Abrupt surface drying and fire weather Part 2: a preliminary synoptic climatology in the forested areas of southern Australia

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The climatology and synoptic environments in which abrupt surface drying events, such as those associated with two 2003 and 2005 wildfire events in Australia can occur, are described. Rules to identify such events over six fire seasons indicate that abrupt surface dryings might be expected to occur several times at a given station, although with considerable regional and interannual variability. It is shown that a significant proportion of the events can be associated with mid-tropospheric dry bands clearly identifiable in geostationary satellite water vapour channel imagery, and that the abrupt surface drying is a result of the exchange of this extremely dry air with the surface. Mechanisms that can contribute to this vertical transport are dry convective turbulence in deep daytime mixed layers, vertical circulations associated with frontal circulations, and topographically-induced flows on the downstream side of topographic barriers. Examples of these mechanisms are presented.

Introduction

Dramatic lowering of the humidity at the surface was observed at Canberra Airport and at Port Lincoln Airport AWS respectively during two recent Australian extreme fire weather events, that of the Canberra fires of 18 January 2003, and that of the lower Eyre Peninsula fires of 11 January 2005. These events have been described in more detail in Mills (2005a) and in a companion paper (Mills 2008), and the latter event also in Bureau of Meteorology (2005). As these two events led to the loss of several lives and massive property and infrastructure damage, and because fire activity increases very rapidly as fuel moistures reach extremely low values (Luke and McArthur 1978, p.88), further investigation of the meteorological factors that lead to such surface drying events is warranted. In Mills (2008) it was proposed that the abrupt surface dryings observed at Canberra and Port Lincoln were due to, first, deep upper to mid-tropospheric subsid-

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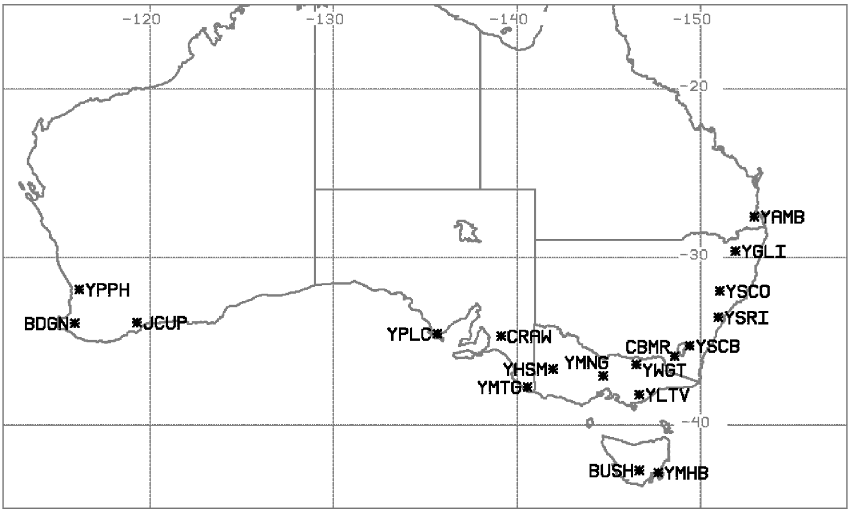
Fig. 1 Locality diagram. The station acronyms are as follows: YPPH-Perth Airport, BDGN-Bridgetown, JCUP-Jacup, YPLC-Port Lincoln, CRAW-Mt Crawford, YMTG-Mt Gambier, YHSM-Horsham, YMNG-Mangalore, YWGT-Wangaratta, YLTV-Latrobe Valley Airport, BUSH-Bushy Park, YMHB-Hobart Airport, CBMR-Cabramurra, YSCB-Canberra Airport, YSRI-Richmond Airport, YSCO-Scone, YGLI-Glen Innes, YAMB-Amberley.



ence generating a layer of extremely dry air in the mid-troposphere that was advected over the areas affected by abrupt surface drying, and second, the mixing of this dry air to the surface by, primarily, dry convective mixing in a very deep mixed layer. The influence of frontal circulations on the lower tropospheric part of this exchange process was also noted.

The extreme fluctuations in near-surface humidity in these two events only came to notice because of the wildfires occurring on those days. Yet if such events are to be forecast, it is necessary to understand their purely meteorological drivers and frequency, as in the absence of extreme fire behaviour they may well go unnoticed. This paper presents a preliminary synoptic climatology of these 'abrupt surface drying' events at a range of stations in the forested areas of southern Australia, in order to interpret the processes described in Mills (2008) in a more general context. In the next section of this paper a set of rules to objectively identify cases during a six-year data-set of hourly AWS data at a network of stations (Fig. 1) is described, and some statistical information as to frequency and time of occurrence is presented. Factors identified in the two case studies referred to above that might provide potential forecast guidance were the coincidence of mid-tropospheric 'dry bands' seen in the 6.7 μm 'water vapour channel' geostationary satellite imagery (WVI), the passage of marked cool changes (dry cold fronts), and the presence of deep mixed layers in the pre-frontal air. Accordingly the synoptic climatology will address these three factors, and in particular will relate the features of the WVI to upper tropospheric (jet stream) level circulation patterns, and discuss aspects of the regional variations that are revealed. Finally the implications of this work are discussed in terms of fire weather forecasting, and the understanding of the dynamics of such events, and a number of 'synoptic ingredients' are described that lead to abrupt drying in different areas of Australia.

Climatology of abrupt surface drying events

Event selection

The stations selected are widely distributed from southwest Western Australia (WA), through South Australia (SA), and along the eastern parts of Australia from Tasmania as far north as southeast Queensland, with the stations being subjectively assessed as representative of the broad regions subject to fire weather forecasts, and at which an at least hourly observation archive was available. The three-hourly 'SYNOP' observations, available from two to seven times daily according to station, do not have sufficient time resolution to resolve the humidity variations seen in the case

Table 1. List of stations used in this study, together with the number of events in total, and by fire season

