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A case study of the 2007 Kangaroo Island bushfires

Mika Peace and Graham Mills

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ABSTRACT

In December 2007, dry lightning ignited numerous bush fires on Kangaroo Island. Four of the fires continued to burn for two weeks, consuming over 20% of the islands' vegetation. The unique environment of Kangaroo Island is strongly influenced by the surrounding cold ocean waters, and the local meteorology, topography and vegetation were factors that influenced the evolution of the bushfires. This case study investigates the fire weather and fire behaviour by examination of meteorological observations, archived high-resolution numerical weather prediction models and documented and anecdotal observations of fire behaviour. The discussion covers three main findings. The first is how atmospheric instability enhanced activity of one fire in a convergent sea breeze regime. The operational index currently used for forecasting instability did not account for the low level process; however FireCAPE indicated potential for development of a convection column. The second finding centres on how local internal boundary layer processes impacted spatial and temporal variation in fire weather parameters on a day of near-severe fire danger. The performance of high-resolution numerical weather prediction models in capturing local processes on this day is assessed and subsequent implications for using atmospheric model output as input for fire behaviour simulations are then discussed. The third finding focuses on a fire regime where local fuel and topography, as well as feedback between the fire and atmosphere were seen to impact fire behaviour. However, as the emphasis of fire weather forecasting and fire management in Australia is on the McArthur ratings, not all environmental elements would typically be considered in anticipating the fire’s evolution. This study will describe processes that occurred which are not explicitly captured in current fire prediction procedures. It will also consider how the discrepancies may be critical to fire-fighter safety and to prescribed burn outcomes.

INTRODUCTION

The Kangaroo Island fires of December 2007 provide a unique opportunity for a bushfire case study. As the fires burned over a two-week period, fire weather and fire behaviour data were collected in an environment strongly influenced by the marine boundary layer.

Case studies have contributed significantly to the science of meteorology. Examples include Potter (unpublished), Charney and Keyser (2010), Sharples (2009), Chandler (1976) and Byram (1959, 1954). Some of the benefits these researchers attribute to case studies include: they provide a learning tool for a range of users, enable insights into processes, act as a mechanism for detailed analysis of real events and identify opportunities for further systematic research and focused enquiry. This case study aims to examine the observed processes and discuss some of the implications in the context of future provision of fire forecasting services. In doing this, it will highlight weather related information that is not included in current operational practice, but is applicable to fire management in Australia. In particular, this paper shows two situations where atmospheric stability information was vital for explaining fire behaviour and suggests it should not be neglected in future weather assessments.

During the 2007 bushfires on Kangaroo Island, the mesoscale meteorological processes varied from day to day under the transient synoptic patterns typically experienced during early summer in southern Australia. At the fire sites, observed fire behaviour responded to the varied forcing. On three days in particular fire behaviour was unusual or noteworthy and this study will discuss the features of each day.

The first day of interest is the 8th December. On this day, low level sea breeze convergence enabled lifting that released potential instability, resulting in an enhanced smoke plume over one of the four active fires, indicating increased fire activity at that particular fire. The enhanced plume shows the role that both spatial variation in weather parameters and vertical atmospheric profiles play in fire weather processes. Three indices for assessing atmospheric stability in fire environments have been calculated, the Haines and C-Haines indices (Haines 1998 and Mills and McCaw 2010, respectively) and FireCAPE (Potter, 2005). FireCAPE was the only method that captured the decrease in stability.

The second day described in this case study is the 13th December. Fire danger ratings were near Extreme[1] and mesoscale meteorology across the island was strongly modified by the complex, diurnally varying boundary layer. High-resolution meteorological guidance is used to examine some of the processes that occurred and verification shows that the model captured some, but not all, of the local effects. The verification results will be discussed in the context of current trends towards employing atmospheric model output as input to run fire behaviour simulations.

The third day that will be discussed is the 9th December, when extreme fire behaviour was observed at a time when fire danger indices from the McArthur system would generally be considered favourable for successful suppression efforts. Examination of the conditions will show that fire and atmosphere interactions, fuel types and interaction with local topography may all have contributed towards the higher than expected fire activity that was observed.

The discussion contained in the study is aimed towards future fire weather research. As numerical weather prediction information continues to improve in resolution and accuracy and processing times decrease, opportunity grows for using such information to initialise fire behaviour simulations and anticipate fire behaviour in real time.

This paper is organised as follows: Part 1 provides background information on the Kangaroo Island environment and the 2007 fires. Part 2 will briefly describe some of the data used in the case study. Part 3 reviews literature and operational use of instability information, leading into Part 4, which describes and discusses the D'Estrees fire on the 8th December. Part 5 examines the fire activity and forecast detail of 13th December and Part 6 describes the fire and its dynamics as it moved through Rocky River on the 9th December. Part 7 discusses aspects of fire behaviour modeling. The final section will conclude the study and make suggestions for further research.

1. THE LOCAL ENVIRONMENT AND THE DECEMBER 2007 FIRES

Kangaroo Island lies off the southern coast of South Australia. It is highly valued for ecological reasons, as the environment has been afforded some protection from the impacts of European settlement due to its geographical isolation. More than one-third of the island is designated as national park or wilderness area and the local fauna holds intrinsic value as well as being integral to the local tourism industry.

[1] In 2007 Extreme Fire Danger was forecast (or observed) when the McArthur Forest Fire Danger Index reached a value of 50 or greater

From a meteorological point of view, the influence of the marine boundary layer is of particular interest. The island is relatively flat, has a complicated coastline, and is surrounded by cold Southern Ocean waters. This environment has a significant impact on local meteorological processes, with cold maritime air contributing to a persistent boundary layer, and sea breezes from all directions occurring during the warmer months. Anecdotal evidence from local fishermen corroborates the complexity of the local meteorology, as they expound that intimate knowledge of local response to prevailing winds is critical in selection of the best fishing spot on a summer day.

The island typically experiences numerous fires each fire season, with many initiated by lightning. However, the December 2007 event was atypical due to the number of active fires, and the extended period of time for which they burnt. The fires started on the 6th December, when thunderstorms developed as a dry frontal change moved into a region of middle-level tropospheric instability, resulting in lightning ignition of several fires. Figure 1 shows the mean sea level pressure chart and Fig. 2 shows the lightning data for the 6th December.

Dowdy and Mills (2009) present a climatology of dry lighting events over south-eastern Australia and describe the atmospheric state associated with ignition. They use dewpoint depression at 850hPa and temperature difference between 850 and 500hPa to explore the phase space of dry and wet and fire ignition and non-ignition strikes. Values for the Kangaroo Island fires, taken from the Adelaide Airport radiosonde data (2300UTC, 5th December, not shown) are:

T – Td (850hPa) = 25C
T(850hPa) – T (500hPa) = 32C

From Dowdy and Mills (2009), their Figs 8 and 9, the Kangaroo Island values fall at the upper bound of the range of dewpoint depression and above the mid-range of temperature difference, well within their range for a high chance of ignition per lightning stroke. Additionally, no significant rainfall was recorded with the storms (Dowdy and Mills use a threshold of 2.54mm to define “dry” lightning) and the strikes occurred between 1200 and 1800CDST (see the slightly obscured time scale in Fig. 2), consistent with Dowdy and Mills’ conclusion that most fires ignited by dry lightning start mid-afternoon.

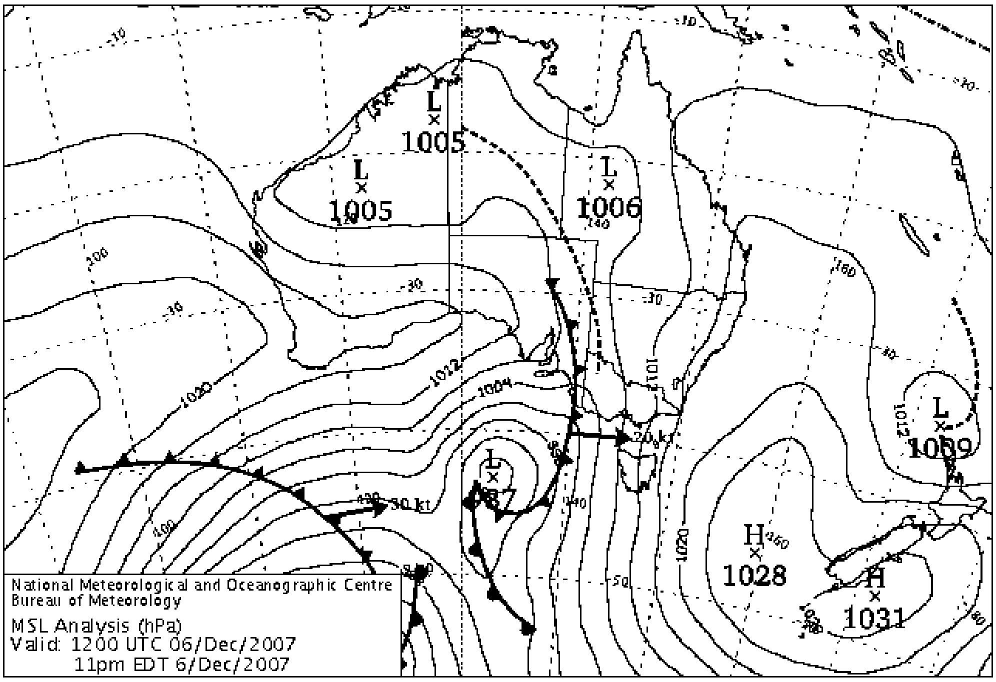


Fig. 1 Australian Mean Sea Level Pressure Chart for 1200UTC 6th December 2007. The fire ignitions were associated with the frontal change over South Australia.

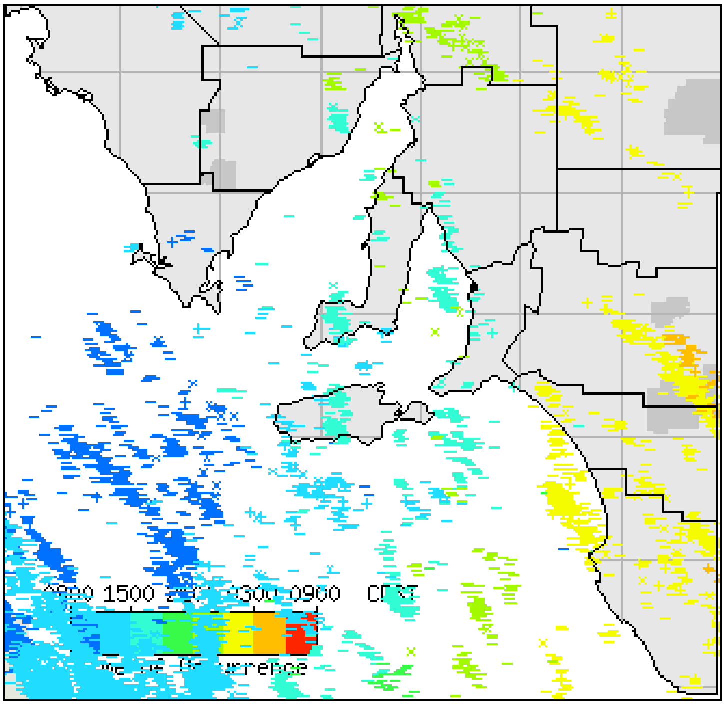


Fig. 2 GPATS lightning strike data for the 24 hours to 9am 7th December. Strikes over Kangaroo Island occurred during the afternoon of 6th December. Colours show time of day of the strikes (slightly obscured in the graphic).

Due to the inaccessibility of the island's wilderness areas, fire suppression efforts were hampered and the fires continued to burn for a two-week period. In total, 95,000 hectares of national park and wilderness protection area were burnt, covering nearly 20% of the island. Four main fires were active during the event. Each fire was named according to locality: Chase, Solly's, D'Estrees and Central. Figure 3 shows the location and area burnt of the main fires. This study will refer to the individual fires as it describes phenomena and processes during the event.

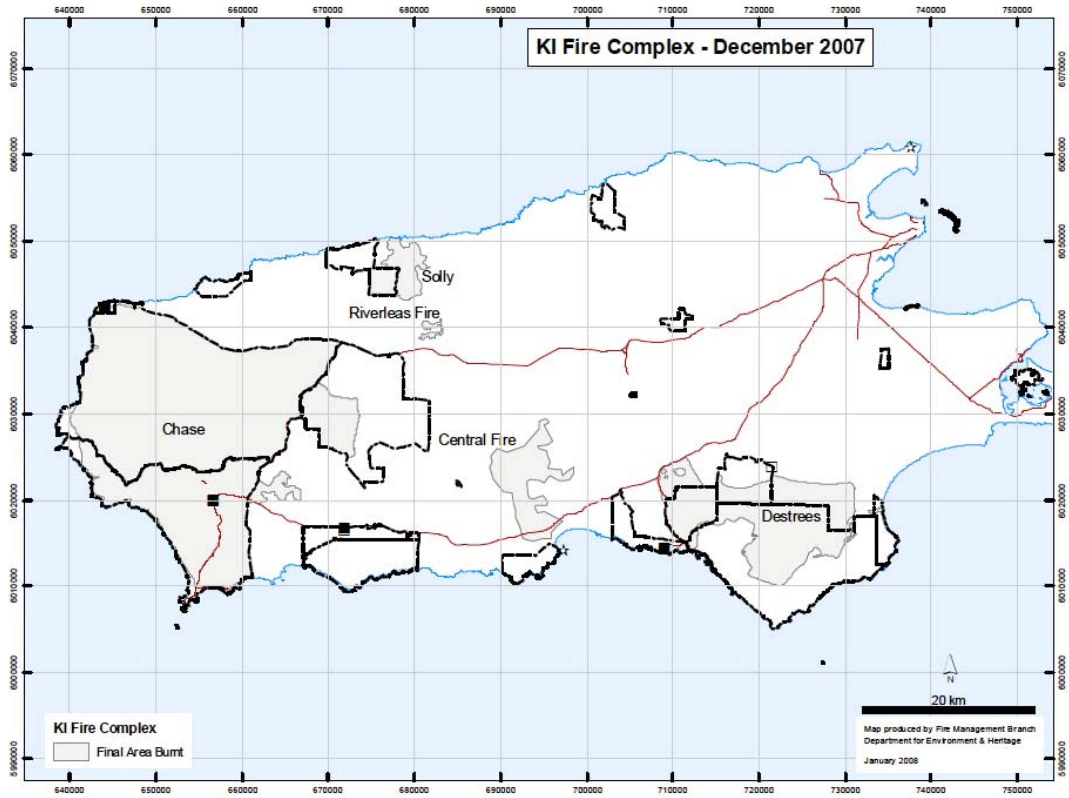


Fig. 3 Map showing locations of the major fires and total area burnt. Note that a proportion of the burnt area resulted from back burning activities. Map prepared by Department of Environment and Natural Resources SA (2008) and provided by Mike Wouters.

Local fire managers (pers. comm. Mike Wouters and Rob Ellis, both of Department of Environment and Natural Resources, South Australia, 2010) describe the main native fuels on the island as heath and mallee. The mallee vegetation carries much of its available fuel load elevated at canopy height; hence, the drying effects of wind at canopy level are important in determining fuel moisture content. The strong influence of wind on fire processes in the local vegetation was of particular importance on the 9th December at the Rocky River fire and this will be discussed in detail in section 6.

The meteorological report prepared by the Bureau of Meteorology (Bureau of Meteorology, 2009) describes the antecedent conditions and the weather conditions between the 6th and 14th December. Two points from the report are worth noting. The first is that, in the lead-up to the fires, antecedent conditions were the driest on record, resulting in exceptionally dry fuels for the time of year. The second point is that observed Fire Danger Indices (FDI's) were relatively low for most of the period, generally well below 20, apart from on the 13th December.

