Meteorological dynamics in a fire environment; a case study of the Layman prescribed burn in Western Australia

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From time to time, bushfires exhibit fire behaviour that was never anticipated in the prevailing environmental conditions. The Layman fuel-reduction burn, in scenic southwest Western Australia, was one such fire. The burn was ignited in mid-October 2010 in benign weather conditions. Late morning on the day following ignition, fire activity escalated rapidly; a convection column developed with a deep vertical circulation that extended from the surface to a height of 4 km. The ensuing intense fire with tall flames caused extensive crown scorch and defoliation, and resulted in concerns about the safety of rural communities adjoining the planned burn. The observations and meteorological model data indicate that the intense fire activity was driven by a combination of meteorological processes not routinely assessed in fire environments. Low-level sea breeze convergence in the wind field, combined with potential instability in the presence of FireCAPE, entrainment of dry air from aloft desiccating already climatologically dry fuels and vertical circulation on a frontal change were all present. The dramatic development of the Layman burn shows how meteorological processes not currently embedded in fire science may produce an environment conducive to intense fire activity. The ways in which fire managers might incorporate innovative meteorological products identified in this paper in order to mitigate against such events in the future are discussed.

Introduction

The Layman prescribed burn was lit on 16 October 2010. On the day following ignition, the fire developed rapidly, transitioning from the intended controlled surface litter and understorey burn to an intense fire with deep vertical circulation. The ensuing intense fire with tall flames caused extensive crown scorch and defoliation, and resulted in concerns about the safety of rural communities adjoining the planned burn.

The intense fire behaviour was unexpected in the prevailing environmental conditions, which were seemingly benign from a fire weather perspective. This case study explores the meteorology in greater detail than is possible in real-time operations, and the complexity of the local weather processes suggests there are good reasons for the fire behaving as it did.

In Australia at present, fire weather forecasts are embedded in the McArthur Fire Danger Meters for forest and grassland in southeastern Australia (McArthur 1962, 1966, Luke and McArthur 1978) and the Forest Fire Behaviour Tables of Sneeuwjagt and Peet (1985) in Western Australia. The emphasis of the fire weather forecast is a precise prediction, for a specific location and at a given time, of near-surface temperature and relative humidity, as well as wind speed at a height of 10 m. Vertical temperature and wind structure, spatial variation, temporal changes, or three dimensional evolution of the atmosphere are not explicitly (or even implicitly) considered in the fire indices.

This study will proceed by describing the Layman burn, then explore the meteorological environment that is believed to have contributed to the observed fire behaviour. A number of processes that are believed to have contributed to the fire behaviour at Layman will be described, including:

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sea breeze convergence, potential instability, dry-air entrainment and pre-frontal circulation. The concept of fire-modified convective available potential energy (or FireCAPE) proposed by Potter (2005) and the numerical simulations of interactions between a plume and density current of Cunningham (2007) will both be drawn on, as they each provide descriptions of processes from a theoretical standpoint that have remarkable parallels to the real-world event of the Layman burn.

The main feature of the Layman burn was vertical development of a spectacular convection column, believed to have resulted from a three-dimensionally varying and time-evolving meteorological environment. As the primary objective of the fire behaviour model of McArthur is to assess fire rate of spread, rather than convection column development, the McArthur model does not provide a mechanism to anticipate the dramatic smoke column, indicative of a high-intensity plume-dominated fire at the Layman burn. The pre-ignition (McArthur-based) environmental assessment conducted by fire managers performing the burn did not contain information pertinent to vertical convection column development, hence there was no reason to anticipate the fire behaviour that developed. As a consequence, we argue that there is a need for fire weather forecasts to progress beyond the current McArthur framework. The discussion will consider some of the issues involved in producing relevant weather information in real time for the fire management community.

Fire observations
The Layman burn was lit on Saturday 16 October 2010. The following day, the fire underwent rapid transition from a controlled burn to an intense crown fire with a well-developed updraft. The transformation is most clearly seen in the two images from NASA’s Moderate-Resolution Imaging Spectroradiometer (MODIS) Terra and Aqua Satellites. Figures 1 and 2, taken just four hours and twenty minutes apart, illustrate the dramatic change in fire size (as indicated by the change in plume size and remotely assessed by the MODIS hot spot algorithm in red). The extent of the smoke plume in Fig. 2 is approximately 55 km by 25 km, covering an area greater than 1000 km².

Figure 3 shows the convection column over the fire. There are several features to note in the image. The first is the deep vertical extent of the convection column. The second, an apparent near-surface convergent inflow into the fire plume from all directions and third, the smoke shield spreading out in the top left of the picture. Some of the features of Fig. 2 and Fig. 3 are worth considering in combination. One is the extensive area of smoke seen from above in Fig. 2, which is likely to be at the same level as the smoke shield seen from below in Fig. 3. Another is the white circular ‘lump’ embedded in grey smoke near the active (red outlined) fire area in Fig. 2. This is likely to be cloud which has developed by moist convection ‘punching through’ the level of the smoke shield. The shadow on the southern edge of the cloud suggests that it is significantly higher than the surrounding smoke. Both the height of the smoke shield and the existence and height of the cloud will be examined further in the meteorology section. The final point to note from Fig. 2 is the presence of two (smaller) fires further east, burning in comparable fuels but not exhibiting the fire behaviour of the Layman fire.