Station	*Lat. (S)*	*Long. (E)*	*No. of events*	*1999-2000*	*2000-2001*	*2001-2002*	*2002-2003*	*2003-2004*	*2004-2005*
Perth Airport	31.9	116.0	5	1	1	1	1	0	1
Bridgetown	34.0	116.1	11	0	0	2	3	2	4
Jacup	33.9	119.1	5	0	1	0	2	0	2
Port Lincoln	34.6	135.9	16	2	0	2	2	3	7
Mt Crawford	34.7	138.9	11	5	1	0	1	3	1
Mt Gambier	37.8	140.8	9	1	3	0	0	3	2
Hobart	42.8	147.5	8	0	2	0	1	3	2
Bushy Park	42.7	146.9	4	0	0	0	0	3	1
Horsham AP	36.7	142.1	16	2	6	0	1	6	1
Mangalore	36.9	145.2	14	2	1	0	7	2	2
Wangaratta	36.4	146.3	50	1	0	10	28	9	2
Latrobe Valley	38.2	146.5	3	1	2	0	0	0	0
Cabramurra	35.9	148.4	16	1	3	0	9	1	2
Canberra	35.3	149.2	15	1	0	1	8	2	3
Richmond	33.6	150.8	8	0	0	1	7	0	0
Scone	32.0	150.8	13	0	0	2	9	1	1
Glen Innes AP	29.7	151.7	14	1	1	2	9	1	0
Amberley	27.6	152.7	14	0	1	3	5	3	2
TOTAL			232	18	22	24	93	42	33

studies described above. The stations chosen are listed in Table 1, and shown geographically in Fig. 1. Data were extracted from the METAR data archive of the Bureau's National Climate Centre for the six 'fire seasons' for the stations selected – December to February inclusive for stations south of Sydney (hereafter the 'southern' stations) and October to January inclusive for stations north of Sydney (hereafter the 'eastern stations') – with data from October 1999 to February 2005 being used. Regional numerical weather prediction (NWP) analyses from the Bureau's LAPS system (Puri et al. 1998) were used to identify the upper tropospheric flow patterns.

The meteograms shown in Mills (2005a, 2008) provided the structures on which a set of rules were developed to objectively identify 'drying events' at the candidate stations. First, it was found, by plotting the full data series one month at a time, that dew-points less than –5°C were quite rare and also frequently were associated with the sharp plunge and recovery seen in the Canberra and Port Lincoln meteograms shown in Mills (2005a, 2008). Second, some of the stations closer to the coast did show similar characteristics without quite reaching –5°C. Accordingly the selection criterion was relaxed slightly, and a preliminary selection was made of events for which the dew-point was <–5°C, or was <–2.5°C and with a relative humidity of <10 per cent. The addition of the relative humidity constraint, together with the restriction of the data-set to the warmer seasons meant that low temperature dry events were not selected.

While many of the events selected above showed an abrupt drying, there were a number that showed a relatively broad, 'flat' time series of dew-point, and so might be considered to be due to a larger-scale dry airmass, rather than the abrupt drying paradigm that was typical of the case studies. Accordingly, for each of the events identified using the criteria in the preceding paragraph the following additional calculations were made, for all observations falling in the 24 hours from 1200 UTC and including the event:

- The variance V of the dew-point – the variance about the daily mean of the dew-point observations.
- The dew-point range R – the difference between the highest and lowest dew-point – on a given day.
- The deviation D of the lowest dew-point from the 24-hour mean dew-point

Then an 'event score' was constructed so that each of:

$V > 16°C^2$
$R > 14°C$
$D > 8°C$

counted as a hit. Then if the minimum dew-point was <–5°C and two of the above three criteria were satisfied the event was selected, or if minimum dew-point was <–2.5°C and the relative humidity <10 per cent and all three criteria were selected, that also constituted an 'event'. The number of events thus selected at each station is listed in Table 1, with a total of 232 events being selected. While these rules eliminate a few cases that this author might have subjectively included, and perhaps also vice-versa, they are objective, reasonably consistent with the author's subjective assessment of each individual meteogram, and include a sufficiently large sample to assess common factors associated with these abrupt dryings, and that might assist in understanding and forecasting the processes that may lead to these events.

Broad statistics

Frequency of events

Table 1 lists the number of events at each station over the six-year analysis period. The average number of events is approximately two per season, but there is wide station-to-station variation, as well as considerable interannual variation. The times of day on which the lowest dew-point was observed show a marked diurnal variation (Fig. 2), with the majority of the events occuring between mid morning (1030 Local Standard Time, LST) and early evening (1930 LST). This suggests that either horizontal circulations associated with strong daytime thermally forced flows, and/or vertical mixing associated with the deepening well-mixed boundary layer are dominant mechanisms leading to the occurrence of these events. This is consistent with the hypothesis in Mills (2008) that it is the development of a deep, statically neutral boundary layer that contributes to the link between mid-tropospheric dry slots and the surface. There are, however, a number of events that occur overnight, and given the usual diurnal variation in relative humidity and expected fire activity, these are of considerable interest.

Seasonality

Table 1 shows the considerable interannual variability in event numbers, with the largest number of events occurring in the 2002-2003 fire season – the year of a major drought in southeastern Australia. Indeed, the fact that few events were observed at the eastern stations in other than that year suggests that antecedent drought may influence the occurrence of these events. Using the national time series of Keetch-Byram Drought Index (KBDI, Keetch and Byram 1968) developed by Finkele et al. (2006), the average KBDI for each season and its anomaly from the 30-year mean at the station locations were extracted from the gridded KBDI archive. These data are plotted against the number of drying events per season at each station in Fig. 3. Of the 232 events, 159 (69 per cent) occurred with a seasonal average KBDI > 60 mm, 176 events (76 per cent) occurred with a seasonal average KBDI greater than the norm (i.e. drier), and 121 events (52 per cent) in seasons when the seasonal average was more than 20 mm drier than the long-term average. These patterns are particularly marked for the stations in northeastern Victoria and southern NSW. However, correlation between the seasonal numbers of events and deviation of the seasonal mean KBDI from the long-term (30 year) station mean only has a value of 0.443, indicating that the relationship between these events and drought is, while positive, not particularly strong. Comparing daily, rather than seasonal, KBDI values and their departures from the long-term station averages on the days of the events shows a similar result, with 72 per cent having a KBDI > 60 on the day of the event, 79 per cent being drier than average, and 58 per cent being more than 20 mm drier than average.