Boundary layer processes

As mentioned previously, the surrounding marine boundary layer has a strong influence on the island's environment. The following section aims to expand on the significance of this to the discussion of individual fire days that follows. The island is 155km long and up to 55km wide. The Southern Ocean lies to the west and south and the Australian continent to the north and east. Kingscote (see Fig. 4) is the largest town on the island and the only site where land-based temperature observations are available (the other two permanent sites, Cape Borda and Cape Willoughby are exposed coastal sites). The mean December maximum and minimum temperatures at Kingscote are 24.8C and 10.8C respectively. Maximum temperatures over 40C are reached once or twice a summer. As the temperatures of the adjacent ocean waters in December are generally in the low to mid-teens, the island is usually warmer by day and cooler by night than its surroundings. This temperature variation between land and sea has an impact on the dynamics of the boundary layer.

Stull (1988) provides a detailed description of boundary layer processes, some of which are highly relevant to Kangaroo Island. Stull describes boundary layers as forming in response to their adjacent surface, so that when air crosses over a new surface (with different thermal and roughness properties), the boundary layer will be modified from below, with the depth of the modified air (the internal boundary layer) increasing with distance downwind from the transition point. Above the layer of modified air, the boundary layer maintains the characteristics it had over the upwind site. Thus, two atmospheric layers may exist, the original boundary layer (or mixed layer) modified by the main downstream airmass and below that, adjacent to the (new) surface, a (local, shallower) internal boundary layer. Stull separates the internal boundary layers into two types; stable internal boundary layers and convective internal boundary layers. Stable internal boundary layers are formed when air flows from a warmer to a cooler surface, and convective (thermal) internal boundary layers are formed when air moves from a cooler surface to a warmer surface. Both kinds of boundary layer increase in depth downstream of the boundary, although the rate of growth varies. A distinguishing feature in the structure of the two types is that convective layers have sharp, well-defined tops and vigorous turbulence above them, whereas well-developed stable layers have poorly defined tops.

Over Kangaroo Island in southerly or westerly airstreams, as air flows from cool sea to warm land during the day, a convective thermal internal boundary layer forms over the island. This layer develops below the maritime boundary layer and deepens with distance downwind of the shoreline. In a northerly airstream, following the arguments of Stull, it is possible for series of layers to form, with a shallow (island) convective thermal boundary layer, overlain by a (slightly deeper) marine boundary layer that has developed over the ocean water to the north, with that overlain by the main boundary layer of the continental land mass, which may be several kilometres deep. The significance of this layering to fire weather will be discussed in part 5 and the skill of the Bureau's then operational Meso-LAPS NWP model in capturing this phenomenon will also be shown.

2. DATA

In this section, the data used will briefly be described in order to provide context for the interpretations and conclusions made. The main data sources are: the Bureau of Meteorology's Meso-LAPS 0.05 model, imagery from NASA's MODIS (Moderate Resolution Imaging Spectroradiometer satellites), Automatic Weather Station (AWS) data and radiosonde data from Adelaide Airport.

Automatic Weather Station data

Automatic Weather Stations (AWS) conforming to World Meteorological Organisation standards are permanently sited at three locations on the island; Kingscote Aerodrome, Cape Willoughby and Cape Borda. During the fire campaign, four additional portable AWS's (PAWS) were located near the active fires in order to provide additional observations. Although efforts were made to locate the PAWS in accordance with specifications for exposure, including adjacent trees and buildings etc., the PAWS sites may not be entirely in accordance with standard sites. Additionally, the PAWS anemometers are 8m rather than the standard 10m height. Figure 4 shows the location of the AWS's.

Fig. 4 Map of the island showing Automatic Weather Station locations. Kingscote, Cape Willoughby and Cape Borda are permanent sites, CFSA, B C and D are portable instruments, deployed by the Country Fire Service of South Australia to provide additional data during the fire campaign.

NWP model data

The Meso-LAPS 0.05 model (approximately 5.5km grid) was the Australian Bureau of Meteorology's high-resolution operational numerical weather prediction model in 2007. (In 2009, the LAPS suite of forecast models was replaced by the ACCESS system.) Limited verification studies of individual parameters in the Meso-LAPS have been conducted, however some verification work relating to fire weather conditions has been published. Huang et al (2008) provide a detailed assessment of the performance of the Meso-LAPS model in wind change situations and Mills (2005) discusses the performance of output from the LAPS suite of models at various resolutions in his analysis of the Eastern Australian fires of 2003. Vincent et al (2008) also provide verification details of Meso-LAPS in the context of wind farm forecasting applications.

Forecasters in the South Australian Regional Forecasting Centre have used Meso-LAPS for several years and their experience is that the low-level winds show strong localised response to the complex South Australian coastline. Depiction of both wind direction and wind speed is considered to provide accurate guidance and the data verifies well (subjectively) against local observations. The model has skill in capturing sea breeze dynamics, although sea breeze wind speed has a tendency to be under-forecast by a few (<5) knots.
Depending on the prevailing airstream, typical gradients of temperature and dewpoint

depicted by Meso-LAPS across the island’s 150km length are approximately five degrees. Comparison of Kingscote observations and model data indicates that maximum temperature is generally under-forecast by two or three degrees.

3. FIRE DANGER RATINGS AND ATMOSPHERIC INSTABILITY

In Australia, fire danger ratings are produced by the Bureau of Meteorology using the McArthur Fire Danger Indices for Forest and Grassland, generally referred to as Forest Fire Danger Index (FFDI) and Grassland Fire Danger Index (GFDI) respectively. The formulae, following Noble et al (1980) are shown below:

$$GFDI = 10^{(0.009254 - 0.004096(100-C)^{1.536} + T + 0.2798*W^{0.5} - 0.9577RH^{0.5})}$$

$$FFDI = exp^{(ln2 - 0.45 + 0.987ln(DF) - 0.345RH + 0.338T + 0.0234W)}$$

DF = drought factor
C = curing
RH = relative humidity
T = temperature (C)
W = wind speed (km/h)

The input parameters to the FFDI and GFDI indices are temperature, humidity, wind speed and a measure of fuel dryness. Fuel dryness is described by curing in grassland areas (0% (moist) to 100% (completely dry)), and by the drought factor (ranging from 1-10) in forested areas. The drought factor reflects the number of days since rain and, in South Australia, incorporates the Mount Soil Dryness Index (Mount, 1972). Discussion in this paper will focus on FFDIs, as FFDIs are the reference for imposition of fire bans on the island.

Fire management policy in Australia is heavily based on the McArthur indices shown above. The indices are primarily focused on fire spread, as attested by Luke and McArthur (1978), wherein it states “both the forest and grassland indices are directly related to rate of forward spread on a scale of 1 to 100”. In Australian fire weather forecasting operations, subjective consideration is given to other meteorological processes that may impact fire behaviour but are not captured in the McArthur indices. These processes include the effects of instability, and spatial and temporal phenomena such as sea breezes and fronts. However, such information is not explicitly contained in fire danger ratings.

The difficulty in inclusion of instability information was acknowledged by Luke and McArthur (1978), who noted, “…although the (instability) condition can play a dominant role (our emphasis), it cannot be readily incorporated in a fire danger ratings system”. Phenomena described in this case study will show that due to the emphasis on fire spread, under certain conditions the McArthur indices will not capture information impacting fire behaviour- information that would be critical in enabling fire managers to make decisions regarding safe and effective deployment of resources.

At a similar time to when Luke and McArthur were establishing the foundations of fire science in Australia, Byram and Rothermel provided much of the framework for fire science in the USA. Like McArthur, Rothermel focused on linear rate of fire spread and proposed a mathematical model for prediction of wildfire spread (Rothermel 1972), which, as with McArthur's model, is still used today. Byram, however, placed greater emphasis on the vertical structure of the atmosphere and described fire activity in three dimensions rather than two. This emphasis is seen in case studies examining the influence of low-level jet structure on fire behaviour (Byram, 1954) and discussion of the three dimensional structure of large fires, leading to his hypothesis on the 'power of the fire' and 'power of the wind' and their relative roles in driving fire behaviour (Byram, 1959). The previously unpublished derivations of Byram's power of the fire and power of the wind equations were expressed mathematically by Nelson (1993). Nelson's analysis serves to highlight the relative ease of describing wind effects compared to instability effects, both conceptually and by calculation using available data. In this, Nelson's work reaffirms Luke and McArthur's earlier assertion regarding the difficulty of including instability in a fire prediction system.

Incorporation of stability parameters in fire weather forecasting progressed in the late 1980s with the development of the Haines index. The Haines index uses a vertical temperature differential and elevated dewpoint temperature and temperature separation to calculate an index valued from 2 to 6 (Haines, 1988 see Table 1 for details). The index was developed for conditions in the USA, using a limited data set. It has been assessed for its application to forecasting for Australian conditions (pers. comm. regional forecasters 2010, also McCaw et al 2007, Mills and McCaw, 2009). Although it has been shown to have some benefits, most notably in Tasmania (Bally, 1995), formal and informal studies indicate the index has limitations in forecasting for Australian conditions due to the differing climatology of the two continents.

Mills and McCaw (2009) proposed an extended Haines index, the continuous Haines or C-Haines index, tailored for the Australian climate. Their methodology uses a similar approach to the original index to calculate vertical temperature and horizontal moisture differentials: However it extends the scale from 6 to 13 in order to discriminate at the higher end of the scale and avoid saturation of high-end Haines days in the dry, hot Australian summers.

Potter (2005) introduced the concept of "FireCAPE" as a forecasting tool. His approach uses modified values of temperature (due to heating of the atmosphere above the fire) and moisture (due to moisture released in the combustion process). As the simple equation for the combustion of cellulose (plant fuel) is:

$$C_6H_{10}O_5 + 6O_2 \longrightarrow 6CO_2 + 5H_2O + heat$$

As a very rough approximation, burning one tonne of cellulose will release slightly under half a tonne of water into the atmosphere, hence increasing the mixing ratio above the fire. The (near surface) estimates of temperature and moisture as modified by fire processes are used to calculate convective available potential energy (CAPE, see equation below), as FireCAPE, which can be interpreted in an analogous manner for the fire environment as CAPE is in a thunderstorm environment.

$$CAPE = g \int_{LFC}^{EL} \frac{\theta parcel - \theta env}{\theta env} dz$$

Potter qualifies the work published on the approach as preliminary and discusses the limitations to the model, particularly with reference to the uncertainty in estimating heat and fire moisture processes. Consideration of real cases raises the question of how large a fire is required in order to produce convective feedback. Some of the uncertainties of Potter's FireCAPE model are explored by Luderer et al (2009), but remain unresolved.

The inherent difficulty in forecasting effects of atmospheric instability in a fire environment is discussed in the references above. However, appreciation of vertical stability can be critical to understanding and predicting fire behaviour. This paper will show two situations where including stability information provides a more complete description of meteorological processes impacting fire behaviour. The first example is of a convective plume enhanced by sea breeze convergence enabling lifting that released potential instability, leading to convective development; the second a rapid change in the fire environment due to vigorous breakdown of the marine boundary layer. Evidence points to the possibility of a third example of stability processes influencing fire behaviour, that of entrainment of dry air from above a subsidence inversion by vertical mixing in the convection column, however further enquiry is needed in order to prove this case.

The Haines approach, C-Haines and FireCAPE methods for assessing atmospheric instability and their respective uses as a forecasting tool for this case study will be considered for the first example in the next section.

4. D'ESTREES FIRE, 8TH DECEMBER

This section of the case study will describe the meteorology and fire behaviour on the 8th December, when sea breeze convergence enabled potential instability to be released, resulting in enhanced fire behaviour at one of four active fires. The highest FFDI recorded on the 8th was a value of 17 at Kingscote AWS at 14:00 local time. However, satellite imagery suggests that the fire behaviour observed at the nearby D'Estrees fire is unlikely to have been consistent with FFDIs in the mid-teens. Unfortunately, no fire behaviour observations were recorded at the time. Two main factors will be described due to their influence on fire behaviour: low-mid troposphere atmospheric instability and local sea breeze convergence.

Figures 5 and 6 show the 0000UTC mean sea level pressure charts for the 7th and 8th of December. Under the weak synoptic forcing, mesoscale dynamics dominate the meteorological processes.

Synoptic pattern

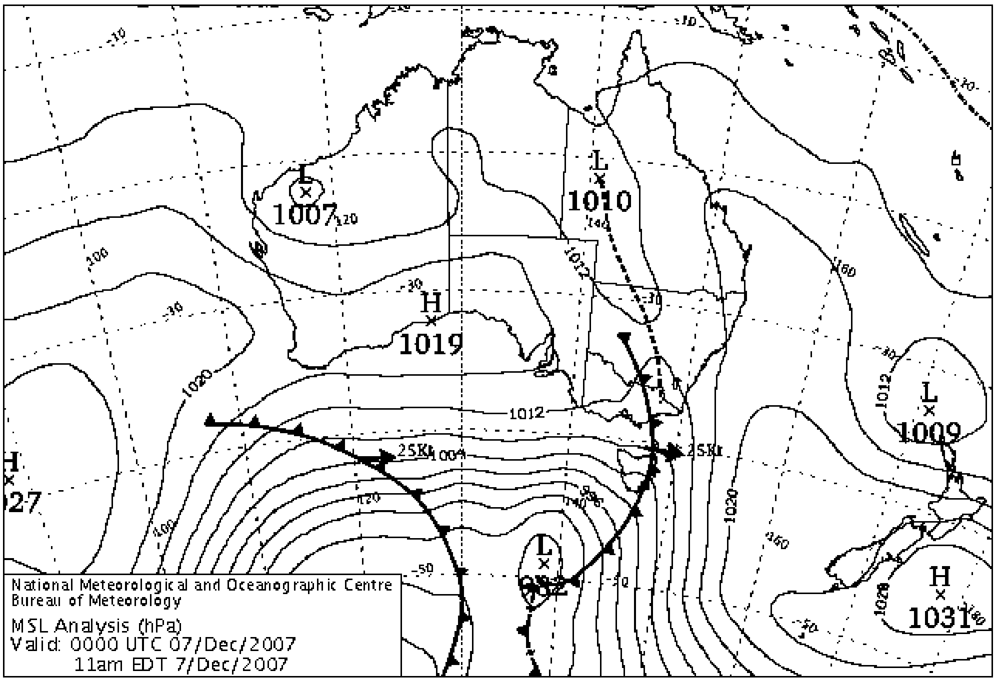


Fig. 5 Australian region MSLP chart for 0000UTC 7th December

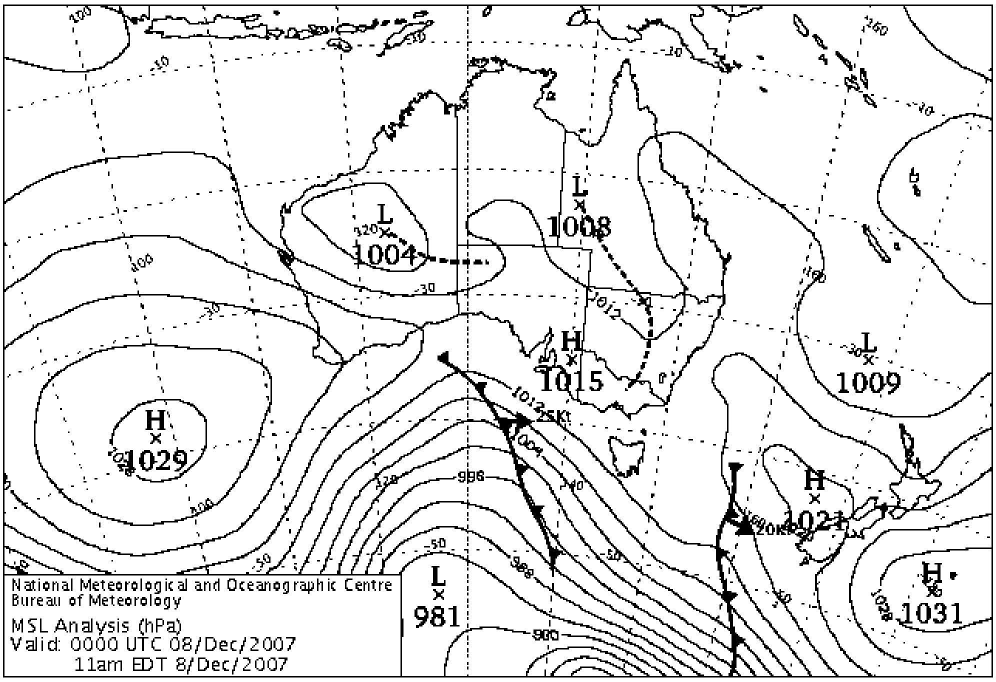


Fig. 6 Australian region MSLP chart 0000UTC 8th December

MODIS imagery

MODIS satellite imagery shows the smoke plumes at (local time) 14:50 on the 7th December (Fig. 7) and 11:20 (Fig. 8) and 15:35 (Fig. 9) on the 8th December. Comparison of the three images reveals a dramatic change in the smoke plume of the D'Estrees fire (on the southeastern side of the island) on the afternoon of the 8th. At 15:35 local time the D'Estrees plume is the largest in extent and densest in opacity of the plumes from the (four) active fires. The larger smoke plume indicates greater energy release and hence a more intense fire at the D'Estrees site. Analysis of the plume direction and wind regime shows that the plume was higher than the other fires. Vines (1981) states "the height to which a plume can rise is dependent on the burning rates of the fuels on the ground and the stability of the air above the fire". Following Vines, the question we wish to explore is … "By what process is the D'Estrees fire the most active of the four on the island?"