Timing of events on the fire-ground
Personnel from the Department of Environment and Conservation have provided a description of the sequence of events leading up to the blow-up and the map at Fig 4 shows the fire area. Ignition commenced on Saturday 16 October on the western boundary of the burn area (along a 9–10 km north to south stretch of Sues Road). Easterly winds late Saturday morning shifted southwesterly on
Saturday afternoon, pushing the fire across the northern boundary (Crouch Road) of the intended burn area. The escape on the Saturday resulted in a north-to-south active fire line of approximately 10 km on the morning of Sunday 17th. On Sunday morning, north-northwest winds drove the active fire line in a southeasterly direction. Fire activity increased markedly around 10.30 am (the image in Fig. 1 was taken at 10.00 am), and at around 1.00 pm the fire reached the southern edge of the burn area (Blackwood Road). At around 2.00 pm, winds on the southern edge of the fire ground turned southwesterly as a frontal change moved across the area. An entry was made in the (Department of Environment and Conservation) fire diary that fire behaviour dropped between 3.30 pm and 4.00 pm.

The fire site lies on the Blackwood Plateau, which has an elevation between 40 m and 120 m above sea-level. Vegetation is mostly open forest of jarrah (*Eucalyptus marginata*) and marri (*Corymbia calophylla*), and varies in height from 15 m on upland soils to 30 m near the Blackwood River, which cuts through the fire site. Fuels in the burn area varied in age from eight to twenty years and predicted minimum fine fuel moisture on 17 October was between six and a half per cent using the Project Vesta Field Guide of Gould et al. (2007), and seven per cent from the Forest Fire Behaviour Tables (or Red Book) of Sneeuwjagt and Peet (1985). The burn plan was for a low-intensity fire with a rate of spread of 20–30 m/h and canopy scorch heights up to 6 m. The purpose of the burn was to protect and maintain local riverine ecosystems and to reduce fuel loads in order to minimise the threat of intense bushfires to local communities.

Meteorology

This section will provide a brief overview of the prevailing meteorology of the area, before describing in detail the unusual combination of processes that were believed to produce the observed fire behaviour on 17 October. Figure 5 shows the location of the fire and the nearby (Bureau of Meteorology) automatic weather stations which will be referred to in this section.

Overview

The southwest of Western Australia has complex local meteorology. There are a number of reasons for this: the warm waters of the Leeuwin Current to the northwest meet colder Southern Ocean waters to the south; the Margaret River region is bounded to the north, south and west by sea, thus allowing sea breezes from three different directions; and a persistent feature of the area is the ‘west-coast trough’, a semi-permanent mobile trough which
lies across the region, particularly during the warmer months. The meteorological observation network in the area is limited—in addition to the dearth of observations over the vast ocean waters to the west and south, coverage by automatic weather stations is sparse, with widely spaced sites reporting mostly at hourly intervals.

Most years, plentiful rainfall combined with mild temperatures results in dense vegetation and heavy fuel loads. In the winter leading up to the Layman burn, conditions had been extremely dry. Figure 6 shows rainfall as being close to ‘lowest on record’ for the May to October period. Bureau of Meteorology (2010) provides the Drought Statement for the period and Fig. 7 shows the soil dryness index for Witchcliffe, the closest monitoring site (see Fig. 5 for the location of Witchcliffe). The soil dryness index reflects the dryness of soils, deep forest litter, coarse woody debris and some living vegetation (Mount 1972). The resulting very dry fuels are likely to have contributed to the observed fire behaviour. However, fuel conditions would have been the same at the Layman burn on the previous day and at nearby fires on the 17th (see Fig. 2), and neither exhibited the same dramatic development as occurred over Layman on the 17th. Additionally, other seasonal prescribed burns in the area had not been unusually active (pers. comm. Department of Environment and Conservation, Western Australia personnel). Therefore, the long-term fuel dryness is considered to have been a contributing, rather than dominant factor.

**Broadscale synoptics**

The 0000 UTC 17 October 2010 MSLP chart (Fig. 8) shows a typical spring-time pattern, with a ridge of high pressure over southern Western Australia and a semi-permanent trough of low pressure along the coast. A weak east-west oriented front is positioned south of Western Australia. The chart does not depict features normally associated with ‘severe’ (or higher) fire weather, which would be a tight (windy) pressure gradient with an upstream trajectory sourcing very hot, dry air from the interior of the continent.

In Figs. 9(a) and 9(b), showing wind structure and geopotential height at 500 hPa, the main point of note is the lack of any significant dynamical forcing mechanism in the upper atmosphere over the region of interest. The upper level wind shows zonal flow. Winds between 800 and 500 hPa were mostly 5–10 knots (upper winds are not shown here, but were examined in operational forecast grids). One implication from the upper wind structure is that (analogous to thunderstorm forecasting) there is no (vertical) wind shear to inhibit deep vertical development of a convection column.