Developing hypotheses to describe the physical link between rainfall deficiency and abrupt surface drying events is a little speculative, but factors might include a lower surface moisture availability leading to lesser evaporation and thus a generally drier atmosphere, allowing horizontal advection to play a role in

Fig. 2 **Histogram showing the frequency of abrupt surface drying events by time of day (Local Standard Time).**

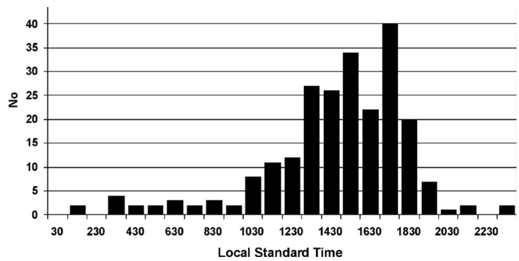
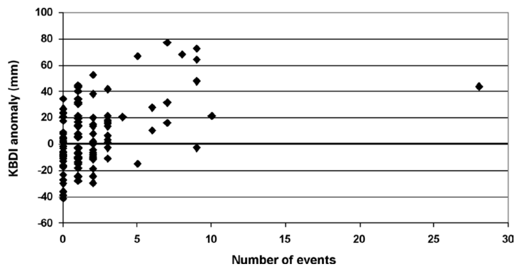


Fig. 3 **Scatterplot showing number of abrupt surface drying events per season at each station versus the Keetch-Byram Drought Index seasonal anomaly at that station.**



influencing lower local humidities. Another plausible factor is the increased partitioning of sensible to latent heating at the surface as the soil dries. This would lead to higher near-surface temperatures and deeper mixed layers during the afternoon, and would be consistent with the results discussed above (Fig. 2). As a corollary, moister than normal conditions would lead to increased evaporation and lesser surface heating, the consequent increased low-level stability may inhibit mixing of dry air from aloft.

There may, of course, be other factors than any direct causal relationship between drought and abrupt surface drying events, as the regional circulation during these periods may be conducive to both drought and to the drying events. In addition the event selection process itself may implicitly predispose these events towards drought years.

Spatial and/or temporal coherence

As each event was assessed in turn, it was found that there tended to be a clustering of events either with multiple stations in the same broad region on the same day (as was seen in Mills (2008)), or events at the same station on successive days. Table 2 lists the dates on and stations at which an abrupt drying event occurred at three or more 'nearby' stations on the same day (although not necessarily at the same time). It should not perhaps be a complete surprise that some 20 per cent of the events are listed here, given that the case study in Mills (2008) showed a very strong spatial coherence of abrupt surface drying associated both with the passage of the upper-tropospheric 'dry slot' and the post-frontal descent.

Table 3 lists the stations at which abrupt drying events occurred on successive days, and 32 per cent of the 232 events are represented here (although Wangaratta is strongly represented, and so does bias the results somewhat). This suggests that some environmental preconditioning/larger-scale controls may be acting as necessary ingredients in order for these events to occur, and but also tends to make the events rather more episodic rather than randomly distributed through the fire season and the landscape.

In conjunction with the diagnosis in Mills (2008), and noting that even the 'nearby' stations listed in Table 2 are some hundreds of km apart (Fig. 1) Tables 2 and 3 indicate that a large number of these events, while extreme, are subject to controls on the space and time-scales of upper-tropospheric wave/jet and/or lower tropospheric frontal systems. It is also notable that there was both multi-day and large spatial coherence in the abrupt dryings that occurred on 8 January 2003 (the day of the lightning ignitions that led to the southeast Australian fires in that year) and also on 17-18 January 2003 (the Canberra fires occurred on the 18th). Mills (2005a, 2007) has advanced hypotheses that explain the coherence of the abrupt dryings observed in the region of Canberra on 18 January. The appearance of abrupt drying at a number of stations on 6, 7 and 8 January 2003 is interesting from the point of view of the possible pre-conditioning of the fuels prior to the lightning outbreak, and this event is to be the focus of a later study.

Table 2. List of dates at which three or more stations in the same region experienced a drying event

Date	*Station list*
15 December 1999	Mount Crawford
	Mount Gambier
	Horsham
20 February 2001	Mount Gambier
	Hobart
	Mangalore
	Latrobe Valley Airport
	Cabramurra
4 November 2002	Scone
	Richmond
	Glen Innes
21 December 2002	Mangalore
	Wangaratta
	Cabramurra
	Canberra
	Hobart
7 January 2003	Mangalore
	Wangaratta
	Canberra
8 January 2003	Mangalore
	Wangaratta
	Canberra
18 January 2003	Wangaratta
	Cabramurra
	Canberra
12 February 2003	Mangalore
	Wangaratta
	Cabramurra
	Canberra
19 January 2004	Port Lincoln
	Mount Gambier
	Horsham
6 February 2004	Horsham
	Mangalore
	Wangaratta
17 February 2004	Mount Crawford
	Horsham
	Bushy Park
	Hobart
18 February 2004	Horsham
	Wangaratta
	Bushy Park
	Hobart
4 February 2005	Perth
	Bridgetown
	Jacup

Table 3. List of dates at which a station observed a drying event on at least two successive days.

Station	*Year/month*	*Dates*
Bridgetown	2002 / February	23, 24
	2005 / January	16, 17
	2005 / February	3, 4
Port Lincoln	2005 / January	10, 11 (twice)
Mount Gambier	2001 / February	20 (0600 and 1730 UTC)
	2004 / January	19 (0500 and 1830 UTC)
Hobart	2004 / February	17, 18
Bushy Park	2004 / February	17, 18
Horsham	2000 / December	19, 20
	2004 / February	5, 6
	2004 / February	17, 18, 19
Mangalore	2003 / January	6, 7, 8
Wangaratta	2002 / January	5, 6,
	2002 / January	9, 10, 11
	2002 / December	14, 15, 16, 17, 18
	2002 / December	20, 21
	2003 / January	6, 7, 8
	2003 / January	16, 17, 18, 19
	2003 / February	14, 15
	2003 / February	17, 18
	2004 / February	6, 7
	2004 / February	18, 19
	2005 / January	12, 13
Latrobe Valley	2001 / February	19, 20
Cabramurra	2001 / February	17, 18
	2003 / January	7, 8
Canberra	2003 / January	7, 8
Richmond	2002 / November	8, 9
Scone	2002 / October	29, 30
Glen Innes	2002 / October	20, 21
Amberley	2002 / October	23, 24
	2002 / December	5, 6
	2003 / November	1, 2

Association with WVI features and upper flow structures

The examples shown in the two case studies described above suggest that the source of the extremely dry air associated with the abrupt surface drying was a band of mid to upper tropospheric dry air that could be associated with identifiable dark (dry) features in the WVI, and Mills (2005a, 2008) suggested that monitoring the movement of these dark bands may provide some useful forecast guidance of the potential for an abrupt surface drying event. Therefore, in this section the WVI closest in time to the time of the humidity minimum for each event was extracted from the Bureau's GMS-5 or GOES-9 geostationary satellite archives and subjectively assessed for the presence of a dark feature that might be over or near the station in question. As the WVI dark bands are associated with areas of low humidity in the mid-troposphere, they generally represent areas that have undergone descent over, typically, the previous 6-24 hours (see, for example, Fig. 6 of Mills (2008)), and so the upper tropospheric flow patterns associated with these WVI patterns will be also discussed in this section.