Two assumptions will be addressed prior to exploring this question. The first assumption is that the relative size and opacity of individual smoke plumes directly correlates with fire intensity. To substantiate this claim, a subjective comparison can be made between the afternoon MODIS imagery on the 7th (Fig. 7) and 8th (Fig. 9). On both days, observed FFDIs were similar (in fact FFDIs were slightly higher at all island AWS's on the 7th). Plumes from all fires on the 7th are similar in extent and opacity to the Chase and Solly's fires on the 8th, in marked comparison to the D'Estrees fire on the 8th, which is larger and denser. The second assumption is that fuel type and fuel quantity were not a varying factor. Information provided by local fire manager Rob Ellis (pers. comm. 2010) indicates vegetation was not significantly different at the D'Estrees fire.

The causes of meteorological forcing producing the enhanced D'Estrees fire plume will be explored in terms of the vertical atmospheric structure and the sea breeze wind regime over the southern part of Kangaroo Island.

Fig. 7 MODIS image 14:50 7th December 2007 from NASA/GSFC MODIS Rapid Response. Red pixels show thermal anomalies, interpreted as flaming or smouldering fires of size approximately 1000m^2 or greater, (depending on conditions)

Fig. 8 MODIS image 11:20 8th December 2007.

Fig. 9 MODIS image 15:35 8th December 2007

Vertical atmospheric profile

The Adelaide radiosonde plot (Fig. 10) shows the evolution of atmospheric stability between 1200UTC on the 7th and 1200UTC on the 8th. Cooling and destabilisation occurred above 850hPa associated with the approaching front. The subsidence inversion evident on the 7th near 780hPa had broken down 24 hours later. Potential for vertical smoke plume development was thus enhanced on the 8th due to the decreasing stability. The Meso-LAPS forecast vertical profiles (not shown) were compared with the observed Adelaide trace and the comparison showed the guidance failed to capture the changes in vertical stability, thus, the Meso-LAPS profiles will not be considered here and discussion will focus on the Adelaide observations. Due to proximity, the observed profiles should provide reasonable representation of vertical stability over the island, apart from in the lowest 1-2km where boundary layer processes would be dominant.

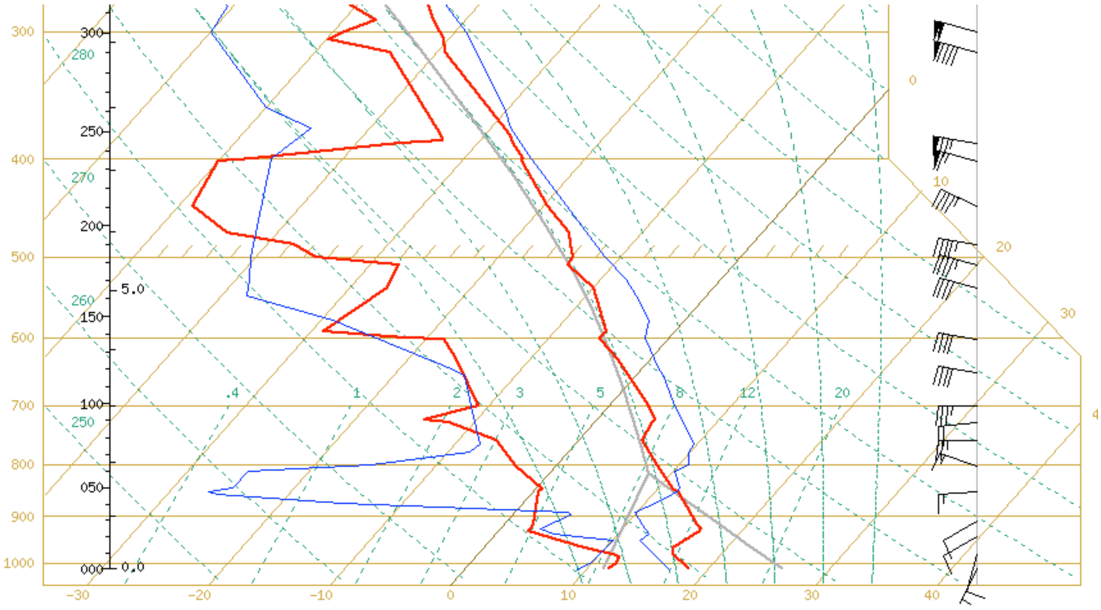


Fig. 10 Adelaide Airport radiosonde flight showing temperature and dewpoint temperature vs height for 1200UTC 8th December (red) and 1200UTC 7th December (blue). Cooling and destabilisation occurred through the mid-levels between flights. Winds (right margin) are for 1200UTC 8th December. Winds in knots (short barb=5knots, long barb=10knots, flag=50knots).

On the 7th, it is likely the subsidence inversion inhibited vertical development of the smoke column, capping the plume at ~750hPa. This is consistent with the spread of the plume to the east (seen in Fig. 7) and the observed wind profile (not shown). On the 8th, the fire plume from the Chase and Solly's fires is again directed towards the east (Fig. 9), consistent with a plume height to around 800-900hPa (refer wind barbs of Fig. 10), whereas the plume from the D'Estrees fire has spread to the southeast, indicating a plume height to 750hPa or above. In addition, the much greater opacity of the plume from the D'Estrees fire is evidence of enhanced fire intensity. Byram (1959) makes the important distinction between a smoke plume and a convection column. He describes a convection column as being associated with a "blow-up" fire, with the characteristics: darker smoke with a dense, solid appearance and pronounced movement of gases within the column. He describes smoke plumes, by comparison, as having a lack of pronounced vertical motion, being lighter in colour and with relatively low density. Comparison of the plume signatures seen in Fig. 8 and Fig. 9 with Byram's description would suggest the D'Estrees fire exhibits features consistent with a convection column and the other fires as smoke plumes. Thus, the observations indicate that fire activity at the Chase and Solly's 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. It is worth noting at this point that there is no evidence of moist convection in the convection column (if moist convection occurred, it would be expected to manifest as white cloud, rather than grey smoke). The interpretation of moist and dry convection over a fire will be discussed later.

Low level convergence

Examination of the Meso-LAPS low-level wind field provides insight as to how the D'Estrees fire was able to realise the potential instability. Figure 11 shows convergence over the D'Estrees fire (southeast corner of the island) between the northwesterly synoptic flow and the sea breeze. Through application of the continuity equation, the local convergence triggers lifting and therefore plume development. Elevated dewpoint temperatures in the onshore, moist sea breeze airstream act to increase low-level moisture and hence raise moist convective potential in the vicinity. In addition, temperatures in the southwest corner are the highest on the island (shown in Fig. 11 as red contours), due to the long land trajectory to the northwest. Positive feedback loops would also occur due to the heat generated by the fire. The heat over the fire ground would contribute to local buoyancy by increasing the temperature differential between the cold Southern Ocean waters to the south of the island, thereby producing an enhanced sea breeze effect and creating a mechanism for increased local convergence.

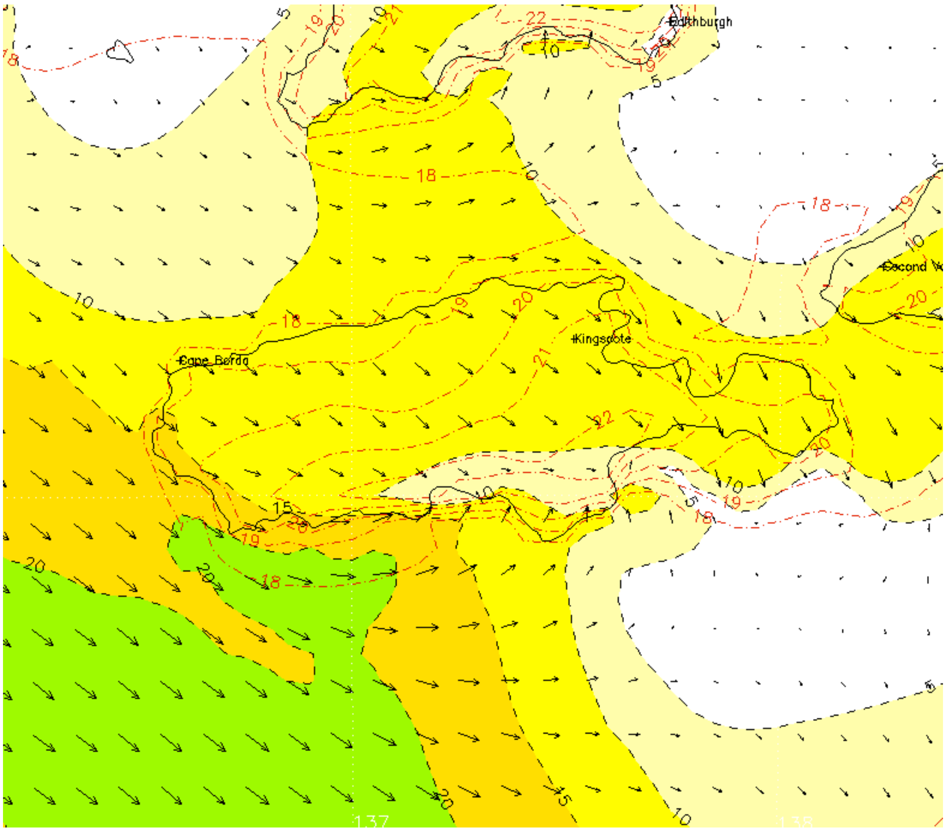


Fig. 11 Meso-LAPS winds (knots) centred on Kangaroo Island at 0400UTC 8th December 0000UTC model run, 9943 sigma level (approx 45m above sea level). White <5knots, beige 5-10knots, yellow 10-15knots, pale brown 15-20knots, green 20-25knots. Red dashed lines temperature deg C.

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.

This observation of dynamic interaction of a fire and sea breeze is not unique, and it is likely the phenomenon occurs reasonably frequently. Hanley et al (2005) describe the interaction of a wildfire and a sea breeze front in Florida. From radar observations and by simulation of a density current and buoyant plume they conclude that the interaction results in a temporary, but significant, increase in fire activity. The next section will consider different methods by which instability over fire environments may be calculated and the results will be discussed.

Haines and C-Haines calculations

Tables 1 and 2 show the algorithms for calculation of the Haines and Continuous-Haines (C-Haines) Indices respectively. Following Mills and McCaw (2009) the mid-level Haines Index is used here. The Haines index gives a value from 1 to 6 and the C-Haines a value from 1 to 13. Lower (C-)Haines values indicate greater stability and higher values decreased stability, with higher values indicating an environment suitable to producing wild land fires of increased severity.

Table 1 Mid level Haines index algorithm following Haines (1988), but using the thresholds from Mills and McCaw, 2010.

Mid-level Haines Index HI = stability score + moisture score			
stability term T_{850} - T_{700}	stability score	moisture term T_{850} - Td_{850}	moisture score
<6	1	<6	1
6 - 10	2	6 - 12	2
>10	3	>12	3

Table 2 Continuous Haines Index algorithm (from Mills and McCaw, 2010).

Continuous Haines Index C-Haines = CA + CB	
$CA=0.5\ (T_{850} - T_{700}) - 2$	$CB=0.3333\ (T_{850} - Td_{850}) - 1$
with conditions if $(T_{850} - Td_{850}) > 30$, then $T_{850} - Td_{850} = 30$ if $CB > 5$, then $CB = 5 + (CB - 5)/2$	

From the algorithms in Tables 1 and 2, Haines and C-Haines values were calculated from the Adelaide radiosonde observations for 1200UTC and 2300UTC on the 7th and 1200UTC on the 8th. The results are shown in Table 3 and are somewhat surprising. At 1200UTC and at 2300UTC on the 7th, Haines values of five were calculated, but at 1200UTC on the 8th the index had reduced to four. The decrease in the Haines Index coincident with an increase in the size of the smoke plume would not necessarily be expected. The result can be explained by analysing the components of the index separately. As stability decreased, the stability term increased slightly, but its value remained constant at two. The moisture term responded more strongly to the approaching front, decreasing from three to two as low-level moisture increased, causing the Haines Index to change from five to four. A similar trend is seen in the values of C-Haines. Calculated values decreased on average over the 24 hours, due to the stronger influence of the moisture term over the stability term. It is worth pointing out that the C-Haines Index was designed to discriminate high-end fire danger days, when an increase in moisture at 850hPa would be unlikely. However, this example shows that temporal changes in both the Haines and C-Haines algorithms may produce decreasing values in a situation of increasing low-level moisture, even though vertical stability weakens. In this particular case study, neither algorithm suggested that enhanced convection was likely with the approaching front.

Table 3 Haines, C-Haines and FireCAPE calculations from Adelaide radiosonde observations.