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*In October 2010 ‘severe’, ‘extreme’ and ‘catastrophic’ fire weather were defined as having calculated fire danger values 50–74, 75–99 and greater than 100 respectively, on the McArthur scale.*
Forecast and observations

Figure 10 shows the observations and corresponding forecast data from the Australian Community Climate and Earth System Simulator (ACCESS) for the nearby automatic weather stations (AWS) (see Fig. 5 for locations). ACCESS was installed as the Bureau of Meteorology operational forecasting model in late 2010 (Puri et al. 2010). The 5 km horizontal resolution ACCESS forecast for the Perth region is used. A subjective verification of the ACCESS data in Fig. 10 indicates the model predictions of the parameters used in fire weather forecasts (temperature, dew point temperature, wind direction and wind speed) provide reasonable guidance for observed conditions.

On Sunday 17 October, the McArthur indices peaked in the mid to high teens across most of the region. Peak values were mostly mid afternoon, a few hours after the convective column development seen in Fig. 2 and Fig. 3. Maximum FFDI values for the automatic weather stations on Sunday were: Busselton: 19 (4.00 pm), Manjimup: 19 (3.00 pm), Bridgetown: 22 (4.00 pm) and Witchcliffe: 14 (1.00 pm). A spot forecast3 was issued at 3.23 pm Sunday 17th. Table 1 shows the spot forecast and observations from Witchcliffe. The Layman burn and Witchcliffe are approximately 28 km apart (see Fig. 5 for locations) and Witchcliffe is closer to the coast, thus the sites provide an indicative, rather than direct, comparison. As the forecast adheres to the McArthur parameters, which focuses on surface conditions, it provides no indication that dramatic vertical development was likely. In addition, the validity of the spot forecast is several hours after the peak convective column development (although close to the time of peak values in McArthur fire indices at three of the four nearby sites).

From the description of the fire and analysis of observations and model data, it can be seen that conventional approaches to predicting intense fire behaviour from prevailing weather conditions following the McArthur method would not have anticipated the fire intensity that occurred.

However, the ACCESS meteorological data shown here did give accurate guidance on the surface parameters of temperature, moisture and wind. Similarly it will be shown in the next section that the ACCESS grids provide insightful guidance on the vertical structure and temporal evolution of the atmosphere. Thus, although the forecast data did not provide useful guidance on likely fire behaviour following a McArthur interpretation, the vertical, spatial and temporal structure were well depicted, showing that ACCESS provides sufficient detail and accuracy at 5 km resolution to show some of the atmospheric structure that impacted the fire behaviour, given appropriate interpretation. The following section will examine further the three-dimensional aspects that contributed to the observed fire behaviour.

Atmospheric stability and its sensitivity to fire modification

The temperature profile from the closest observation site at Albany, approximately 250 km to the east-southeast (Fig. 11(a)) provides insights into the mechanism for the vertical convective development, however, in order to understand the processes that occurred, the concept of fire-modified CAPE (or FireCAPE) described by Potter (2005) will be introduced.

Combustion of cellulose creates carbon dioxide and water. Approximately half a tonne of water vapour is released for each tonne of fuel burnt. Above a fire site, the released water vapour is mixed through the low levels of the atmosphere to an uncertain depth. Consequently, the mixing ratio above the fire is elevated from background environmental levels. Additionally, heat generated by a fire increases the temperature in the vicinity. Potter (2005) proposed that, at a fire site with a given vertical temperature profile, surface dewpoint and surface temperature may be

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3Spot forecasts are point forecasts for a fire location, prepared manually by forecasters (not model generated) when requested by Fire Agencies.
Fig. 10. AWS observations (blue lines temperature and wind gusts, red lines dewpoint temperature and wind speed, blue stars wind direction) and ACCESS data (black open circles temperature and wind direction, red open circles dewpoint temperature and wind speed) 17 October midnight to midnight. ACCESS data from the 0000 UTC model run of 17 October 2010.

(a) Witchcliffe
(b) Bridgetown
(c) Manjimup
(d) Busselton

Table 1. Spot forecast for the fire site (grey) issued by the Bureau of Meteorology and Witchcliffe observations (white).

<table>
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<th>Time</th>
<th>Temp</th>
<th>Dewpt temp</th>
<th>RH</th>
<th>Wind dir</th>
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<td>11 °C</td>
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</tr>
<tr>
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<td>94%</td>
<td>SE</td>
<td>10 km/h</td>
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</tr>
<tr>
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<td>98%</td>
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<tr>
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<td>6.7 °C</td>
<td>99.3%</td>
<td>-</td>
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<td>0.5</td>
</tr>
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incremented to account for the moisture and heat released by the fire. Conceptually, this is similar to modifying surface conditions and calculating convective available potential energy in a thunderstorm environment, hence the alias ‘FireCAPE’. Modification of surface values by 1–5 °C and 1–3 g kg⁻¹ may be considered approximate starting values, following Potter (2005). However, research to date has not resolved the vertical and horizontal extent of the fire influence and appropriate values of modified temperature and water vapour remain uncertain. In particular, Luderer et al. (2009) put forward detailed arguments against the values proposed by Potter. Notwithstanding the debate on how to describe the heat and moisture released quantitatively, we believe that the conceptual model still holds and hopefully future work will resolve the current uncertainty.