For each event a subjective assessment of the presence of a dark band was made, with assessments being either 'definitely yes', 'probable/maybe', or 'no'. Generally, a near-vertical association between the event location and the WVI dark feature was required for a 'yes' categorisation, but based on the post-frontal drying described in Mills (2008), where the dark band in the WVI was well upstream of the location of the observed surface drying, but could be associated through downward-sloping descent, WVI cases that clearly fit this paradigm were also counted as 'definitely yes'. Some 60 per cent of cases show a clear dry area/feature that could be associated with the surface drying event, and this percentage increases to ~80 per cent if the probable/maybe cases are included.

This is a remarkably high percentage, particularly given the wide variety and complexity of patterns seen in WVI (e.g. Weldon and Holmes 1991, hereafter WH), and so provides support for the conjecture that monitoring WVI might be a useful component of fire weather forecasting in support of existing fires. What this assessment does not do is assess how often dry slots are visible in WVI and strong surface drying does not occur. As dark (dry) features are seen in essentially every WV image, such an assessment is impractical. In this section, though, the morphology of the WVI dark bands associated with the 232 events will be described, together with their associated upper tropospheric flow patterns, and in subsequent sections we address the mechanisms that might lead to a linking between the mid-tropospheric levels represented in the WVI and the surface.

There was no single characteristic morphology in the WVI for these events. However, there were several structures that could be associated with characteristic upper-tropospheric flow patterns. Examples of these are shown in Figs 4(a)-(k), and include:

- Events which occur on the edge (generally the southern edge) of vast dark/dry areas. These areas are generally associated with anticyclonic curvature and/or shear in the upper flow (e.g. Figs 4(a)-(d)), and tend to have indistinct southern boundaries. While some of these are relatively large-scale ridges (see areas A, B, C in Figs 4(a)-(c) respectively), others such as area 'D' in Fig. 4(d) are rather shorter wavelength features, with weaker wind speeds, and the associated flows can be highly involuted. Corresponding to the shorter wavelength of these ridges, the associated dark areas in the WVI also tend to be rather smaller than those seen in Figs 4(a)-(c).

  The upper-tropospheric descent associated with these systems can be qualitatively explained using quasi-geostrophic arguments of anticyclonic differential vorticity advection. While the dark areas in the WVI tend to extend upstream of the ridge axis, the instantaneous descent is generally in the region downstream of the ridge axis, consistent with the quasi-geostrophic arguments above. However, the mid-tropospheric dry (dark) air-mass is a result of longer-term descent, and so must be viewed in a Lagrangian framework, rather than the dark areas having an instantaneous correspondence with areas of upper-tropospheric descent. The abrupt surface drying events associated with these ridge patterns have been observed both upstream and downstream of the respective ridge axes. Graham (2003) has also discussed the role of subsidence associated with upper ridges in his discussion of the Hayman fire.
- Long dark bands between zones of moisture, such as are seen in Fig. 4(e) extending west-northwestwards from Port Lincoln, and in Fig. 4(f) extending from the northwest across the southwest of WA and into the ocean south of Australia. These dark bands, as in these two examples, are generally seen on the cyclonic side of a jet stream, and so in the terms of WH would be termed jet-edge boundaries. Descent in these cases is a result of the convergence on the poleward-entrance side of the jet streak due to air-parcel acceleration.
- Some of these apparently jet-edge boundary dark bands are relatively narrow, elongated dry slots 'pointing' at or over-running the surface observation site. Such systems were associated with the Canberra and the Wangary fires (Mills 2005a, 2008), and in those cases were shown to be associated with the overlapping transverse ageostrophic circulations of two jet streams (see Figs 3 and 8 of Mills 2008). These events can be associated with either converging jet streaks, as in Fig. 3 of Mills (2008), or diverging jet streaks (e.g. the area surrounding YWGT in Fig. 4(g)). While the varying morphologies seen are almost infinite, a simple concept that is based on the 'four quadrant' model of jet entrance and exit circulations for the southern hemisphere (see Velden and Mills 1990, Fig. 11) requires that for these overlapping transverse ageostrophic circulations to reinforce descent, there must be parcel acceleration (jet entrance) in the northern jet streak and parcel deceleration (jet exit) in the southern jet streak. As curvature effects are normally present care must be taken in making these interpretations. However, some 25 per cent of the cases assessed fell into these overlapping jet streak categories, including the two major events – the Canberra and the Wangary fire events.
- Dry slots associated with movement of jet streaks past the apex of a sharp upper trough can be very marked, and are usually associated with post-frontal abrupt surface dryings such as that discussed in Mills (2008), and thus are usually upstream of the event location and linked to the surface by sloping descent paths. Such patterns are seen in Figs 4(h), (i). The pattern in Fig. 4(h) marked by the 'H' is that of the classic 'comma cloud' dry intrusion (WH), while the image in Fig. 4(i) is from the afternoon of 8 January 2003, the day of the lightning ignitions over southeastern Australia that led to the extensive fires over the subsequent six weeks, and the critical dry area in that figure is the small area over YWGT rather than the much larger area further northwest.