	1200UTC $7^{th} Dec$	2300UTC $7^{th} Dec$	1200UTC $8^{th} Dec$
Haines Index (mid level)	5	5	4
C-Haines index	8.2	6.6	7.1
FireCAPE	0	0	$469 J/kg$

FireCAPE calculations

FireCAPE was also calculated for the data set, by modification of the Adelaide radiosonde observations using the Bureau of Meteorology's operational program Sondtool. The results are also shown in Table 3. On the 8^{th}, the calculated (Fire)CAPE of 469 J/kg with an equilibrium level of 9497m over the D'Estrees site indicates good potential for plume development. To produce this result, a surface temperature of 27C and a dewpoint of 14C for 1200UTC were input for the 8^{th} December. The selection of temperature value was taken from Kingscote's observed maximum temperature (24.9C), plus 2C to account for both land trajectory (estimated from Meso-LAPS data) and heat from the fire. The moisture content of 14C dewpoint temperature used in the calculation includes components from two sources: moisture released in the combustion process, as described by Potter (2005); and moisture from the onshore sea breeze (12C dewpoint temperature from Meso-LAPS). The dewpoint temperature of 14C is equivalent to a mixing ratio increase of 1g/kg, a conservative increment consistent with Potter's (2005) assumption of moisture release from a large fire of 1-3g/kg. The values are also (conservatively) consistent with the numerical simulations of Jenkins (2002, 2004), where she concludes "at approximately 15 m above the fire, a fire parcel is warmer and moister than ambient values by 2-3K and 1-3g/kg". Additionally, the observations of Taylor et al (1973) from the Darwin River fire showed a more significant temperature increase of 5.5C, indicating the 27C used here may be an underestimate.

FireCAPE discussion

The concept of FireCAPE has been applied by Potter (2005) to a number of examples in the USA, however the method has not previously been used in Australia. The example considered here shows that FireCAPE may be used as a fire index in which sea breeze moisture may be accounted for, as a sea breeze profile may be too shallow to be resolved by either the Haines or C-Haines indices. This example also demonstrates that the technique can enable comparison of adjacent fires in slightly different meteorological regimes. Two main points are worth noting before the discussion progresses to considering the fire behaviour implications.

The first is that the vertical profile here is a typical "skinny CAPE" environment. In a thunderstorm forecasting context, updraught strength is inhibited in a "skinny CAPE" regime due to precipitation loading. However, in the fire environment being considered, analogous water loading arguments may not apply due to reduced water loading in the dry fire environment.

The second point is that low-level rotation induced by vortex stretching of background cyclonic flow (evident in the veering of the sea breeze, seen to approximately 500m on Meso-LAPS guidance but not shown here) may also be acting to enhance vertical motion. It is possible that enhanced rotation leads to reduced entrainment (unless dilution of the plume exists), contributing to organisation of the updraught vortex, maintaining the integrity of the plume column.

As mentioned earlier, this case raises some uncertainty as to how conceptual models of moist and dry convection apply in a fire environment. Photographs of many fires (taken from the surface and from space) show evidence of moist convection occurring, by formation of pyro-cumulus or, more infrequently pyro-cumulonimbus. When white cloud is seen within a grey smoke plume, it is reasonable to assume that condensation is occurring. However, in the MODIS image of the D'Estrees fire, the apparent absence of cloud suggests moist convection may not be present. Conceptual models of vertical parcel motion describe a process by which; if a parcel is lifted (along a dry adiabat) to its lifting condensation level, subsequent upwards motion is along a moist adiabat. However, if there is no evidence of condensation (ie no cloud) it is uncertain as to whether this conceptual model is appropriate. This question of dry and moist convection in a fire environment, particularly where "FireCAPE" is present, remains an open question for further research.

Potter (2005) points out that fire convection, particularly in severe fires, has the potential to create downdrafts, resulting in erratic changes in wind and in fire behaviour. However, as downdrafts typically occur due the to energy released by phase change in the evaporation process, it may be a requirement that moist (rather than dry) convection is present. Another way of looking at this is the distinction between positive and negative buoyancy of an (ascending) air parcel. If a parcel is lifted to the level of free convection, it is implicit that vertical motion then follows moist adiabatic processes and the parcel remains positively buoyant until precipitation loading results in the parcel becoming negatively buoyant, thus the parcel reaches the top of its upwards trajectory and descends. In a dry fire environment where precipitation loading is negligible, downdrafts may be less likely to occur.

Implications for fire behaviour

Having described the meteorology, the following section will discuss the implications of the enhanced plume development for subsequent fire intensity and fire behaviour.

Fireline intensity in simple form is determined by forward rate of spread and dry weight of fuel consumed (AFAC 2010). Forward rate of spread is strongly dependent on wind speed, however at the D'Estrees fire, observed and forecast wind speed was relatively light and not significantly different to the other three active fire sites on the island (refer Fig. 11). Also, the afternoon fire spread map produced by the Department of Environment and Natural Resources, South Australia (not shown) shows a relatively small increase in fire area. This is consistent with the conceptual model that a convergent wind regime inhibits the mechanism for fire spread. However, the development of the convective plume indicates enhanced fire intensity and as the winds were light, the fire activity may be attributed to high fuel consumption. Therefore, as the evidence indicates the D'Estrees fire was more intense than the other fires (due to the development of a convection column), the dry weight of fuel consumed is likely to have been much greater at the D'Estrees fire than the other fires on the island. The convergent wind environment would also create a more stationary fire (as opposed to a moving fire front) enabling a more efficient burn with complete combustion, as fuels remain in the burn area for longer, with a hotter burn due to increased flame residence time in a convergent wind regime. The convective process also provides opportunity for crown fires as well as increased spotting potential. Such fire behaviour characteristics have implications for difficulty of fire suppression as well as ecological impacts.

Throughout southern Australia, seasonal prescribed burns are undertaken in order to reduce build-up of fine fuels. As regional rainfall is highest along the coast and in elevated terrain, vegetation targeted for prescription burning is frequently concentrated along the coastal fringe. Prescribed burn activities are generally performed in spring and autumn and often on days when synoptic forcing is weak, as these are generally conducive to benign fire weather, with FDI's in the low-to-moderate range. Such days are most likely to exhibit strong local meteorological response as mesoscale effects dominate over synoptic scale forcing: thus, the meteorological processes described above have the potential to compromise prescribed burn intentions in some scenarios. Sea breeze influences in particular are typically observed to be strongest during spring months, due to the land-sea temperature contrast. Therefore prescribed burns in coastal areas have the potential to experience sea breeze convergence and concomitant enhanced fire behaviour. Implications for firefighter safety are clear, as a higher intensity fire is associated with greater risk. There are also implications for resource management, with respect to positioning of assets in relation to timing of onset and cessation of the sea breeze wind shift.

5. CHASE FIRE, 13TH DECEMBER

This section of the paper will describe conditions on the 13th December, when in near extreme conditions, the Chase fire spread rapidly across the west of the island.

On the 13th December, boundary layer dynamics played an important role in modifying the mesoscale meteorology. The observations and gridded weather guidance will be examined and a verification of the gridded guidance will be shown and discussed. Such verification is appropriate in light of current trends towards the use of gridded weather parameters to run operational fire models, as appreciation of the accuracy and limitations of model weather output is critical for objective assessment of the results from fire behaviour simulations.

Synoptic pattern

Figure 12 shows the mean sea level pressure chart for the 13th December at 1200UTC. Northerly winds carrying a hot, dry continental airmass preceded the passage of a cold front (shown as a trough over land in the MSLP chart), with a cooler, moister maritime airstream in the wake of the frontal change. In the upper levels of the atmosphere, a broad trough lay south of WA. The surface reflection of the weak upper forcing resulted in a gradual change in surface wind direction from north to southwest, as opposed to a sharp wind shift. The wind speed in the post-change southwest stream was only moderate: therefore the main weather concern was the fresh pre-frontal northerlies. The potential for enhanced fire behaviour on the change day had been anticipated several days in advance.

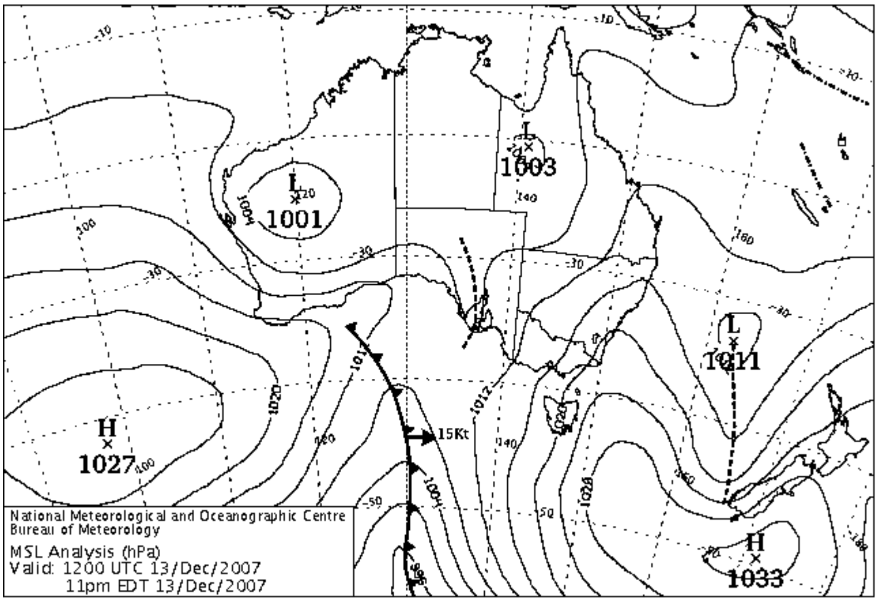


Fig. 12 Australian region MSLP chart 1200UTC 13th December 2007.

Rob Ellis (pers. comm. 2010) stated that both the fire activity and suppression efforts on the 13th were focused on the Chase fire. Early in the day, the fire breached containment lines under easterly winds and control was not able to be regained. Fanned by hot, dry northerly winds, the fire headed south, consuming huge amounts of fuel and spotting considerable distances. The fire front was several kilometers wide, with flame heights reaching 25-30m. Intensity of the fire was extreme and water bombing from aircraft had no effect (Rob Ellis pers. comm. 2010). Approximately two-thirds of the area burnt by the Chase fire over a two-week period occurred on this single day.

Figures 13 and 14 show the extensive smoke plume spreading southwards. Convective cloud in the imagery is consistent with middle-level moisture near 4000m. Convection and turbulence within the plume is likely to have been enhanced by a dry adiabatic layer to around 4000m. Figure 15 shows the Adelaide Airport (mid-morning) radiosonde flight, with dry adiabatic low levels and moist mid-levels apparent.

Fig. 13 MODIS image 11:40 13th December 2007.

Fig. 14 MODIS image 15:55 13th December 2007.

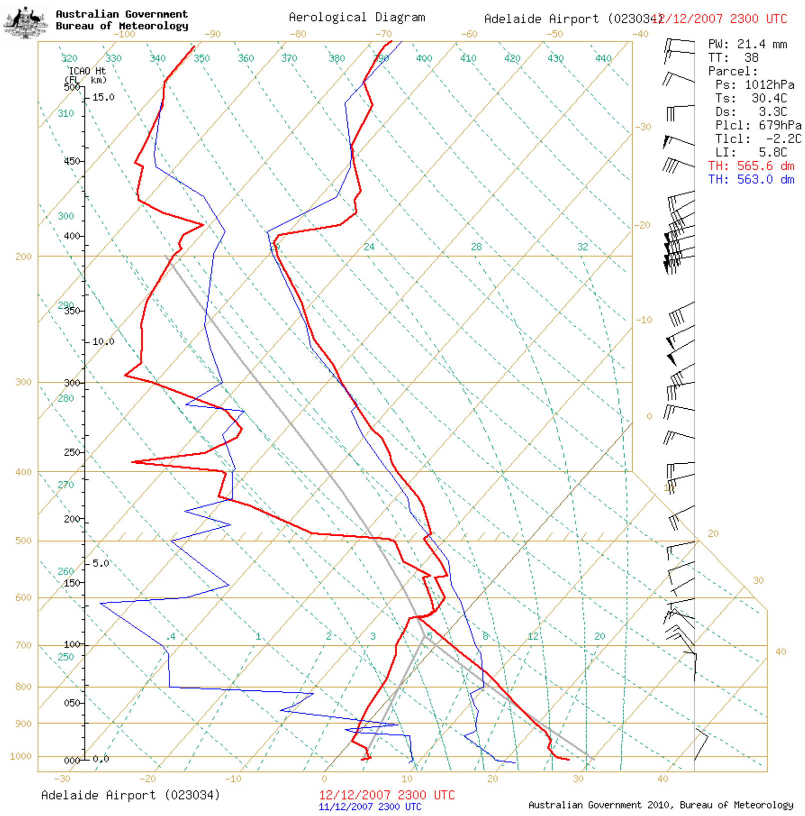


Fig. 15 Adelaide Airport Aerological Diagram 2300UTC 12th December 2007

Boundary layer

The AWS observations show significant differences in the timing and breakdown of the nocturnal boundary layer during the morning. Figure 16 shows the AWS observations and meteograms from the 0000UTC and 1200UTC Meso-LAPS model at the locations of the seven stations. On the northern side of the island at CFSD AWS, located very close to the coast, temperature increased gradually, dewpoint decreased gradually and wind speed and direction was relatively steady. At Kingscote, slightly further inland, temperature also increased gradually, however dewpoint and wind changed markedly late morning when light, variable winds shifted fresh northerly. At both CFSA and CFSC AWSs, on the southern side of the island, a sudden change in conditions occurred in the late morning. At both sites, temperature increased rapidly and dewpoint dropped rapidly, coincident with a sudden increase in wind speed. The most dramatic change was seen at CFSA, where temperature rose more than 10˚C, dewpoint dropped by 10˚C and wind speed increased by 20km/h in a short period. This resulted in an abrupt and alarming increase in FDI, seen in Fig. 16 (bottom row). The change in conditions (and FDI) occurred quite late in the morning, with the peak change at around 11am local time, five hours after the 6am sunrise.

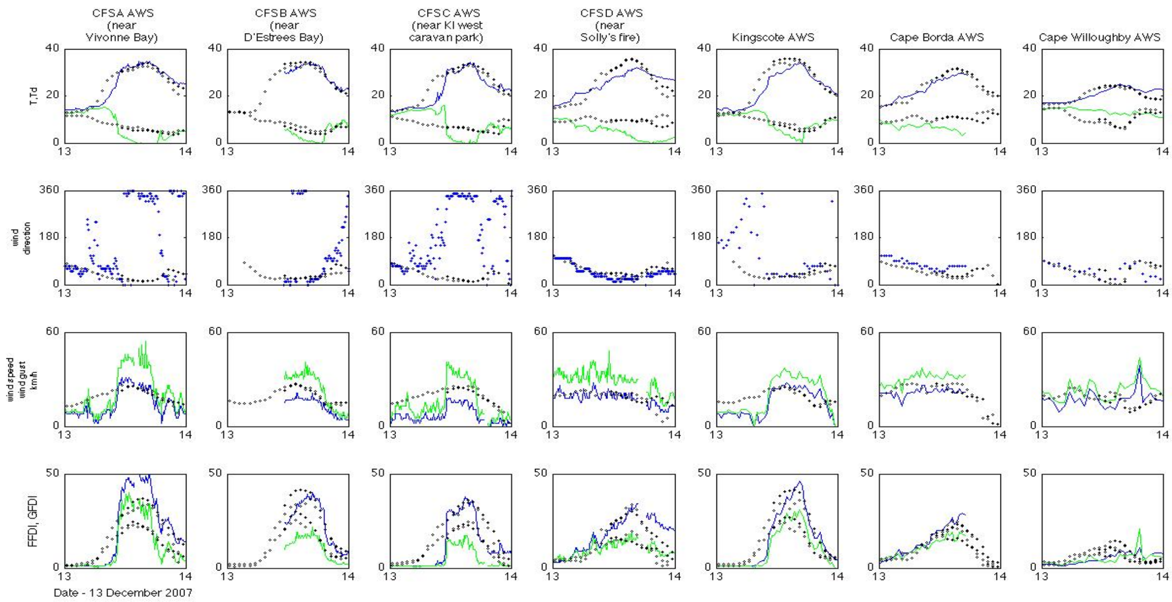


Fig. 16 Observations and Meso-LAPS model output for the seven automatic weather stations located on Kangaroo Island. for the 13th December, midnight to midnight local time. Locations across the top, weather parameters vertically. Meso-LAPS output shown for 1200UTC and 0000UTC model runs. All plots – open diamonds from 1200UTC model run from previous day, crosses show 0000UTC model run (valid from 11:30am local). Row 1 – blue lines observed temperature, green lines observed dewpoint temperature. Row 2 – blue marks observed wind direction. Row 3 – blue lines observed wind speed (km/h), green lines wind gusts. Row 4 – blue lines FFDI calculated from observations, green lines GFDI calculated from observations.