Application of the FireCAPE concept to the Albany profile (Fig. 11(a)) produces the following insights. Surface values of ~7 g kg⁻¹ and approximately 26–28 °C produce free convection to the inversion just below 600 hPa (marked by arrow in Fig. 11(a)). This suggests development of a vertical circulation to

Fig. 11. Observed (a,c) and ACCESS (b,d) vertical temperature and dewpoint profiles at Albany and Perth. Observations from 2300 UTC 16 October 2010 (200 am) and model from 1200 UTC model run 16 October, 2300 UTC time step shown in red (2200 UTC in blue, 0000 UTC in green).
around 4000 m, which is consistent with the vertical column extent seen in Fig. 3. Conversations with meteorological observers conclude that around 4000 m is a reasonable estimate of the smoke shield height in Fig. 3 (not withstanding the difficulty of estimates from a photograph). Also seen in Fig. 3 is the smoke shield spreading at a constrained height. The presence and height of this smoke shield are consistent with an ascending air parcel (vertical smoke column) reaching the inversion (at 600 hPa, see Fig. 11(a)) from beneath and then spreading horizontally at that level (in much the same way as a thunderstorm may generate a cirrus shield at the troposphere). The ACCESS upper wind forecast shows that the direction of the smoke drift is consistent with forecast wind direction at 600 hPa (by 0600 UTC the forecast winds (not shown) had shifted more northwesterly that those seen in the 2300 UTC Albany observations).

Further insight into the vertical structure over the fire can be made by examining Fig. 2 and Fig. 11(a) in combination. As described 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 600 hPa and

Fig. 12. ACCESS vertical temperature and dewpoint profiles at the Layman burn site for Sunday 17th October 2010. 0100 UTC, 0300 UTC, 0500 UTC, 0700 UTC time steps (T) shown in red, with T minus 1 hour in blue, T plus 1 hour in green. 0000 UTC model run 17 October 2010.

(a) Fire site 0100 UTC  
(b) Fire site 0300 UTC  
(c) Fire site 0500 UTC  
(d) Fire site 0700 UTC
continue unimpeded to around 500 hPa, at which height cloud has the potential to form due to the shallow layer of moisture near that level. A cloud top height of 500 hPa is also consistent with the shadow seen on the southern edge of the cloud in Fig. 2.

As Albany is not adjacent to the fire site (Albany is approximately 250 km to the east-southeast), a comparison of the observed and ACCESS vertical profiles has been made. Figure 11 shows the observed vertical profiles for Albany and Perth (a and c) and the corresponding ACCESS model profiles (b and d). The vertical profiles of both temperature and moisture show ACCESS captured the potential instability and the shallow moisture overlain by extremely dry air. The inversion near 600 hPa is also hinted at by the model, although vertical resolution is insufficient to reproduce the feature accurately.

Figure 12 shows the evolution of vertical atmospheric structure over the fire site in the ACCESS data and indicates the conclusions drawn above for convection column development based on the Albany observations may be reasonably applied to the fire site.

The importance of vertical atmospheric structure on fire behaviour has been recognised for some time, although the idea of FireCAPE is relatively recent. The Haines Index (Haines 1988) provides a method for assessing vertical atmospheric structure in a fire environment, with the continuous Haines (or C-Haines) Index (Mills and McCaw n.d.) preferred in Western Australia (and across southern Australia generally) due to the very dry summers. C-Haines values calculated from ACCESS were between 6 and 7 on Sunday 17th, which is close to the top 5th percentile (7) for Bridgetown. However, the C-Haines (or Haines) index only examines limited levels in the vertical. It is worth noting that the dewpoint temperature at 850 hPa (used in C-Haines) was approximately -3 °C, whereas at 700 hPa (not considered in C-Haines) the dewpoint temperature was below -30 °C. The significance of this dry air will be discussed further in the next section.

Dry air

A history of dry air over the burn site provides another element to the story of meteorological processes contributing to the unexpected fire behaviour. The water vapour 6.7 μm satellite image of Fig. 13 shows a reservoir of dry air (in the upper atmosphere) around 36 hours before the rapid development of the fire. Examination of observations and numerical weather prediction guidance indicates that in the intervening 36-hour period the dry-air layer between 200 and 500 hPa subsided to around 600 hPa (see Fig. 11a and Fig. 14). In Fig. 14, the horizontal axis shows the (36) hourly time steps from 1200 UTC Friday to 0000 UTC Sunday. The dry air between the 0.2 and 0.5 sigma levels at the beginning of the time series has lowered in height to lie between the 0.6 and 0.7 sigma levels by the end of the time series. In the ACCESS forecast grids, the dry air layer is depicted as a layer of dewpoint temperature drier than -26 °C. Although the graphics presented here show the process from an Eulerian perspective, in actuality, the subsidence would have occurred in a Lagrangian sense under the influence of large-scale jet/trough circulation systems. Dry air descending from the mid-upper troposphere by such meteorological processes to a fire site where extreme fire behaviour occurred has previously been described by a number of authors: Zimet et al. (2007) document the Mack Lake Wildfire, Charney and Keyser (2010) the Double Trouble Wildfire and Mills (2008) the Wangary fire.