Fig. 4 **LAPS analyses of 300 hPa wind barbs, overlaid with speed contours (m sec^{-1}) for drying events at (a) Perth (YPPH), (b) Bridgetown (BDGN), (c) Port Lincoln (YPLC), (d) Mt Gambier (YMTG), (e) Port Lincoln (YPLC), (f) Bridgetown (BDGN), (g) Wangaratta (YWGT), (h) Mt Gambier (YMTG), (i) Wangaratta (YWGT), (j) Scone (YSCO) and (k) Richmond (YSRI). Contrast-stretched Water Vapour Imagery is included, and the letters mark features discussed in the text.**

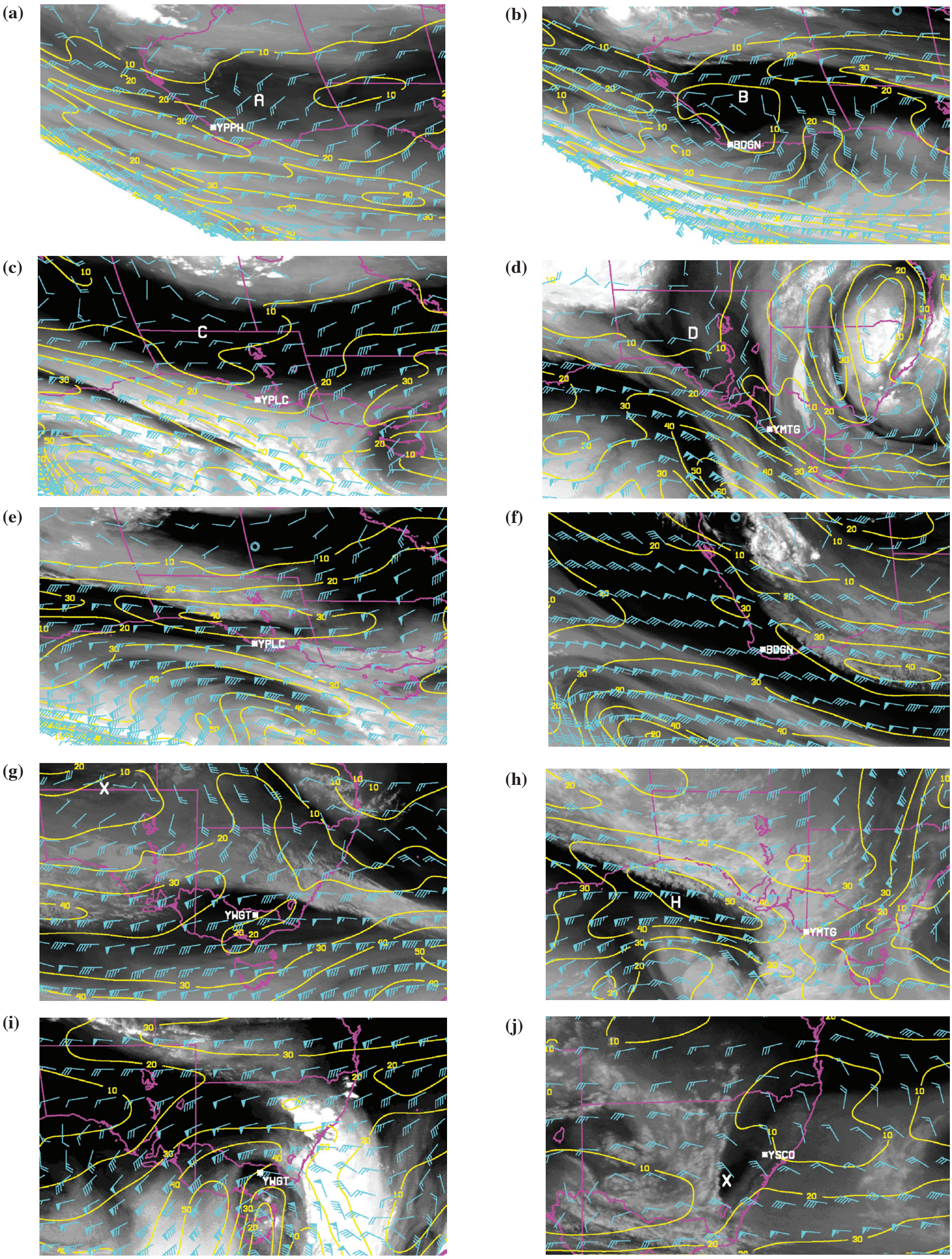
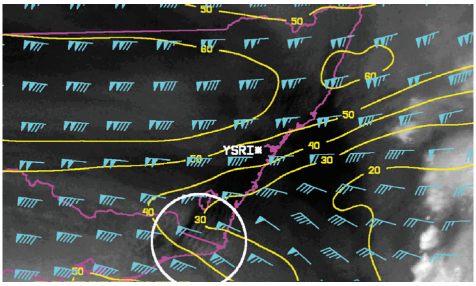


Fig. 4 Continued.

(k)



- The dry areas can be quite small, as is the case for the small area just north of the ACT in Fig. 4(j) (marked X), and this feature appears to be associated with the small ridge seen immediately to its east. This event was associated with drying at Scone (see Mills 2007), but there was also a drying signature at Canberra (dew-point -5.1°C) on that day, although not counted in the events at Canberra listed in this paper because of its November date.
- Banded structures are often seen in the WVI in cases of strong cross-mountain flows (e.g. the circled region in Fig. 4(k)), and while these might not be directly indicative of mid to upper-level descent, they may indicate that wave-breaking or topographic interactions are occurring. These processes will be discussed at greater length in the next section, and such patterns are seen most commonly with drying events at the stations north of Canberra, and for the Tasmanian stations.

A subjective inspection of the 300 hPa height/wind analyses at the time closest to each of the 232 events suggested that a large proportion of the events occurred under conditions of upper-tropospheric anticyclonic shear and/or curvature, and that this tendency was more prevalent for the 'southern' stations. To test this hypothesis, the 300 hPa relative vorticity from the LAPS analysis closest in time to the drying event was extracted for each event to provide an event distribution. Then the 300 hPa relative vorticity for each station at 0600 UTC for each day of the six seasons studied was extracted to provide for each station a fire season climatology of 300 hPa relative vorticity. It is problematic to devise a truly objective way of comparing the two distributions as the number of events is low compared to the number of days, particularly if only a single station is considered, and there are undoubtedly regional and seasonal variations over such a wide geographic area. In order to provide some overview that might support the subjective assessment, frequency distributions of relative vorticity for the southern and eastern station groups are presented in Fig. 5 and some simple statistics are presented in Table 4. Allowing for the differing numbers in the climate and the event distributions, for the southern stations there is a marked shift in the distribution to more anticyclonic values of 300 hPa relative vorticity (Fig. 5(a)), with all of the mean, median, and the percentile rank of $\zeta = 10 \times 10^{-6}$ sec^{-1} (a value found to correspond to a threshold for subjective assessment of anticyclonic curvature/shear) indicating an anticylonic shift in the event distribution. Many of these anticyclonic patterns were either with relatively weak flows and/or sharp, and even involuted, upper flow patterns, such as shown in Fig. 4(d).