Reference to the earlier discussion on boundary layers and examination of the potential temperature (Θ) cross-sections shown at Figure 17 provides insights into the processes that were occurring at the different sites. At 2000UTC warmer air aloft overlies cooler air at the surface, due to radiational cooling overnight (Fig. 17a). At 2200UTC (Fig. 17b), differential heating over land and sea produces a shallow, higher Θ internal boundary layer over Kangaroo Island, overlain by lower Θ air advected from the marine boundary layer (seen more clearly in 0.1˚C increments, not shown), which is itself overlain by higher Θ air advected from the mainland. Over the next two hours, the structure weakens (seen in the 0000UTC plot) and by 0200UTC the marine boundary layer is very shallow (of the order of 10's of meters), does not extend across the island. The Θ profiles over the mainland and island are indistinguishable, suggesting the same air mass is vertically mixed across them, with a shallow stable internal boundary layer overlying the marine region between. The rapid change in conditions seen at the inland sites, in contrast to the gradual change at CFSD near the coast, may be explained by the difference in structure of the top of the layer described by Stull (1988). The convective thermal internal boundary layer (over land) has a sharp, well-defined top, and would therefore be expected to break-down rapidly once the layer had grown to sufficient depth (by entrainment of the overlying marine layer) for turbulence to mix it with the continental air aloft, whereas the stable layer over sea has a poorly defined top, allowing turbulent mixing across its boundary, hence the more gradual change observed at CFSD.

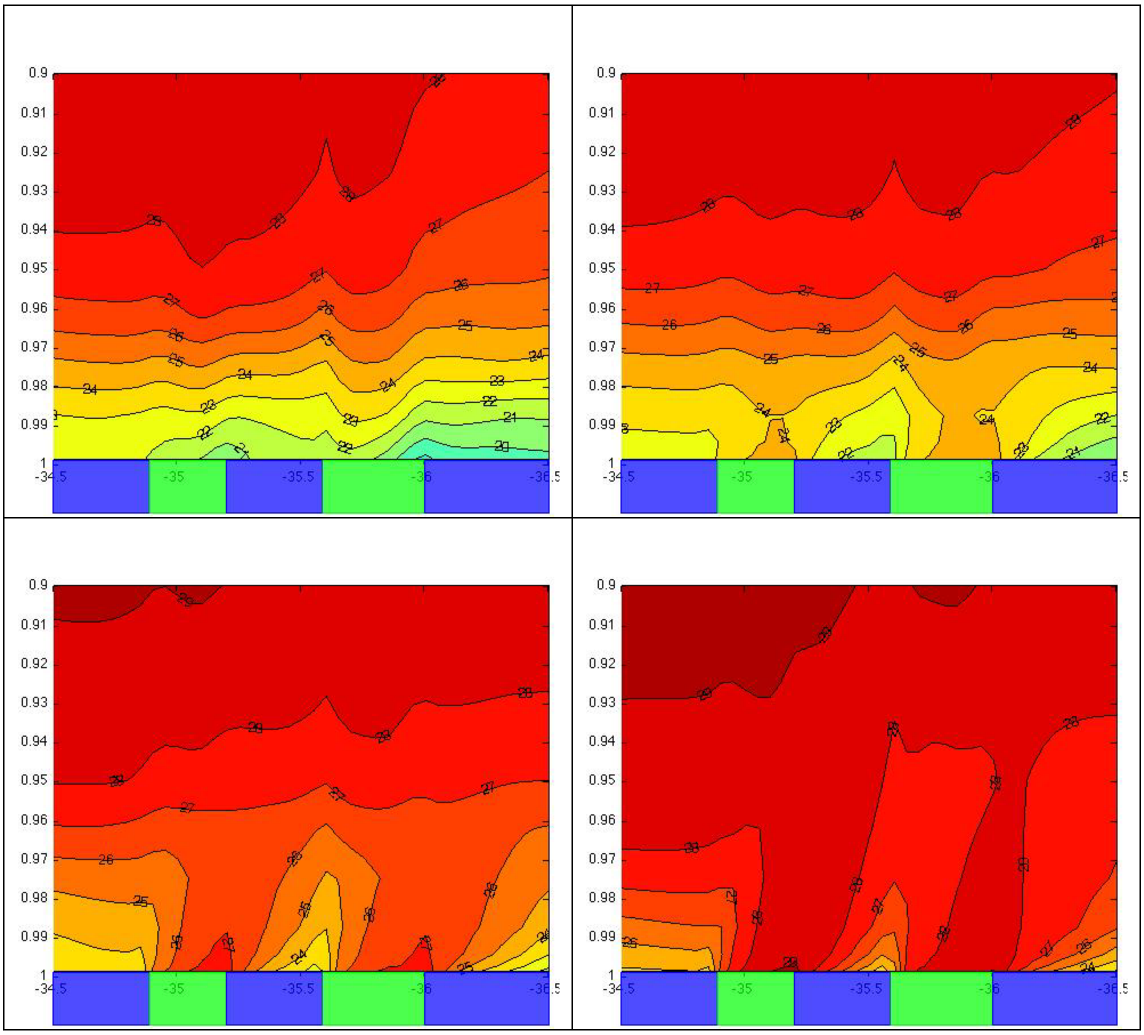


Fig. 17 Meso-LAPS potential temperature (Θ) (degrees C) from 34.5S to 36.5 S through longitude 137.2E for sigma levels 0.9988 to 0.9 (approximately 430m). December 13th. Left to right from top left (a) 2000UTC, (b) 2200UTC, (c) 0000UTC, (d) 0200UTC. Shading below the plot shows land (green) and sea (blue) through the cross section shown in Fig. 18.

Fig. 18 Map showing position of cross section in Fig. 17. Markers, from north to south positioned at: 34.5S, 35.0S, 35.5S, 36.0S, 36.5S.

The rapid transition in weather conditions has implications for fire behaviour, and this is reflected in the FFDIs and GFDIs calculated from the observations at each site, also shown in Fig. 16. Of particular concern from a fire management perspective is the change seen at CFSA, near the Central fire, where conditions at the fire ground changed from relatively benign, with light winds and high relative humidity, to dry and windy within the space of half an hour. The change in fire activity is apparent in the MODIS satellite imagery (Fig. 13 and Fig. 14) where the red pixels depicting fire area increase significantly at both the Central and D'Estrees fires in the four-hour period between images. The implicit change from a low flame height, slow-moving fire to a more intense, fast-moving fire with high spotting and crowning potential has clear implications for positioning of assets and safety of firefighting ground crews.

Examination of the observations and Meso-LAPS data in Fig. 16 shows the following;

- The hourly Meso-LAPS point forecasts picked the general trends, but failed to capture the rapid transition in wind and dewpoint late morning at Kingscote, CFSA and CFSC AWSs.
- The decoupling of the winds at inland sites overnight and well into the morning was not resolved, either in speed or direction, an issue frequently found in numerical weather predictions.
- Afternoon dew points were forecast several degrees too high, the drying trend was underestimated.
- Overall, prediction of FFDIs and GFDIs, particularly in forecast afternoon maxima are quite good, providing some confidence in the use of meteorological model output for running fire behaviour models.

The rapid transition in late morning weather conditions highlights the need for fire managers to have skilled fire weather forecasters and up-to-date forecast information at fire sites. As seen in this example, current conditions may not be indicative of conditions a short time later and having accurate information in advance of such a change has the potential to save lives. PAWS frequently provide excellent weather observations from fire sites, however real-time monitoring of observations is complementary to, not a substitute for, use of the predictive guidance included in weather forecasts. With good communication channels, relevant weather information can be relayed within a matter of minutes to hours, well within the timescale for movement of resources.

Nocturnal effects

The observations from CFSD highlight an important aspect of fire activity in coastal locations. The AWS was sited very close to the coast and as a result well exposed to northerly winds overnight. In conceptual models of bushfires, fire activity is expected to die down after sunset due to radiative cooling producing higher relative humidity, thus increasing uptake of fuel moisture. Simultaneously, a decrease in wind speed occurs due to decoupling inhibiting vertical mixing during the overnight period. Along the exposed southern Australian coastal environment, this model of diurnal variation is not always appropriate, as decoupling does not always occur and wind speed can remain high overnight. Cruz and Gould (2010) describe mallee-heath fuels as having a stronger response to wind and fuel moisture than to temperature and relative humidity and in some coastal environments (for example Kangaroo Island and Wilsons Promontory), these fuels are dominant, therefore fire activity may not decrease significantly overnight. The Wilsons Promontory fire in 2005 provides an example of nocturnal decoupling failing to take place at a coastal site. A peak in overnight wind speed resulted in the escape of a fuel reduction burn (at approximately 11pm) and a wildfire that eventually consumed 7000 ha of National Park (Bureau of Meteorology, 2007). The winds at the time were blowing from the northwest, a marine trajectory across northern Bass Strait to the west of the promontory. The maritime trajectory would inhibit the establishment of a radiative cooling driven nocturnal inversion, thus enabling mixing of wind and temperature from the low levels of the atmosphere to be sustained through the overnight period. The Bureau of Meteorology report describes a marked overnight increase in temperature and wind, which opposed the normal diurnal cycle.

Veering winds

The observations of wind direction at the seven AWS's show significant variation across the island during the afternoon (see Fig. 16). In the northerly synoptic flow, at sites on the northern side of the island wind direction is east of north, while at the southern sites it is west of north. Cape Borda held a 50-70^o direction for several hours, while a short distance away at CFSD AWS, wind direction was 10-30^o during the same period (10am-5pm local time). At CFSA and CFSC, wind direction was west of north from midday onwards. Figure 19 shows that the Meso-LAPS captured the trend across the island, but not the full extent of the backing of the wind direction.

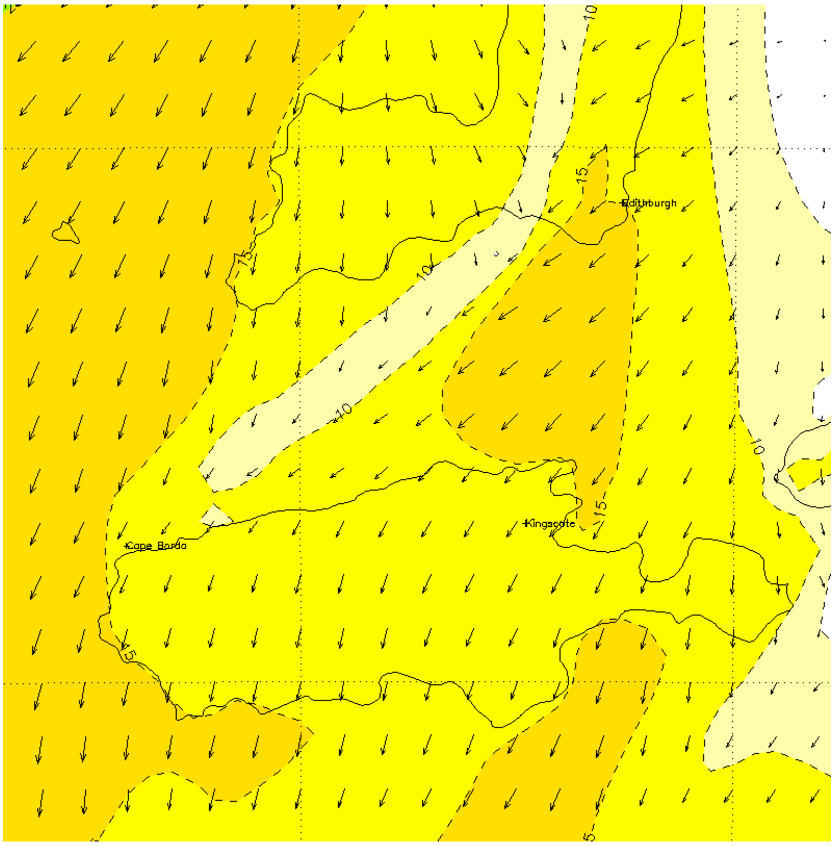


Fig. 19 Meso-LAPS sigma level 0.9943 winds 15:30 local time 13th December.

Sea breeze

Observations from Kingscote, CFSA, CFSB and CFSC AWS's all show development of a late sea breeze between 1730 and 1930 local time. The sea breeze onset in each case is identified by a decrease in temperature and increase in dewpoint coincident with a local onshore shift in wind direction. The sea breezes were not forecast by the Meso-LAPS guidance. Absence of a forecast sea breeze on the south of the island is consistent with gradient wind theory which suggests that the northerly winds blowing offshore perpendicular to the coast may have been of sufficient strength to prevent sea breeze development. Houghton and Campbell (2005) suggest 25 knots is the threshold for a gradient offshore wind to hold out the sea breeze, indicating the observed gradient wind was sufficient to prevent a sea breeze on the day. However, the observations show that sea breezes did occur, and penetrated several kilometers inland.

There are two possible explanations why development of a sea breeze was not depicted in the Meso-LAPS model. The first is that the resolution of the model, or its representation of physical processes, were insufficient to resolve the sea breeze, possibly due to the smoothed model topography. The second is that the active fires had modified the environment sufficiently for a sea breeze to develop counter to the strong gradient wind. The area burnt by the Chase fire covered several thousand hectares by late afternoon, and although not all the area would be actively flaming or smouldering, the fire may have altered the local temperatures, as well as created convection in the smoke plume, hence modifying the local wind regime. These fire-induced changes to temperature and wind may have been sufficient to alter conditions sufficiently that the Meso-LAPS initialization and forecast integration was invalid as the model output would be for sea breeze dynamics in a non-fire affected environment.

6. ROCKY RIVER (CHASE) FIRE, 9TH DECEMBER

Extreme fire behaviour was observed on the 9th at the Chase fire, which was at the time burning through the Rocky River gully on the western end of the island (Fig. 20). Much of the terrain in the area is inaccessible national park, dissected by a network of creeks and rivers. Rocky River is the largest river on the island and was the location of the observed extreme fire activity. Early on the 9th, the fire was burning in the gully north of the visitors centre (approximate fire area marked A on the map in Fig. 20). During the day, the fire burnt northwards, up the gully (approximate area marked B in Fig. 20) and breached the Playford Highway at the top of the gully. Figure 21 shows the topography of the gully. The southern end of the gully, near fire area A, is approximately 100m above sea level. At the Playford Highway, elevation rises to approximately 300m above sea level. Thus, the gully rises approximately 200m over a distance of ~20km, a small slope gradient of less than one degree.