Dry-air entrainment at the Layman fire was certainly possible if vertical mixing extended from the surface into

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*Sigma levels are a vertical coordinate used in meteorology to simplify the computations required to account for topography. Sigma = 1 at the surface and sigma level 0.6 is 600 hPa.*
the dry layer. Deepening of the boundary layer is a possible mechanism for entrainment of the dry air. The ‘boundary-layer height’ from the ACCESS grids (not shown) gives the following time sequence of development during the morning: between 10.00 am and 11.00 am the boundary layer grew from (a nocturnal layer of) a few hundred meters, to approximately 2 km, near the base of the dry air layer; between 11.00 am and midday, the layer increased from 2 km to 2.5 km and between midday and 1.00 pm reached its maximum height for the day of approximately 3 km (700 hPa). Thus, by 11.00 am the boundary layer was near the base of the dry air level at just above 2 km, and between 11.00 am and by 1.00 pm extended well into the dry air layer, further supporting the suggestion of dry air entrainment. The time sequence is also consistent with the timing of fire activity shown in the MODIS images (Fig. 1 and Fig. 2) and the description from the fire site of fire activity increasing at about 10.30 am. The timing is coincident with the boundary layer transitioning from a nocturnal layer to daytime adiabatic layer and reaching the base of the dry air. An additional mechanism for a deep boundary layer is seen in Fig. 15, which shows broad scale convergence over the burn site at the intersection of three sea breezes. The convergence will be discussed further in a subsequent section.

The Witchcliffe AWS observations provide some support for the suggestion of dry-air entrainment by growth of the boundary layer. Between 3.00 pm and 4.00 pm, dewpoint temperature dropped from 7 °C to 4.5 °C, with no significant change in wind direction (280° to 290°). The main southerly wind change at Witchcliffe did not occur until 6.00 pm, when dewpoint temperature rose to 9.7 °C. Entrainment of dry air from aloft is a possible explanation for the Witchcliffe observation between 3.00 pm and 4.00 pm. However, although the observations from Witchcliffe AWS support the suggestion that dry air may have been entrained by vertical circulation, the timing of between 3.00 pm and 4.00 pm is too late to explain the enhanced fire behaviour observed from around 11.00 am. The timing is coincident with the boundary layer transitioning from a nocturnal layer to daytime adiabatic layer and reaching the base of the dry air. An additional mechanism for a deep boundary layer is seen in Fig. 15, which shows broad scale convergence over the burn site at the intersection of three sea breezes. The convergence will be discussed further in a subsequent section.

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By reference to the timing inconsistency noted above, if entrainment may be attributed to the fires convection column, and since vertical motion in moist convective processes and fire plumes is of the order of 10–20 ms⁻¹, entrainment from a height of 2–3 km could occur in five to ten minutes, well within the time frame for development indicated by the images and description of fire activity increasing at the Layman burn.

Mixing of dry air from aloft has significant implications for fuel dryness and subsequent fire activity. Near-surface relative humidity was around 30 per cent in the area (20–25 per cent at Bridgetown and 30–35 per cent at Witchcliffe). Entrainment of dry (-26 °C) air from aloft, allowing for mixing with the low-level environmental air mass, may have reduced relative humidity to below ten per cent. The response time of fine fuels is of the order of one hour, well within the time frame for entrainment to impact fire behaviour. As discussed earlier, the (unmodified) fuel moisture was calculated to be 6–7 per cent. With a reduction in relative humidity to 10 per cent or less, fuel moisture could decrease by 1–2 per cent, which, due to the near-exponential effect of fuel moisture on fire activity, could double or triple the fire behaviour phenomena seen.

Convergence

The low-level wind fields show another contributing element to a local meteorological environment conducive to convection-column development and intense fire behaviour. Figure 15 shows convergence over the burn location at the intersection of three sea breeze boundaries from the south, west and north. The convergence is depicted in the forecast grids as being similar in speed and direction through the lowest 600 m of the atmosphere. 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 the frontal change over the ocean (seen in Fig. 8).

As mentioned earlier, the broadscale convergence is likely to have contributed to a deeper boundary layer over the Layman burn, providing an environment favourable for development of the deep convection column seen in Fig. 3.

