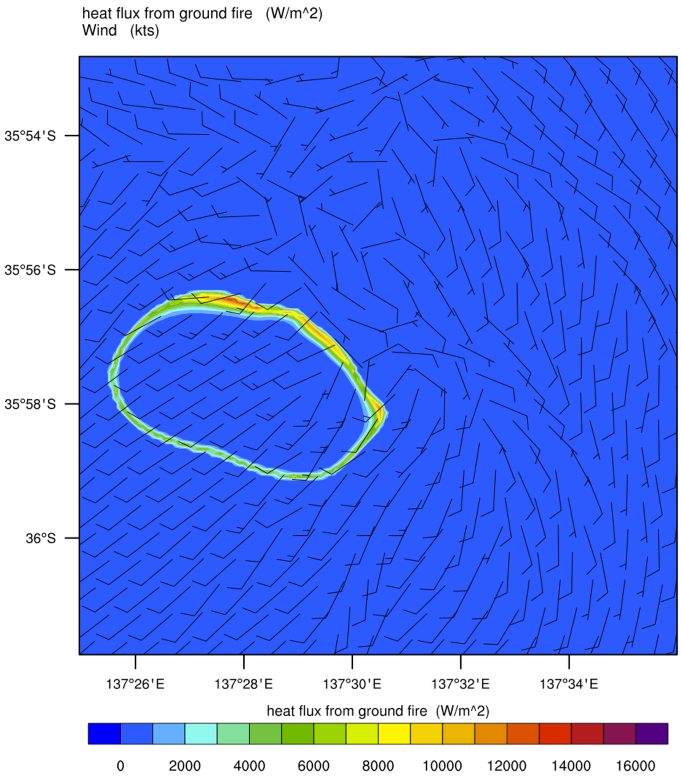

Figure 11: Ground heat flux from the D'Estrees Bay fire as a proxy for fire perimeter and 10m wind vectors

Analysis of the vertical structure of the simulations did not show enhanced fire behaviour due to dry air entrainment. This is not unexpected, as the fire equations in WRF-fire have no dependence on temperature or humidity and fuel dryness is input a constant, not a dynamic parameter. Examining vertical motion cross-sections suggests entrainment of dry air from above a subsidence inversion by fire convection was possible, however further evidence is required to conclusively demonstrate this.

Our simulations of the D'Estrees fire did not show strong convection column development above the fire. Two reasons are proposed; the vertical profile over the fire ground showed a low level inversion that may have inhibited vertical development. Alternatively; the heat and moisture fluxes produced from the propagating fire line and constrained burn time in our simulated fire may not have been of sufficient magnitude to generate vertical development.

WRF-fire provided valuable insights into our questions regarding (1) fire-atmosphere coupling and (2) current ability to reproduce observed phenomena by numerical simulation. Our research goals are to continue to explore case studies in combination with simulations in order to better understand the role of atmospheric stability, just one element of the work required to progress fire science. In future WRF-fire simulations, we intend to incorporate higher resolution topography and vegetation data to the simulations described here. A further research avenues is idealised simulations exploring the processes described in the case studies.

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