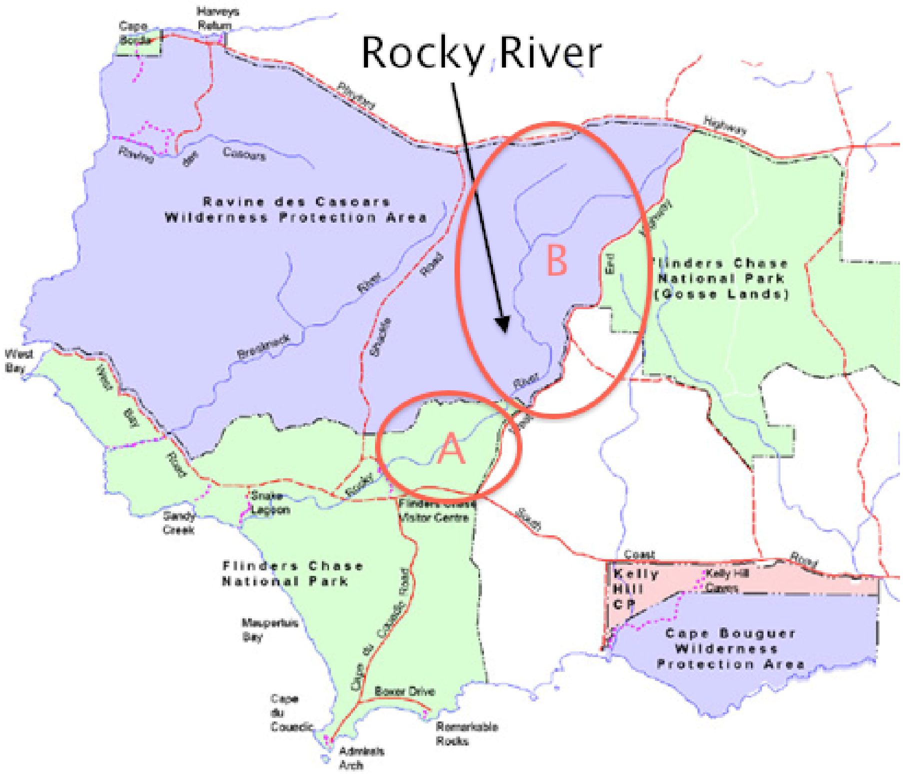


Fig. 20 Western end of Kangaroo Island, showing location of Rocky River. Regions A and B show approximate burn area early 9th December (A) and early 10th December (B).

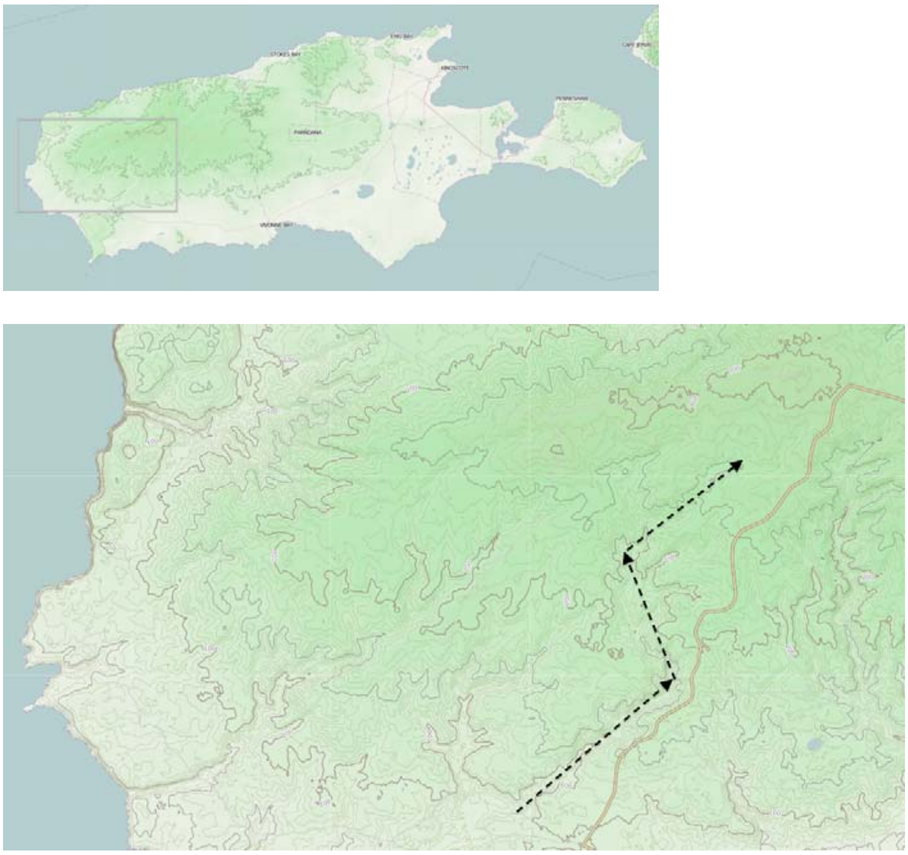


Fig. 21 a & b. Topography of Kangaroo Island (a) with (b) showing the Rocky River area (depicted in a).

The meteorology of the day could be considered relatively benign by fire weather standards in southern Australia due to the mild temperatures. Conditions were typical of an early summer post-frontal change day. A ridge of high pressure was pushing strongly in from the west in the wake of the front that passed across the previous day (see Fig. 22). Temperatures peaked in the mid-to-high teens mid-afternoon and dewpoint temperatures decreased throughout the day in the drying airstream circulating the developing ridge. Cloud cover was scattered to broken, with a base around 1500m and capped by a relatively strong inversion at around 2000m. MODIS imagery (Fig. 23) suggests the smoke plume from the fire(s) did not penetrate the inversion and was confined within and beneath the cloud layer, although there is some uncertainty in this that will be discussed later. The smoke plume from the fire was well dispersed through the eastern quadrant, driven by low-level west-to-southwest winds.

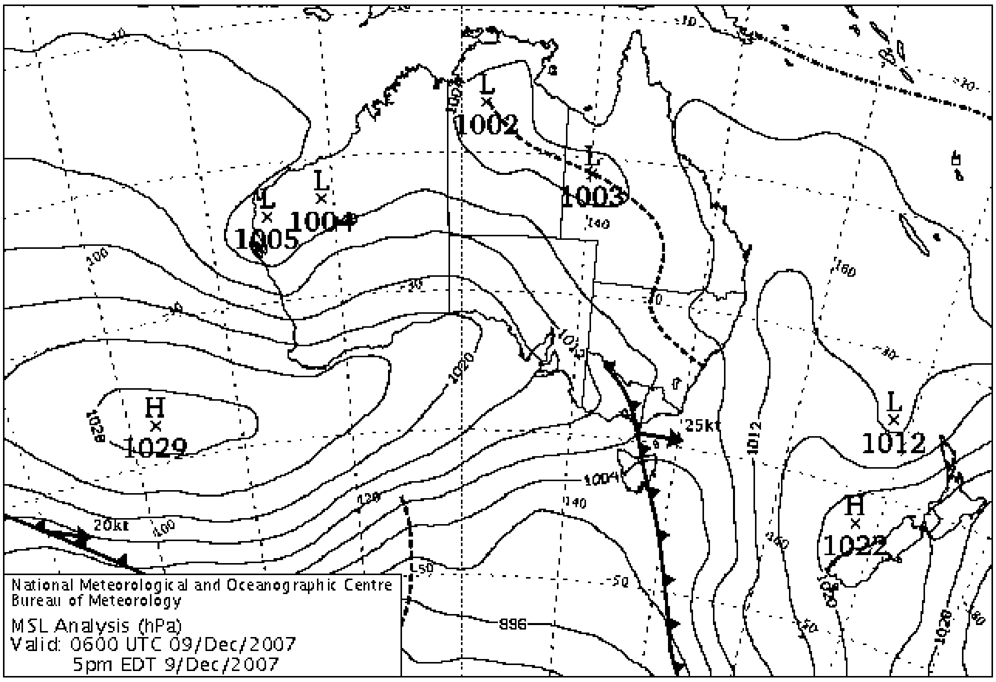


Fig. 22 Australian region MSLP chart 0600UTC 9th December 2007.

Consideration of the FDI ratings on the day is insightful. Figure 24 shows the observations from the Solly PAWS (CFSD), located closest to the Rocky River head fire (see Fig. 4 for location). From the observations, FFDI and GFDI peaked at 13 and 14 respectively, values inconsistent with any expectation of extreme fire behaviour. These FFDI and GFDI values in the low teens did not discriminate the 9th as being significantly different to any other day in the first week of the fire, contrary to the experience of the fire fighters, who found that the day produced some of the worst fire ground conditions they had ever experienced.

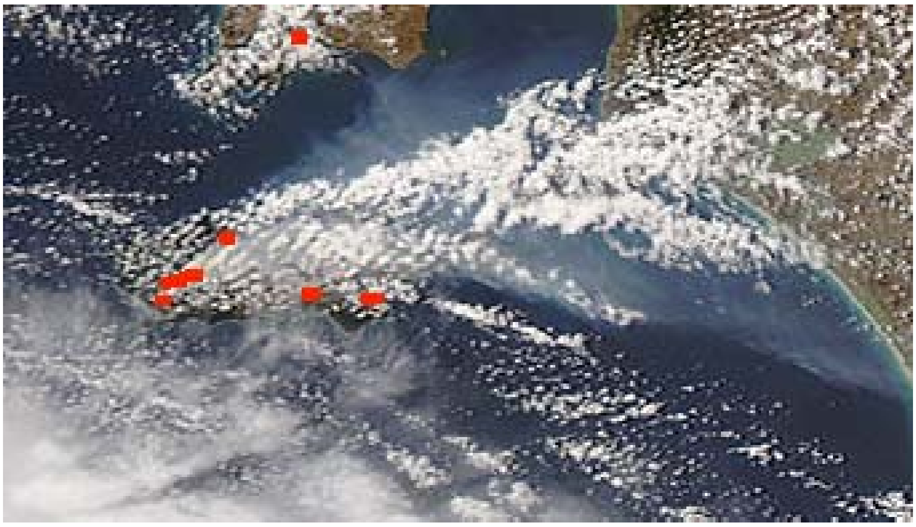


Fig. 23 MODIS image 14:40 9th December.

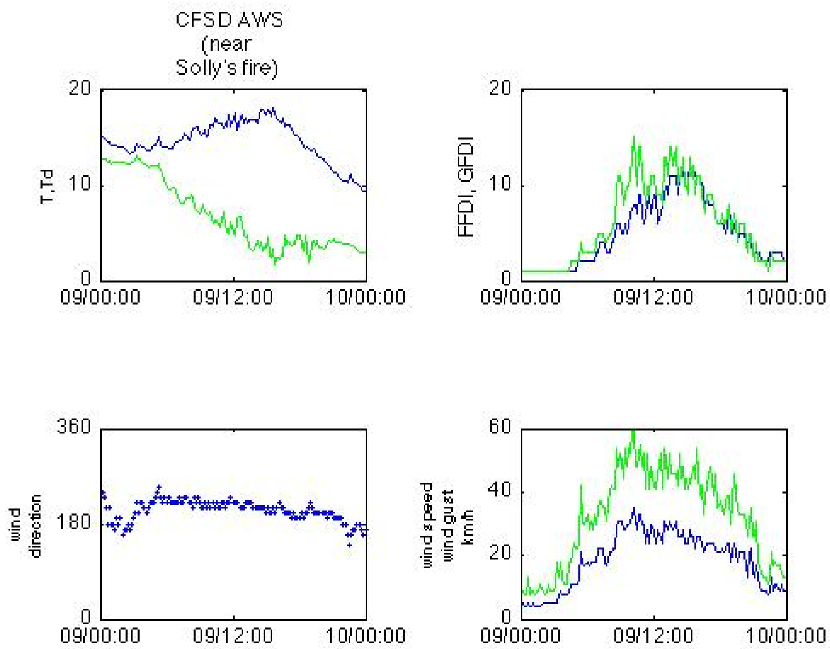


Fig. 24 Observations from CFDS (near Solly's fire) for the 9th December, midnight to midnight local time. Clockwise from top left: Frame1 – blue lines observed temperature, green lines observed dewpoint temperature. Frame 2 – blue lines FFDI calculated from observations, green lines GFDI calculated from observations. Frame 3 – blue lines observed wind speed (km/h), green lines wind gusts Frame 4 –. blue crosses observed wind direction.

Conversations with Kangaroo Island fire manager Rob Ellis provide the following (paraphrased) description of the Rocky River vegetation and fire behaviour on the 9th December:

The dominant vegetation in Flinders Chase National Park [and adjacent Ravine des Casoars Wilderness Protection Area] varies from creek line to ridgetop. Along the creek lines, sugargum and stringybark predominate, which, in combination with a heavy understorey, creates a regime of extreme fuel loads. On the ridges the main vegetation is mallee [Kangaroo Island mallee ash and coastal white mallee]. The riparian vegetation along Rocky River creek line provided the engine for the fire on the 9th. The area had previously been burnt in 1990 and 1991 when two fires consumed parts of the north of the reserve. Prior to the early 90's, the area was last burnt in 1958.

On the 9th December the Chase fire moved rapidly along the Rocky River riparian zone. The movement of the fire was confined to the creek line. The fire followed the valley as a finger of fire. The ridges didn't burn. Drivers for the fire were the heavy loads of volatile fuel, the strong southerly winds and the local topography. Fanned by the south-southwest winds, the fire moved 12km in 9 hours.

The fast moving fire was inaccessible within the gully, hampering any suppression activities. The head fire was expected to reach the [Playford] highway during the day, therefore efforts were focused on containing the fire at the highway. Chaining and back-burning activities were only just completed before the fire came out onto the road. The intensity of the rapidly approaching fire resulted in crews being evacuated from the area *before the eventual breach of the barrier. Aircraft bombing efforts had no impact on the intense fire.*

As the head fire approached the highway, spotting activity resulted in the ignition of a second fire on the northern side of the highway, 1-2 km ahead of the main fire front. As fire fighting personnel watched, the second fire was drawn back into the main head fire, against the prevailing winds, over a distance of a kilometer or more. As the spot fire was 'sucked backwards' flame heights were estimated to reach 45-50m. Fire managers present had never seen such a phenomena in several decades of experience, particularly in mild temperatures not expected to be conducive to extreme fire behaviour. The fire behaviour observed was equivalent to that seen in regimes of FDIs 50 or greater (Rob Ellis, pers. comm. 2010).

Figures 25 and 26 show the fire as it emerged from the head of the Rocky River gully onto the Playford Highway.

Fig. 25 Flinders Chase fire 9th December 2009. Picture R. Ellis.

Fig. 26 Flinders Chase fire 9th December 2009. Picture R. Ellis.

There are a number of factors that will be considered in the discussion of this day.

- Applicability of the McArthur meters to different fuel types.
- Channelling in the gully, local slope and vegetation.
- Fire and atmosphere interaction.

Local vegetation and the McArthur meters

As previously discussed, fire management in Australia relies heavily on use of the McArthur meters for grassland and forest. These two fuel types do not represent the diversity of vegetation regimes that exist across the Australian continent, and mallee-heath fuels are one vegetation type that does not fit the fire behaviour profile described by either the grassland or forest meter.

Cruz and Gould (2010) describe fire behaviour in mallee-heath fuels based on experiments in the semi-arid conditions of Ngarkat Conservation Park in inland southeastern Australia. Cruz (2010) provides a fire behaviour guide encapsulating the results of the study. The study and guide describe fire spread in mallee-heath fuels as being dependent on the parameters of wind, fuel moisture and fuel load, as well as the arrangement of the vegetation. The guide gives a “go/no go” threshold for sustained fire spread in mallee-heath based on the above parameters. As the Kangaroo Island mallee fuels are described as ‘wet’ mallee with an intact understorey they are dissimilar to the semi-arid mallee-heath fuels for which the fire behaviour guide has been developed. However, the mallee-heath model proposed by Cruz (2010) may be more applicable to fuels on Kangaroo Island than the McArthur models for forest and grassland. In December 2007, fuels were very dry due to an extended drought, fuel loads were high and, most notably, wind speed was well above the maximum value of 15km/h used in the fire behaviour guide.