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1Department of Environment and Natural Resources, SA, have recorded a number of events when unexpected fire behaviour occurred below shallow inversions (mostly subsidence inversions). [Unpublished data provided by Mike Wouters and Rob Ellis.]
Of note is that the near-surface winds depicted by ACCESS are very light (below 5 knots) in the vicinity of the burn site. Thus, the convergent inflow seen in Fig. 3 is more likely to be driven by vertical development of the fire plume and local inflow into the fires convection column in the environment of light background winds, rather than being reflective of the broadscale convergence seen in Fig. 15.

Attributing the convergence seen in Fig. 3 to a local fire-driven mechanism rather than broadscale meteorology is consistent with the observations from the burn site, of westerly winds during the morning and early afternoon, ahead of a south-southwest change at around 2.00 pm on the southern edge of the fire.

The ACCESS grids depict the wind change moving across between 2.00 pm and 3.00 pm (ie. by 3.00 pm the wind change was north of the burn site), which verifies well against observations taken on site. The entry made in the (DEC) fire diary stating that fire behaviour dropped between 3.30 pm and 4.00 pm confirms that within an hour of the wind change, the shallow near-surface layer of cooler, moister, more stable air had reduced the fire activity significantly.

Vertical circulation was clearly a feature of the Layman fire. Figure 16 shows the strong vertical circulation on the sea breeze-enhanced frontal line(s), with upmotion (red–pink) and downmotion (orange–yellow) on the respective leading and trailing edges of the front. The 0600 UTC time step shown corresponds to the time the observed southwest wind change was observed at the southern edge of the burn site at 2.00 pm. However, although atmospheric vertical motion is often associated with a frontal line, and a front was a feature of the meteorology at the Layman burn, the timing of events indicates that convective development was prior to, rather than concomitant with the frontal line. The photograph in Fig. 3 was taken approximately 20 minutes before the westerly wind shift and, in combination with the extent of the smoke in the MODIS image (Fig. 2) shows the vertical circulation was established well ahead of the frontal change that moved across between 2.00 pm and 3.00 pm. However, the structure and timing of the southwest change are likely to have played a critical role in the fire behaviour that developed.

Density current and buoyant plume dynamics.
The role of the southwest change on fire behaviour will be explored in this section and Fig. 17 shows features pertinent to the coming discussion. Figure 17 shows a north to south velocity cross section taken through the burn site (burn location near 34.03°S) approximately two hours ahead of the frontal change approaching from the south, but within the time frame of the fire developing ‘blow-up’ characteristics. Note the following features, that are likely to be conducive to the convective development: (1) the shallow structure of the change, (2) wind speeds are higher in the approaching front compared to the synoptic flow, (3) winds above the front are in the opposing direction to the post-front winds and (4) vertical circulation on the leading edge of the frontal line, (coincident with the location of the burn site).

The features noted above, observed in the observed vertical structure of the three-dimensional wind field at the Layman burn, exhibit remarkable similarities to idealised simulations described by Cunningham (2007). Subsequent to radar observations of the interaction of a fire with a sea breeze front (described by Hanley et al. (2005)), Cunningham performed a series of idealised simulations to investigate the interactions between a density current and a buoyant plume. The simulations of Cunningham (2007) are of particular interest in the context of the Layman burn, because his results showed a significant increase in plume (fire) activity preceding (rather than concomitant with) the arrival of the (frontal) density current.

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**Fig. 15.** ACCESS-Perth wind vectors (ms⁻¹) on the 0.995 sigma level at 0500 UTC (1.00 pm local) Sunday 17 October 2010. Burn site shown in red.

**Fig. 16.** ACCESS-Perth vertical velocity (ms⁻¹) on the 0.825 sigma level 0600 UTC (2.00 pm local) Sunday 17 October 2010.
The simulations of particular relevance to the Layman burn are Cunningham’s ‘opposing wind case’, in which the ambient winds are directed against the propagation of the density current. The simulations showed enhanced plume activity (vertical motion) with this wind configuration, which was very similar to that at the Layman burn (seen in Fig. 17). In Cunningham’s results, convergence at the base of the plume increases gradually as the density current approaches and plume activity increases (as measured by increase in vertical velocity) preceding the passage of the front. Cunningham attributes the dramatic increase in vertical motion as the density current approaches as being due to the interaction between the plume and density current. In particular, he notes that the plume becomes vertical in response to the pressure perturbation and associated convergent winds that precede the head of the current. He points out that the increase in vertical velocity is not a superposition of the individual (plume + current) flows, but arises from the interaction between the two. Similarly, his simulations show strong horizontal convergence at the plume base ahead of the density current arrival, with the convergence produced by the interaction greater than the sum of the individual (plume and density current convergence) components.

Cunningham’s simulations show that the strongest interactions (vertical velocities) occur when ambient wind speed is low and less than the speed of the advancing current, as was the case at the Layman burn. As ambient wind speed increases, the interactions become less well defined. No fire-atmosphere feedback was incorporated in the simulations, although Cunningham notes that simulations with feedbacks included are planned in future research. The atmospheric dynamics of the Layman burn are a remarkable replication of Cunningham’s idealised simulations in a real event. It is of interest that the simulations show maximum vertical velocity in the plume increases rapidly as the density current approaches (see Fig. 3(b) in Cunningham’s paper), which has implications from a fire operations perspective, as it suggests plume development may occur extremely rapidly, with subsequent implications for safety of fire crews.