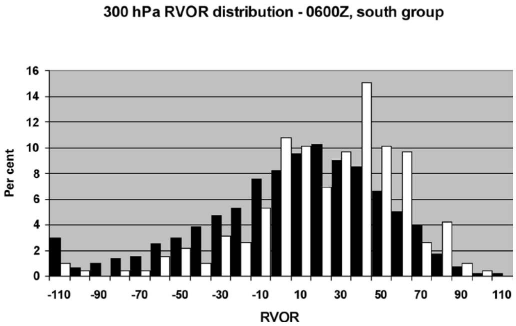
Table 4. Mean, median, and percentile rank of relative vorticity ($sec^{-1} \times 10^6$) for the southern and for the eastern station groupings, for the event group (case) and for the six fire-season climatology generated from LAPS numerical analyses. The percentile rank is for a relative vorticity of 10 $sec^{-1} \times 10^6$.

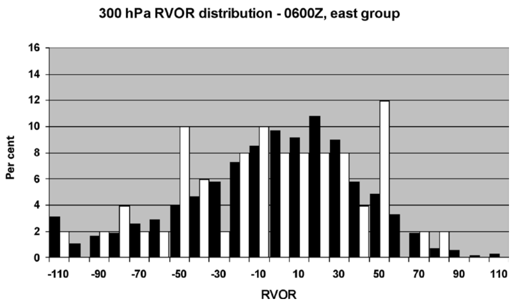
	Mean	*Median*	*% rank(10)*
Case (south)	22.0	28.6	31
Clim (south)	5.0	11.8	48
Case (east)	-6.1	-4.4	59
Clim (east)	-4.4	1.8	58

There is little discernible difference in the distributions for the 'eastern' group of stations, perhaps partly due to the earlier season selected for these stations when the subtropical jet might be expected to be more active in those latitudes, perhaps due to the lesser number of events consequent to the smaller number of stations, but also perhaps due to the differing environments, both geographic and synoptic, characterising events at the eastern stations. Subjective assessments indicate a greater proportion of these events occur with active jet structures and strong deep-tropospheric baroclinicity.

In summary, the upper tropospheric patterns that lead to deep descent into the middle troposphere exhibit anticyclonic curvature and/or shear, which (rather simplistically, but probably justifiably) indicates that upper tropospheric descent was being forced by quasi-geostrophic forcing (anticyclonic vorticity advection), or at the jet exit (descent on the anticyclonic shear side) due to deceleration of the air parcels. Cyclonic flow patterns that lead to deep descent occur on the cyclonic side of the jet entrance, where parcels are accelerating, or where curvature effects cause deceleration. While these cases are less common than those under anticyclonic conditions, they still do occur sufficiently frequently to be important, and are associated with significant abrupt surface drying events.

Fig. 5 **Frequency distribution of 300 hPa relative vorticity at station locations from LAPS analyses at 0600 UTC for the southern (top) and eastern (bottom) station groupings. Black bars show the distribution for all days in the six fire seasons studied, white bars show the distribution for the abrupt surface drying events. Units of relative vorticity are sec^{-1} x10^{6}.**





Association with surface troughs and fronts

The two event case studies discussed earlier (Mills 2005a, 2008) were associated with significant frontal passages, and there is some indication that the circulations associated with these fronts also contributed to the observed surface drying. For each of the 232 events identified by the objective rules the archived MSLP analyses from the National Meteorological and Oceanographic Centre (NMOC), the LAPS (Puri et al. 1998) archived numerical analyses and the station meteograms for the day of the drying were used to make a judgement of whether a trough/frontal passage also occurred on that day. While these assessments are by their very nature subjective, this judgement shows that on 187 of the 232 events (~81 per cent), a trough or frontal passage was either approaching or just past the station at the time of the drying. While a large number of these events were superficially frontal, or at least pre-frontal trough-like in their appearance, there are a significant number of the Tasmanian and the east coast events that had a component of lee trough associated with the trough feature, while some of the Western Australian (WA) events were associated with the early stages of the west-coast trough, where flow is essentially offshore on the (north)western flank of an anticyclone, and exhibits cyclonic curvature of the isobars as the flow moves offshore. These three situations will be discussed in broad terms first, and then some regional groupings of stations will be discussed to highlight particular aspects of these events.

While some of the drying events occurred in the post-frontal airmass, a preponderance of them occurred on the warm-air side of the front. A typical cold front has a thermally-direct cross-frontal ageostrophic circulation associated with the sloping isentropes of the classic 'cold wedge' frontal model, and so while the post-frontal drying events may be associated with vertical advection, as was shown in Mills (2008), and was also the case for the event at Mt Gambier on 15 December 1999 (Fig. 4(h)) it is less obvious that circulations directly associated with the front lead to pre-frontal abrupt drying via vertical advection.

However, based on the case studies, and general synoptic considerations, there are several aspects of the frontal circulations that might contribute to abrupt surface drying. First, the northerly airflow ahead of a typical cold front in southern Australia will tend to advect hot, dry air from the interior of the continent. Second, given that a pre-frontal low-level jet is a regular feature of summertime dry cold fronts in southern Australia, it is a reasonable hypothesis that in at least some of these events descent associated with low-level acceleration such as that at the entrance of the pre-frontal jet, as was diagnosed in Mills (2008), would be likely to occur. Indeed, in any circumstance where the low-level flow is accelerating, divergence, and thus lower tropspheric descent, might be expected. Such a situation may also occur in offshore flow (as would be expected in pre-frontal airflows in most of southern Australia), where the reduced friction as the air flows from land to sea allows acceleration of the flow, coastal divergence, and thus compensating descent in the lower troposphere. While this effect is often hard to identify in the southeast of the continent due to the additional effects of the topography close to the coast there, it is evident in several of the WA cases, and will be discussed further below.

Finally, and perhaps most importantly, the enhanced entrainment of air from above the mixed layer due to the vertical displacement of the isentropes at the top of the mixed layer by the ascending branch of the cross-frontal ageostrophic circulation in the immediate pre-frontal environment may lead to enhanced drying immediately before the change passage, as was hypothesised for the easterly changes such as that which reached Canberra on the day of the 18 January 2003 fires (Mills 2005a, 2007). This characteristic is also regularly identified with the more traditional westerly (eastward-propagating) cool changes in southern Australia, as also shown in the Port Lincoln case described in Mills (2008).