In order to provide a comparison of the fire behaviour in different vegetation types, values for fire danger, fire spread and other relevant parameters were calculated from the observations from CFSD PAWS, north of the fire.

Table 4 Fire behaviour parameters in grassland from archived and calculated data.

Weather observations at time of maximum GFDI (10:10)			
Temperature	Relative humidity	Wind speed & direction	GFDI (obs)
16.1°C	51%	35km/h 220°	15
GFDI calculations from observations			
	Rate of spread	Fuel moisture	GFDI
Mark 5	2.4km/h	13.4%	19
Mark 4	2.0km/h	n/a	16

Table 5 Fire behaviour parameters in forest from archived and calculated data.

Weather observations at time of maximum FFDI (13:30)				
Temperature	Relative humidity	Wind speed	Wind direction	FFDI (obs)
16.9°C	41%	31km/h	220°	14
FFDI calculations from observations				
	Flame height	Spotting distance	Rate of spread	FFDI
Fuel load 15t/ha	4.17m	0.37km	0.21km/h	11
Fuel load 25t/ha	8.29m	0.74km	0.35km/h	11

Table 6 Fire behaviour parameters in mallee from archived and calculated data following "Quick guide for fire behaviour prediction in semi-arid mallee-heath".

Fire behaviour in mallee from "quick guide"		
Step 1A	Estimated fuel percent cover score	PCS = 3-4
Step 1B	Estimated elevated fuel hazard score	FHS = 3-4
Step 2	Estimated dead suspended fuel moisture content	FMC = 11.5
Step 3	Likelihood of sustained propagation	100%
Step 4b*	Estimate rate of fire spread for Mallee shrublands for 4m fuels	3.5km/h with active crown fire propagation

The calculated grassland indices are unlikely to be appropriate for the Rocky River area. It is worth noting, however, that the model produces a fast rate of spread (~2-2.5km/h), which is similar to observed estimates of the movement of the head fire up the gully. Using the McArthur model for forest provides an unsatisfactory result, as the rate of spread of less than 0.5km/h with flame heights 4-8m is highly inconsistent with the observations provided by Rob Ellis, to the extent that operational reliance on these estimates would have significant potential to compromise fire fighting strategies. The mallee-heath guide, although developed for semi-arid fuels, provides indicative estimates of fire spread of the Rocky River fire, as sustained propagation occurred and the rate of spread 3-4km/h is consistent with observations, given that the speed of travel of the fire front would vary during the day and crown fire propagation clearly occurred (see Fig. 26). Information provided by Rob Ellis indicates that during the afternoon, the fire moved 8-9km in a 4 hour period.

These observations emphasise the need for appropriate fire behaviour models to be applied to different fuel regimes in the Australian biota. There is widespread agreement amongst the Australian fire management community that the two models of fuel type (grassland and forest) proposed by McArthur are not sufficient to describe the range of vegetation types that occur in fire prone areas across the country. Research in recent years had examined fire response in fuels as varied as mallee scrub, jarrah forest and northern savannah, however the emphasis of operational forecasts remains with the McArthur meters. The Rocky River fire provides a clear example of why updating current operational practice is necessary.

The role of dynamic channelling, local topography and vegetation.

Observations from the fire ground highlight the fact that the advancing head fire was confined to the Rocky River gully and did not progress to the adjacent ridge tops. There are a number of factors that could have contributed to this behaviour.

- The heaviest vegetation loads of sugargum, stringybark and understorey were concentrated along the creek line, providing an abundance of near surface and elevated dry fuel for combustion, in a wind regime conducive to sustained crown fire propagation.
- Channelling and slope effects may have played a role, as the head fire was being driven by winds aligned with the gully and in the upslope direction. However, the

shallow relief of Kangaroo Island provides a relatively weak mechanism (compared to mountain ranges where channelling and slope effects are typically considered).

- Vigorous low-level atmospheric turbulence was present, indicated by the gusty winds in AWS observations and the cellular structure of the cumulus cloud field on MODIS imagery. The low-level convective activity would contribute to vertical mixing over the fire.

Sharples (2009) synthesises a range of papers on general mountain meteorology and places the results in the context of fire management in the Australian landscape. In particular, he draws on the work of Whiteman and Doran (1993) who proposed four mechanisms for valley induced winds. The four mechanisms are: thermal forcing; downward momentum transport; forced channelling and pressure driven channelling. Sharples (2009) groups the latter three mechanisms into the category "dynamic channelling" and refers to two cases where dynamic channelling produced unexpected and extreme fire behaviour resulting in loss of life and property. Although the mechanisms described have been studied in more mountainous terrain than the lower relief of Kangaroo Island, each of the four effects will be briefly considered for the Rocky River fire.

Thermal forcing occurs as part of the diurnal mountain wind system and is also known as an anabatic wind. During the daytime, heating causes a temperature gradient along a valley axis. Air at the top of the valley rises through convection, producing a thermally induced pressure gradient between elevated surface air and lower altitude surface air. This induced pressure gradient drives a wind regime flowing up-valley. For the Rocky River fire, the source air mass for Cape Borda in the southwest flow was of maritime origin, compared with a land trajectory southwest of CFSD. Interestingly, the temperature observations at Cape Borda and CFSD PAWS were not significantly different, perhaps due to the wind strength and mixing effectively shortening the trajectory as well as reduced insolation due to cloud cover. As Whiteman and Doran suggest thermal gradients should be large and ambient upper winds weak, a significant contribution to the fire ground via thermal forcing is unlikely.

Pressure-driven channelling is described by Whiteman and Doran (1993) as winds in a valley driven by the component of the geostrophic pressure gradient along the length of the valley. Whiteman and Doran suggest pressure-driven channelling is a dominant mechanism in shallow valleys with light to moderate geostrophic flow and a stable atmosphere. As these conditions, in particular the requirement for geostrophic flow speed, are not readily reconciled with the Rocky River topography and observed atmospheric observations, it is unlikely that pressure driven channelling occurred.

Downward momentum transport is described by Whiteman and Doran (1993) as the downward transport of horizontal momentum due to vertical mixing caused by convective turbulence. Whiteman and Doran do not clarify the mechanism by which this effect should be different in a valley regime compared to a flat plain. They suggest this is most likely to occur in flat, wide valleys with low sidewalls with strong winds above the valley, especially if stability is weak. The inference is that the mixing mechanism would allow the stronger winds to penetrate the bottom of the valley, where otherwise stable stratification would not permit it. The Adelaide radiosonde and cumulus field observations are both indicators of convective turbulence over the region, however, whether downward momentum transport as described by Whiteman and Doran occurred, and the extent to which it may have impacted the Rocky River fire is undetermined.

Forced channelling is described by Whiteman and Doran (1993) as the alignment of winds with the valley axis due to channelling of the ambient geostrophically balanced winds by the valley sidewalls (Fig. 27). The synoptic pattern of the 9th December was high pressure to the west-southwest and a low to the east-northeast (see Fig. 22), producing geostrophic flow aligned with the south-southwest to north-northeast oriented valley (see Fig. 21b). Therefore, of the mechanisms described for valley-induced winds, the conditions are most conducive to a contribution of forced channelling to the wind regime at the Rocky River fire.

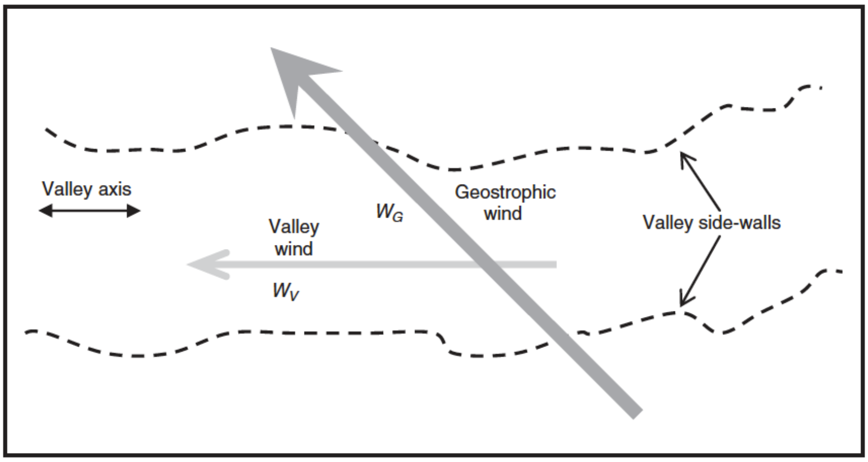


Fig. 27 Schematic of forced channelling as the geostrophic wind is deflected by the valley sidewalls so that the surface wind is forced to flow along the valley. (From Sharples 2009).

Fire atmosphere interactions

There are three fire-atmosphere interaction processes that may have occurred and will be discussed in the next section; the first is the drawback of the spot fire by convergence in the wind field, the second; convergence on the fire flanks leading to confinement of the fire to the gully, the third; dry air entrainment from aloft by turbulent mixing in the convection column.

As described by Rob Ellis, a spot fire ignited in front of the main head fire and the second (spot) fire was then drawn back towards the main fire front, against the south-westerly prevailing winds, over a distance of more than a kilometer.

Fires, particularly large bushfires, generate sufficient energy to modify their local environment. Vines (1981) states "…in an intense fire, interaction with the atmosphere may be of such significance that the fire itself can influence the prevailing meteorological conditions…". In view of this, fire researchers have employed coupled fire atmospheric models to examine in detail the wind regime in the wildfire (USA) environment. A number of studies have simulated fires using coupled atmosphere and fire models to capture feedback in fire dynamics, including Clark et al, (1996), Sun et. al. (2009), Coen (2005), Hanley et. al. (2006) and Jenkins (2002). The results of all of these studies show convergence at the head of the fire. Coen's 2005 simulation of the Big Elk Fire shows how coupling affected the near fire winds to several kilometers from the fire, creating a convergent regime with winds of significant strength at the head of the fire. Similarly, Jenkins (2002) showed wildfire-atmosphere circulations changing atmospheric conditions across the model domain. This is also consistent with the observations from three intense experimental burns conducted in Western Australia and described by Taylor et al (1971). Their study notes that suppression crews consistently observed the winds blowing into the fire at all points on the perimeter.

Inferred from the evidence described above, it is probable that the main head fire at Rocky River was of sufficient intensity to create a convergent wind regime inwards so that the second smaller spot fire was captured within the convergent zone, hence the observed “draw-back” of the second fire into the main conflagration. The distance of one to two kilometers is consistent with the spatial scale described by Coen (2005). The description of the “draw-back” of the spot fire strongly indicates that the fire was modifying the local wind regime.

The fire was described as being confined to the (relatively shallow) gully. Fuel loads in the gully are significantly heavier than on the adjacent ridges, as described by Rob Ellis and others. Although quantitative estimates are not available, the fuel distribution can be clearly seen on satellite imagery. Therefore, it is possible that the high fuel loads in the gully, in combination with localized feedback causing wind convergence into the fire flanks, contributed to confining the fire to the gully. It is reasonable to assume that fire atmosphere interactions caused convergence along the fire flanks, and this convergence was enhanced by the heavy fuel loads in the gully, and these factors combined to cause the fire to follow its distinct path along the gully axis.

Another feature of fire-atmosphere interaction that may have occurred can be inferred by examination of the Adelaide radiosonde observations and consideration of the possible height of the convection column. The Adelaide radiosonde (Fig. 28) shows a strong inversion near 800hPa associated with the developing ridge. Above the inversion lies extremely dry air, with dewpoint temperatures below -40°C. The Meso-LAPS 05 model depicts the inversion near 850hPa over Kangaroo Island, approximately 50hPa lower than over Adelaide, a reduction consistent with the maritime environment resulting in a lower inversion than the (well verified) model forecast over Adelaide. If the convection column from the Rocky River fire was sufficiently strong to penetrate the inversion, mixing of dry air from above the inversion into the fire environment would have the potential to impact fire behaviour due to the difference in relative humidity (around 40% in the ambient stream to as low as 1-2% with entrainment). In order for the convection column to penetrate the inversion, a column height of around 1300m would need to be attained, allowing for elevation above sea level. In order to discuss whether the required column height could be achieved, reference will be made to the results of Morton et al (1956).

Using theory of thermal convection, Morton et al derived equations for predicting the height to which smoke plumes from typical sources will rise in a still atmosphere. They showed that a forest fire consuming 1000t/hr of fuel per hour would produce a smoke plume to 2200m. The fuel consumption of 1000t/hr is comparable to that of the Rocky River fire, allowing for a valley width of ~200m and fuel loads of 20t/ha. However, Morton et al stipulate that their calculations only apply to a still atmosphere and the estimated heights will be too great under windy conditions due to entrainment. Therefore, due to the strong observed winds the results of Morton et al cannot be directly applied to the Rocky River fire, however, their results suggest it is possible that entrainment of dry air from above the inversion may have occurred. As previously mentioned, from the afternoon MODIS image (Fig. 23) it is not possible to determine whether the inversion was penetrated by the fires’ convection column.

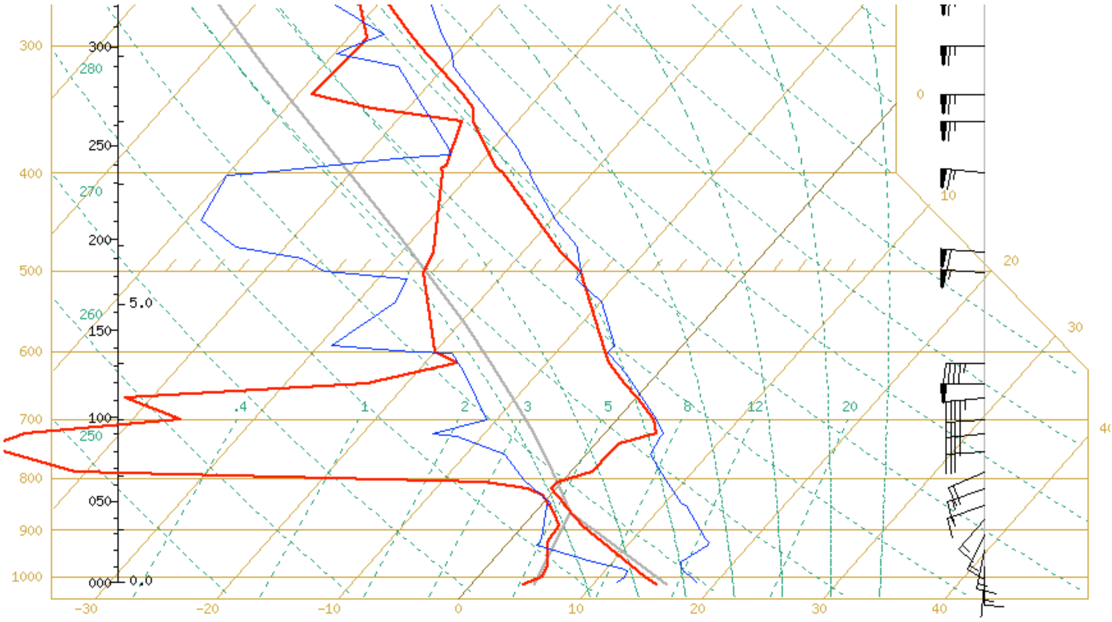


Fig. 28 Adelaide radiosonde, 1200UTC 9th December.