This idea of strong convection developing over a bushfire (or wildfire) in light ambient winds has been known for some time. Byram (1954) and Byram (1959) describe a set of vertical wind profiles when ‘blow-up fires’ occurred and introduce the idea of wind dominated versus plume dominated fires. The light-wind environment at the Layman burn is conducive to a plume rather than wind dominated fire; however, clearly not all fires in light-wind environments display extreme fire behaviour, so other environmental conditions must be considered.

**Discussion**

The Layman fuel-reduction burn escalated into an intense fire in an environment that was seemingly benign. The evidence examined in this study indicates fire activity developed unexpectedly due to a combination of meteorological factors not routinely assessed in fire environments in Australia. Meteorological processes believed to have combined to produce the observed fire behaviour include: entrainment of dry air from aloft, sea breeze convergence and prefrontal circulation, and potential instability in the presence of FireCAPE. Although a number of factors have been identified as likely contributors to the observed fire intensity, it is unclear as to which elements were dominant, or how they interacted.

Our understanding of the circumstances leading to the observed fire activity is as follows: The Layman fire was ignited in very dry fuels on Saturday 16 October 2010. Fire behaviour was active on the Saturday afternoon and overnight, resulting in a 10 km fire line on the morning of Sunday 17 October. Late Sunday morning, fire activity increased dramatically as dry air was entrained down to the fire ground by two processes, (1) turbulent mixing through the dry adiabatic boundary layer and (2) hypothesised entrainment by the fire’s convection column. The development of a deep convection column enabling the dry-air entrainment may be attributed to the release of heat and moisture by the fire into a potentially unstable environment (described as FireCAPE, Potter (2005)). The deep convection column would also have been enhanced by light local winds providing an environment of low vertical wind shear. Broadscale wind convergence at the intersection of three sea breeze fronts is thought to have promoted development of a deep boundary layer conducive to plume development. Fire activity is likely to have been further enhanced by the interactions between the fire’s convection column and an approaching front, similar to the simulations of a plume and density current described by Cunningham (2007).

The ecological impacts resulting from the intensity of the Layman burn were remarked upon in several political and community forums. However, based on the weather conditions must be considered.

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**Fig. 17.** ACCESS-Perth cross section of wind north to south through the Layman burn site (115.4˚E) at 1200 local time. Shading/contours show meridional wind speed (ms$^{-1}$) blue are northerly winds, red are southerly winds. Vectors show meridional and vertical component of wind direction (ms$^{-1}$).
information assessed in the lead up to the fire ignition (temperature, relative humidity and wind conditions), there was no reason to anticipate the dramatic fire behaviour that occurred. The main feature of the fire was its dramatic convection column and resultant intensity, which were not anticipated in advance due to the emphasis on wind driven fire spread in the McArthur fire behaviour model currently used in Australian operational fire management procedures.

The Layman burn provides a powerful example of the circumstances under which fire behaviour can be influenced by the vertical wind, moisture and temperature structure of the atmosphere, and the temporal evolution of those parameters. Such vertical atmospheric structures may more frequently cause prescribed burns and bushfires to be more active than expected than has hitherto been appreciated. Similar scenarios have been described in other case studies and the Layman burn is an additional (albeit particularly impressive) example of how factors influencing fire behaviour that are typically neglected in a weather assessment can combine to produce an unexpected conflagration.

The analysis of the D’Estrees fire on Kangaroo Island (Peace and Mills 2012) describes how a convergent wind regime over a fire ground produced fire behaviour distinct from that of three nearby fires that were outside the area of convergence. As the mechanism for fire spread is inhibited in a convergent wind regime, the more intense fire seen in the D’Estrees Bay convergence zone may be attributed to greater consumption of fuel. Little research has been conducted on the relationship between convergent winds and fire intensity, as the focus on how wind influences fire behaviour is generally on fire spread. There is also the suggestion that, when a well-developed convection column is present above a fire in a convergent wind regime, downdrafts are more likely to occur, which has implications for firefighter safety. However, the evidence for downdrafts is not conclusive, in part due to a lack of understanding of how conceptual models of moist evaporative processes apply in a (comparatively) dry fire environment. Since ‘moist’ downdrafts are attributed to evaporative cooling, which is inhibited in a fire environment due to the limited available moisture and the small droplet size due to the abundance of condensation nuclei produced by the fire, a modified model of downdraft development when a fire is present may be required.