There is considerable regional difference between the stations in terms of the type and structure of the fronts/troughs involved in these events. A brief description of the major synoptic characteristics of these fronts/troughs follows, with regional grouping of stations where appropriate. In the subheadings below, the numbers indicate the number of events associated with front/trough passages, and the total number of drying events at those locations.

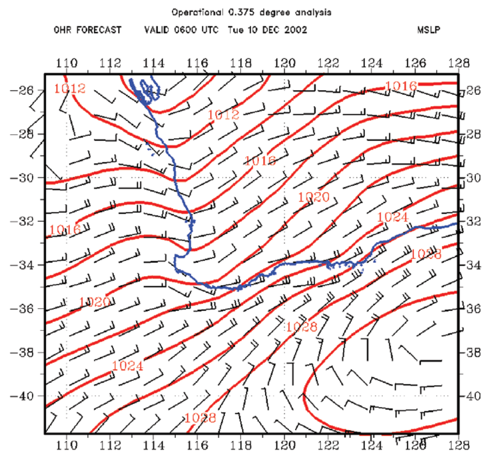
WA grouping – Perth, Bridgetown and Jacup (19/22 events)

As might be expected in southwest WA during summer, most trough passages are associated with the presence of the west-coast trough. The driest air was generally experienced on the warm side of the trough. There are, however, a number of different structures and paradigms that can be identified in these events. Some events occurred in easterly low-level flow, the trough being a result of the land-sea thermal contrast (Kepert and Smith 1992), and marked by cyclonic curvature in the low-level pressure field. The example in Fig. 6 (a day of an abrupt drying event at Bridgetown) is an example of such a pattern, and is characterised by offshore flow (Fig. 6(a)) and descent in the lower troposphere (Fig. 6(b)) associated with the acceleration of the flow as it moves from land to sea.

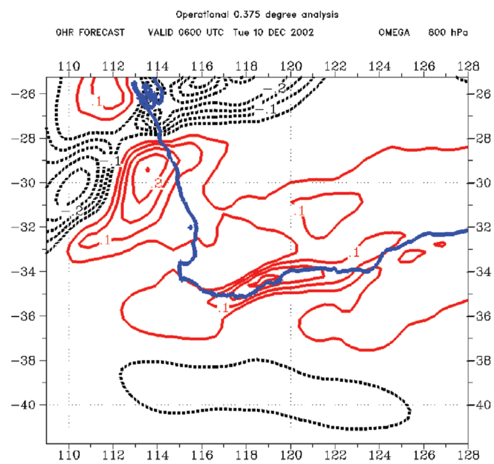
Deep, active, eastward-propagating troughs have much of the character of a (dry) cold front. Such a case is seen in Fig. 7, the day of an abrupt surface drying event at Jacup, where the pressure/surface wind field shows a deep trough inland from the west coast of WA, with a sharp change from northeasterly to southwesterly winds. The vertical motion field at 850 hPa shows a narrow band of strong ascent just east of the change, and a band of descent on the cool side, as is commonly seen with a cold front moving into a deep, well-mixed boundary layer (Reeder 1986). Note that there is a westward displacement of the 'wind change line' from the surface (Fig. 7(a)) to 850 hPa (Fig. 7(b)). An east-west vertical cross-section through this part of the trough along latitude 30.5°S (Fig. 8) shows a deeper mixed layer associated with this ascent on the warm side of the trough, as was also shown in Mills (2007). Another interesting feature in Fig. 7(b) is a marked band of 850 hPa descent associated with the accelerating northeasterly flow near the coastline east of the trough (circled). This feature bears similarity to that seen in Fig. 6(b), and also to the area of descent associated with the accelerating low-level flow over Eyre Peninsula described in Part 1.

Fig. 6 LAPS analysis fields at 0600 UTC 10 December 2002. (a) Mean sea-level pressure contours, with a contour interval of 2 hPa overlaid on the 10 m wind field. The wind barbs have their usual meteorological meaning. (b) Contours of 800 hPa vertical motion, with a contour interval of 0.05 Pa s^{-1}. Negative contours (ascent) are dashed, and the zero contour is suppressed.

(a)



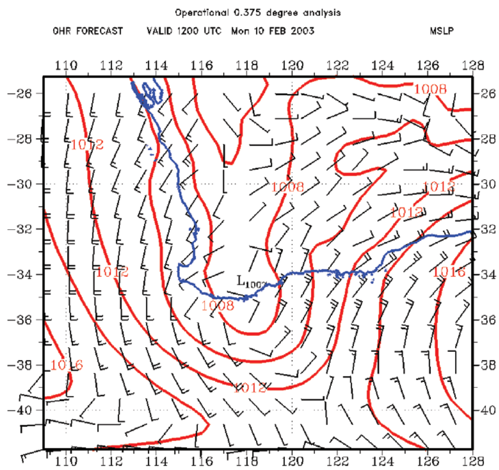
(b)



The shape of the southwest WA coastline affects the structures of cool changes/troughs in this area, as large-scale sea-breeze-like changes can move northwards from the southern coast and eastwards from the west coast, leading to complex interactions, particularly when the two 'changes' converge, as can frequently occur in the southwest land division.

Fig. 7 **LAPS analysis fields at 0600 UTC 10 February 2003. (a) Mean-sea-level pressure contours, with a contour interval of 2 hPa overlaid on the 10m wind field. The wind barbs have their usual meteorological meaning. (b) Contours of 850 hPa vertical motion, with a contour interval of 0.1 Pa s^{-1}. Negative contours (ascent) are dashed, and the zero contour is suppressed.**

(a)



(b)

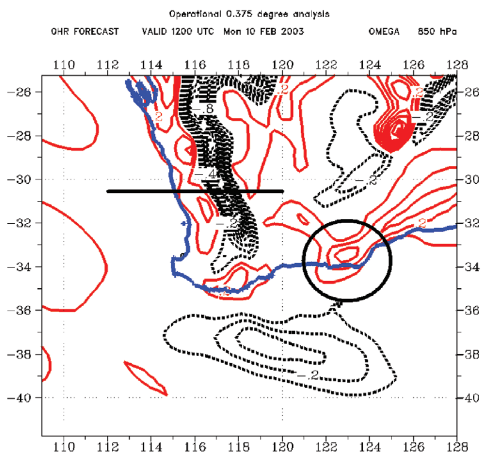
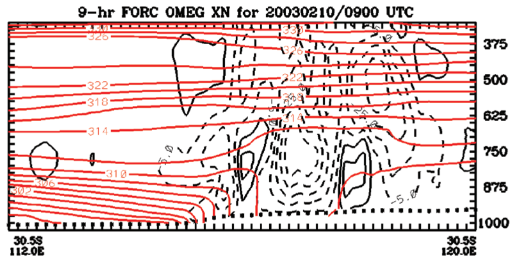