It is therefore hypothesized that the Rocky River fire activity occurred in part due to a fire atmosphere interaction positive feedback loop. The suggested process is that the fire, burning in heavy fuels in the gully, produced a convection column of sufficient height (1-1.5km) to entrain dry air from above the inversion, which mixed dry air through the downward arm of the convection column to the surface. Near surface relative humidity could thereby reduce to ~1-2%, hence reducing fine fuel moisture content below 5%, leading to a more active fire and stronger convection column, hence increasing dry air entrainment, etcetera. The fuel response is consistent with the time scales for fine fuel drying of less than one hour.

Mixing of dry air from aloft as a mechanism for fine fuel drying, resulting in enhanced fire activity has been previously described for Australian case studies by Mills (2005, 2007 and 2008). The atmospheric processes proposed by Mills were (1) mixing from mid-tropospheric dry slots (seen in water vapour imagery) and (2) turbulent mixing due to the vertical circulation on an easterly change. The process proposed here is somewhat different as it is suggested the convection column of the fire itself produced the necessary vertical motion for dry air from aloft to be entrained and brought down to the surface. Further examination is required in order to ascertain the validity of this hypothesized process.

One uncertainty in the hypothesis proposed above is whether the energy contained in the convection column is sufficient to break the stable (inversion) layer and overcome the static stability of the air parcel(s) in the environment. As (very) dry air above subsidence inversions is a pattern periodically observed at prescribed burns exhibiting unexpected fire behaviour (data provided by Mike Wouters, DENR), improved understanding of possible mechanisms for entrainment would be useful.

The presence of dry air above the inversion on the 9th December is well depicted in the Meso-LAPS model fields. Figure 29 shows wind and relative humidity at 700hPa at 0500UTC and dry air can clearly be seen over Kangaroo Island. The black area in Fig. 29 corresponds to relative humidity below 1%.

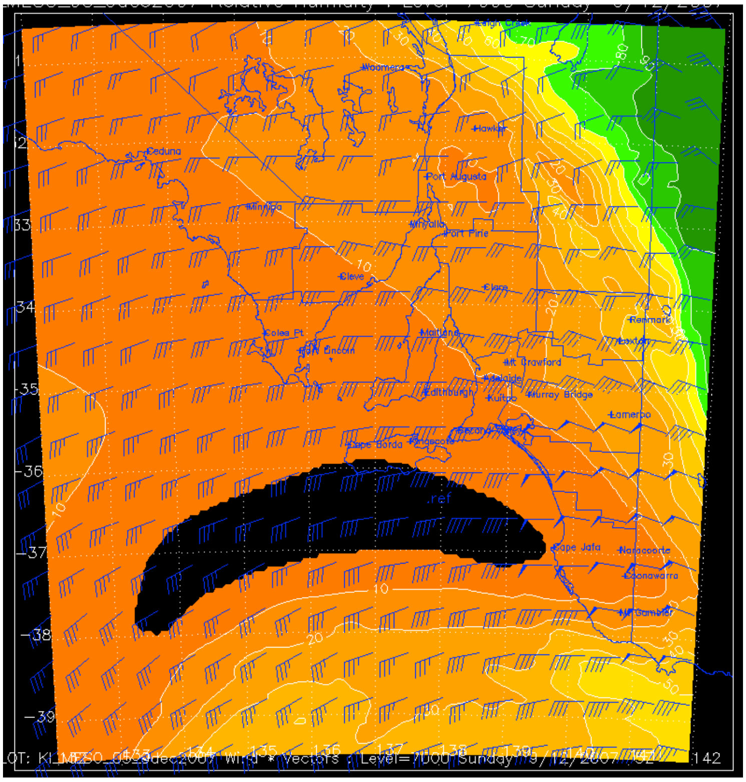
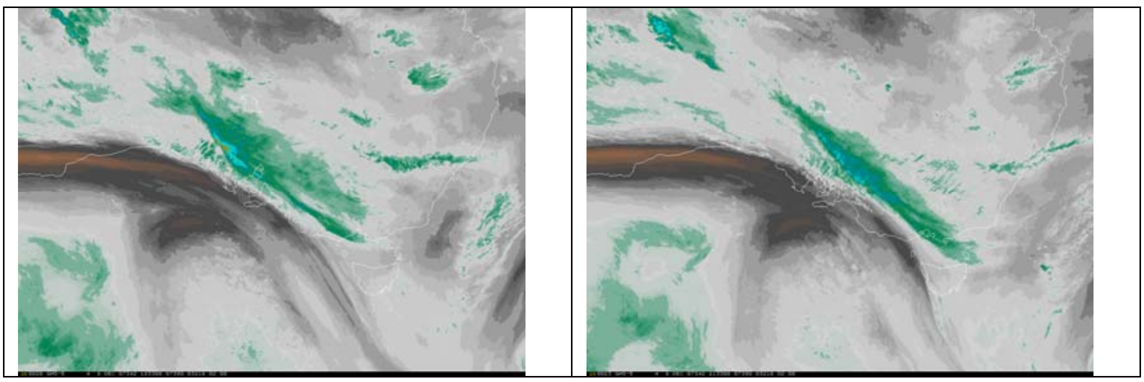


Fig. 29 Relative humidity and wind at 700hPa 0500UTC, 9th December from the 0000UTC Meso-LAPS model run.

The water vapour sequence shown in Fig. 30 shows the origins of the dry air. From Fig. 30 the dry air can be seen to be associated with the ascending arms of both the subtropical and polar front jets in the mid to upper levels. The mid to upper level origins of the dry air are also seen in the 1200UTC observations on the 8th December (blue line in Fig. 28). Strong subsidence with the incoming ridge is likely to have caused the descent of the dry air. From consecutive vertical profiles at Adelaide airport, tracking the height of the dry air, the estimated rate of subsidence is ~12hPa per hour. This descent rate is consistent with the assessment of Mills (2008) and references contained within, that subsidence of 100-200hPa in 12 hours is not atypical for synoptic scale vertical advection in the troposphere. Although Fig. 30 (4) shows increasing water vapour over Kangaroo Island near the time of enhanced fire activity, this increasing moisture is in a layer overlying the extremely dry air seen earlier in the time series (see the increasing moisture at ~400hPa at 1200UTC in Fig. 28).



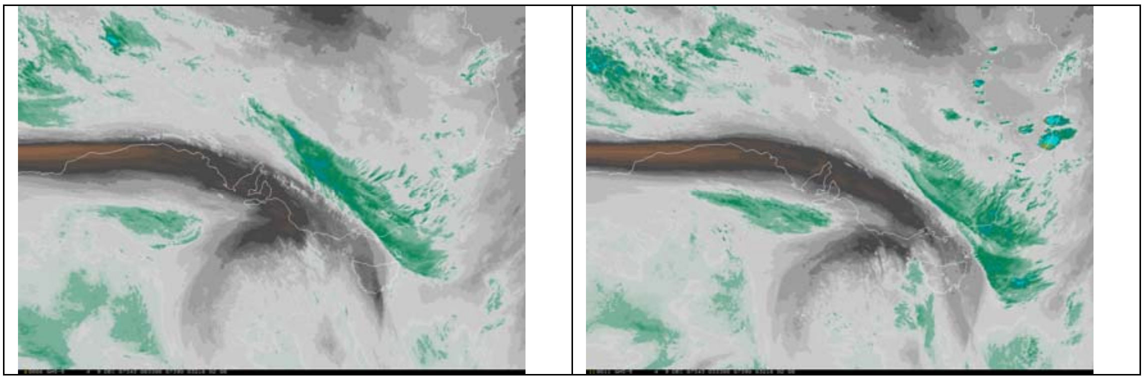


Fig. 30 Water vapour sequence at three hourly intervals to the afternoon of the 9th December. Left to right from top left (1) 8th December 1833UTC (2) 8th December 2133UTC (3) 9th December 0033UTC (4) 9th December 0333UTC.

The hypothesis that dry air was entrained downwards by the fire's convective column, hence contributing to the observed extreme fire behaviour is offered some support by evidence from other cases in southern Australia. Lists of prescribed burns at which unexpected fire behaviour was observed have been compiled by the Department of Environment and Natural Resources of South Australia and the Western Australia Department of Environment and Conservation. Initial, brief, analysis of the dates and locations of the burns shows a number of the cases had an atmospheric profile of relatively moist near surface air, with a low inversion overlain by dry air. This indicates there may be a pattern in dry air entrainment from above an inversion causing the observed unexpected fire activity. Further examination of these cases is warranted, as a link may be proven between unexpected fire behaviour and dry air above (subsidence) inversions.

The Rocky River fire and the cases mentioned above add to the growing body of evidence (see Mills 2005, 2007 and 2008) that entrainment of dry air from aloft (by various turbulent mechanisms) is a recurring feature in observations of unexpected extreme fire behaviour in Australia. Reiterating Mills (2008), due to the potential impacts of such events, further investigation into their occurrence and work on improving predictive capacity for future scenarios is warranted.

A number of factors have been described in the context of the observed fire behaviour on 9th December: the role of fire atmosphere interaction; applicability of the McArthur meters to different fuel types, the role of local topography and possible fire-atmosphere interactions. The discussion shows that although the observed extreme fire behaviour on the 9th was inconsistent with expectations from the FDI values, the observations can to a large extent be reconciled by knowledge of the local environment and by reference to research material. This highlights the need for both continued research into progressing fire science and detailed knowledge of local conditions during bushfires. Continued progress and awareness may in the future allow dangerous conditions to be anticipated in advance of their occurrence. As comprehensive observation sets are infrequently obtained from bushfires and prescribed burns, other tools are required in order to examine the processes that occur in detail. One such mechanism is the use of coupled fire behaviour models and the next section will discuss this.

7. FIRE BEHAVIOUR MODELS

In response to ongoing developments in technology, community requirements and devastating bushfire events, the Australian fire management community is looking towards improved methods of bushfire planning and response. One trend is towards assessing of the usefulness of gridded forecast parameters to drive fire behaviour models in order to predict fire spread in near-real time.

Sullivan (2009a,b and c) provides a comprehensive review of wildland surface fire spread models. He divides the models into three types: physical or quasi-physical, empirical and quasi-empirical and mathematical simulation or analogue. He describes the simulation models as implementations of existing one-dimensional empirical or quasi-empirical models, converted to two dimensions in order to simulate the propagation of fire across a landscape. Such models include Farsite, an American model based on the Rothermel equations (Finney, 1998), Sirofire or Phoenix, developed in Australia (Tolhurst et al 2008) and Prometheus, developed in Canada (Tymstra et al 2010). These quasi-empirical models are currently a focus for research in Australia.

Weather information is a required input for fire behaviour models. The Meso-LAPS model described in this study was superseded in 2010 by the ACCESS-C model. The ACCESS-C output is a primary input for the forecaster edited grids of the Bureau of Meteorology's Next Generation Forecast and Warning System. The forecast and warning products are accessed online through the "Forecast Explorer" user interface, with the data available for a range of user requirements. As the system is implemented across Australia, the weather grids will become available for running fire behaviour simulations both in research mode and in real time.

Uncoupled, empirically based fire simulation models such as FarSite, Phoenix or Prometheus may be run with either grids from ACCESS-C, or grids from the NextGen system. The verification shown in this study indicates good skill in forecasting the parameters that are required as inputs to a fire behaviour model. Equally, the verification shows some limitations, particularly with respect to prediction of moisture and sea breeze effects. These limitations must be taken into consideration when assessing output of a fire behaviour model. Additionally, further research is required to determine the necessary resolution for a weather model in order to give appropriate input to a fire behaviour model.

Trevitt (1991) provides the assessment that "garbage in" results in "garbage out" from a fire behaviour model. He also (more eloquently) provides uncertainty estimates in fire rate of spread due to uncertainty in fuel moisture content and wind speed. Fujioka (2002) highlights the need to quantify errors in fire-spread models and provides a method for error analysis. His results, in part, provide evidence of how accurate weather inputs are critical for producing accurate fire spread results. However, as uncertainties in forecast weather parameters are inherent in the predictive process, a probabilistic approach to mapping fire spread rather than a deterministic approach is likely to prove superior as a risk management tool. Such a probabilistic approach is also suggested by Sun et al (2009).

Use of the models described above would not resolve any interactions of the fire with its environment. By contrast, a coupled fire-atmosphere model such as that employed by Clark et al (1996) and Coen (2005) have been shown to capture fire-induced modifications of the local wind regime. The most devastating bushfire events that have occurred in the Australian landscape since European settlement include Black Friday (1939), Ash Wednesday (1983) and Black Saturday (2009). Due to the extreme size and convective activity in these fires, feedback between fire and atmosphere is exacerbated, therefore objective consideration of the limitations of an uncoupled model become more relevant. These events therefore provide a strong argument for research on the use and development of coupled fire-atmosphere models in Australia.

8. CONCLUSIONS

This case study of the Kangaroo Island fires has described the meteorological forcing and resultant fire behaviour on three different days during the 2007 bushfires. As the local environment and boundary layer processes modified meteorology at the mesoscale, subsequent impacts were seen in behaviour of the fires. The features of each day were: on the 8th December, low level sea breeze convergence enabled realisation of potential atmospheric instability, resulting in an enhanced smoke plume or convective column over one of four active fires; On the 13th December, a day of near-extreme fire danger, boundary layer processes strongly modified the mesoscale meteorology across the island, processes that were partially captured by weather prediction models; and on the 9th December, extreme fire behaviour occurred due to a combination of factors including fire and atmosphere interactions, local fuels and dynamical interaction with local topography. On each day, the fire behaviour was noteworthy or unusual, and, in each case, the forcing mechanism differed.

This case study has aimed to provide insights into the fire environment at Kangaroo Island. In doing this, it aims to identify avenues for further research as well as suggest approaches for improving fire forecasting in order to benefit fire managers. The following conclusions are drawn from the study:

- Mesoscale processes, including boundary layer effects, local convergence and spatial variation are important aspects of fire weather, as these influences can have a dramatic impact on fire behaviour. More detailed information and interpretation could be included to a greater extent in forecast products as these have the potential to benefit operational decisions.
- Instability can play a critical role in fire behaviour. The instability role features at a small scale in this case study. Larger scale examples include the pyroconvection of the 2003 Canberra fires (Fromm et al, 2006) and the Black Saturday fires of 2009. Fire managers are likely to benefit from greater awareness and understanding of the role of instability in fire forecasting. Research into methods for routine inclusion of (in)stability information should be a priority towards improving fire forecasting in Australia.
- Results from coupled fire-atmosphere models clearly demonstrate the value of simulations capturing feedback processes. Such models are likely to provide insights into Australian bushfires and future research should consider coupled as well as uncoupled semi-empirical modeling approaches.
- Verification shows forecast guidance has skill in predicting parameters that input to fire behaviour models and the inference is that weather model inputs are likely to provide useful guidance in an operational fire behaviour model. Development and testing of a system for operational use would be of great benefit.
- Localised forecast guidance, detailed fuel and topographic knowledge used in conjunction with appropriate fuel meters are essential inputs to anticipating fire behaviour. Effective operational policies should encompass all the above information in order that conditions may be anticipated.
- Development and testing of an algorithm encompassing a FireCAPE probability forecast may produce an effective operational tool.

Bushfires will continue to occur in the Australian landscape and in order to mitigate against the impacts of large bushfires prescribed burning activities are likely to increase. Therefore, improved understanding and prediction of the inputs to fire behaviour are critical to enabling fire managers to make informed risk and resource allocation decisions in order to achieve objectives and ensure fire fighter safety.

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