It follows that sea breeze processes have the potential to impact prescribed burns and bushfires in southern Australia. Many prescribed burns are done in spring and autumn when sea breezes are strong, and at times when mesoscale processes dominate over synoptic scale ones. Current trends in fire management are towards increased areas of prescribed fire for fuel reduction, asset protection and landscape management. Much of the targeted area is near the coast or in mountainous terrain due to higher rainfall and resultant higher fuel loads in these areas. Both coastal and mountainous regimes have meteorology frequently modified by the mesoscale, rather than synoptic scale. In these environments processes such as low-level convergence and atmospheric (in)stability have the potential to compromise burn objectives at times. Sharples (2009) provides a comprehensive description of how fire behaviour in mountainous regions can be impacted by mesoscale meteorology. There are several locations where mesoscale coastal processes such as those described here could impact prescribed burns, for example: southwest Western Australia (exacerbated by mobile troughs), South Australia around the complex coastline of peninsulas and gulfs (seen at Kangaroo Island), Victoria along the Great Ocean Road and at Wilsons Promontory (which has been the location of problematic prescribed burns in the past). Also, changes in wind direction resulting from dynamic sea breeze frontal processes can cause fickle and sudden changes in fire direction which may not necessarily be consistently experienced by units at different points of the fire-ground and thus constitute an increased risk to fire crews.

From the Layman burn, it may be concluded that fire managers and meteorologists would benefit from tools that assess how the vertical and spatial structure of the atmosphere interplays with fire behaviour, in order to better anticipate fire behaviour driven by three-dimensional atmospheric processes in future. The Layman burn highlights how assessment of weather conditions at a fire ground must progress beyond traditional methods of producing point forecasts of near-surface conditions of temperature, wind and humidity at a given time in order to improve the use of weather information in Australian fire-management decisions.

A factor that further complicates understanding of three-dimensional and time-evolving fire weather processes is fire-atmosphere feedback, which, in simple terms, occurs when heat and water vapour are released from the fire, resulting in buoyancy processes above the fire modifying local winds. Evidence from the Layman burn strongly indicates that coupling between the fire and atmosphere developed and Fig. 3 clearly shows the convergent inflow into the fire’s buoyant convection column. Numerous numerical simulations (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 is a topic of current research. However, although its existence is recognised and accepted, the coupling process remains poorly understood. Feedback is more likely when ambient (near-surface) winds are light and buoyancy processes are dominant. Additionally, ambient vertical wind structure and ambient vertical temperature as well as possibly fire size may all play a role in the balance between buoyancy and wind driven processes, hence influencing the degree of fire-atmosphere coupling that occurs. Further research is required in order to better understand these processes, and coupled fire-atmosphere models provide an avenue for achieving this.

The findings from this case study have implications for the fire management community, a community that operates
in an environment in which identifying and responding appropriately to risk is paramount. It is important to consider whether the fire behaviour of the Layman burn could have been anticipated in advance and if operational predictions, or near real-time assessment is possible. Most of the data evaluated in this study was available in real time, so it follows that, given appropriate resources, it could be used in a pre-emptive way. However, one major challenge is the subjective manner in which these processes may be assessed. Due to their non-linear nature, there would be inherent difficulty in producing a numerical index similar to that of McArthur. Including data of a vertical and spatial nature would require improved understanding of the science, as well as training of forecasters and forecast users. Due to the increased complexity compared to current methods, there will be inherently more time in producing the forecast, which will need to occur in a resource-stretched operating environment.

Advances in numerical weather prediction models in recent decades means that forecast data are much more comprehensive than what was available when current fire weather services and procedures were developed. Numerical weather prediction models such as the ACCESS model shown here provide for increasingly accurate temporal and spatial data fields of numerous parameters and there is much that could be done to use the available information to greater potential. However, there are a number of factors to consider in making changes to fire forecasts as any ‘new’ weather forecast will be much more complicated than the current system, so significant training and development will be required, necessitating more resources in a resource-stretched environment.

The Next-Generation Graphical Forecast Editor is currently being implemented across Australia by the Bureau of Meteorology. It offers a vehicle for inclusion of spatial and temporal changes and vertically integrated data in forecasts prepared for distribution. It also provides a mechanism for displaying an ingredients based approach to fire risk assessment. These approaches (as well as communications advances) allow for more comprehensive meteorological information to be transferred to Incident Management Teams and fire grounds. However, skilled interpretation of such information is a critical element of an improved decision process.

Further research is required before some of the ideas described here may transition into a real time decision process. The Layman case study described is only one event, and the processes described here are unlikely to occur in all fires. A larger set of events (including ‘null events’) needs to be analysed in order to provide a more rigorous understanding of the processes involved and how frequently they occur. There is also potential to improve understanding of fire-atmosphere interactions through coupled modelling—significant progress in furthering fire science has already been made by researchers following this path and it is a venue we intend to pursue in future work.

The Layman burn was lit in an environment where the local meteorology provided a convergent, potentially unstable and dry-air fire environment that resulted in dramatic fire behaviour of unexpected intensity. Traditional, surface-based assessment of weather conditions provided no indication that the observed fire behaviour could have been anticipated. Improvements in numerical weather prediction models and communication technologies over the past decade means more detailed weather information can be made available to a fire ground. The risk-aware environment in which fire managers operate means we should be looking to include this information in real time, however this is a non-trivial proposition due to the resources required and the complexity of the underlying processes.

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