Fig. 8 **East-west cross-section through the west-coast trough shown in Fig. 7. Red contours show potential temperature with a contour interval of 2K. The black contours show vertical motion (hPa h^{-1}), with negative values (ascent) dashed, a contour interval of 10, and the zero contour is not shown. The cross-section is derived from the 0.125° meso-LAPS forecast valid at 0900 UTC 10 February 2003. Contours are blanked below model topography.**



Port Lincoln (17/17 events)

These drying events were predominantly pre-frontal (15/17), and with a very sharp increase in humidity following the change. Two events were post-frontal, one of which was documented in Mills (2008). The other occurred after an initial change, and before an increase in wind speed associated with strong post-frontal ridging. This latter case could thus be interpreted as being before a 'wind speed change' as described by Huang and Mills (2006), Figs 35 and 39.

Mount Gambier, Horsham (8/9 and 10/16 events respectively)

The bulk of these changes would be classed as pre-frontal troughs, as might well be expected given the general morphology of fronts in this part of the world, but there is a broad range of structures that the different cases exhibit. All of the Mount Gambier front-related abrupt surface drying events are pre-frontal, but five of the ten Horsham frontal events are post-frontal – each of these is associated with quite strong pressure gradients associated with post-frontal ridging. Such strong pressure rises are indicative of deep cold air advection following the front (Mills 2005b, 2008), and so deep post-frontal descent is likely, and in fact is an intrinsic component of this synoptic pattern.

Mt Crawford and Mangalore (2/11 and 5/14 events respectively)

At Mt Crawford the abrupt surface drying events usually occur in a northeasterly flow, sometimes with a relatively weak easterly trough, but do not fit the frontal stereotype particularly well. At Mangalore only five of the 14 events were clearly associated with frontal passage. Both these stations are in ranges of hills, and given the lack of clear synoptic signals, this suggests that local effects may also contribute to the abrupt drying events at these stations.

Wangaratta (28/50 events)

At Wangaratta a range of associations with fronts were observed. Eighteen of the 50 events occurred before or with the frontal passage, ten of the 50 occurred immediately following the initial wind change, and so could be classed as occurring between the pre-frontal trough and the deeper 'final' frontal passage. A further 10 events occurred in southwesterly flow, well after the frontal passage and were associated with deep-tropospheric post-frontal descent. It should be noted that cool changes reaching Wangaratta during the summer are strongly weakened by post-frontal diabatic heating, as described in Mills (2005a).

Latrobe Valley Airport (3/3 events)

All three cases of abrupt surface drying at Latrobe Valley Airport occurred in weak east to northeast background flow, with the suggestion that a lee-trough may have been present south of the Victorian Alps. These changes may thus have more similarity to the inversion-breaking drying events described by Huang and Mills (2006) (their Figs 32, 33) than the more frontal paradigm, although there is usually a synoptic-scale front approaching on such days.

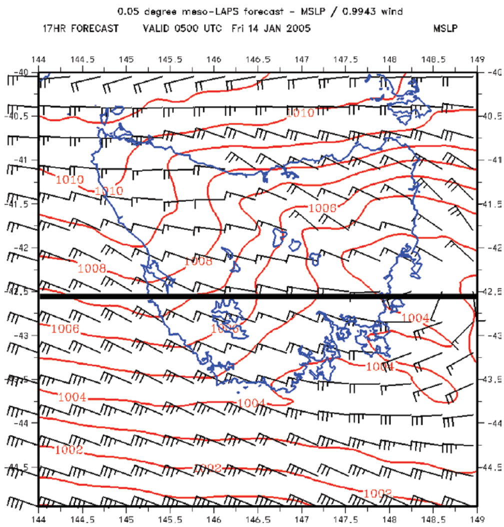
Tasmanian stations – Hobart and Bushy Park (7/8 and 4/4 events respectively)

All but one of the Tasmanian abrupt drying events occurred in strong northwest to west-southwest gradient flow, and a lee trough over southeastern Tasmania was evident in all these 11 cases. In six of these cases low pressure systems of the type described by Mills and Pendlebury (2003) are seen on the lee side of the island. An example is shown in Fig. 9, which shows strong northwesterly flow being apparently diverted by the Tasmanian topography, with weaker flow on the eastern side of the central highlands of Tasmania and a marked lee trough in the MSLP pattern. Thus in association with the cross-topography flow there is a deep mixed layer (Fig. 10) on the lee side, allowing free dry convective mixing to around 800 hPa, and deep middle and lower tropospheric descent that is advecting dry air towards the top of this mixed layer. Marsh (1987) has also noted the contribution of lee effects on increased fire danger in eastern Tasmania.

Cabramurra (4-6/16 events)

Many of the events at Cabramurra occurred overnight (see below); however the change events occurred during the daytime. Most of these change events had a westerly change moving to and through the station from the west, with a sharper easterly change associated with the development of a coastal ridge along the eastern Australian coastline passing through the station in the late afternoon/early evening. Such easterly changes were shown by Mills (2007) to frequently lead to marked abrupt surface drying immediately before the passage of the easterly change, and this characteristic is seen at Cabramurra. One of these events occurred on 18 January 2003, and meteograms from the Cabramurra AWS for that event are presented in Mills (2005a).

Fig. 9 Seventeen-hour forecast from the 0.05° meso-LAPS 'Victoria-Tasmania' model valid at 0500 UTC 14 January 2005. Contours show mean-sea-level pressure (contour interval 1 hPa), with the 10 m wind barbs overlaid. The wind barbs have their usual meteorological meaning, and the horizontal black line shows the position of the cross-section shown in Fig. 10.



Canberra (11/15 events)

The majority of these events were associated with ridging along the east coast, and nine showed a clear evening easterly change, with the humidity minimum occurring just before the easterly change in most cases, as was also described for a number of such changes in Mills (2007).

Eastern grouping (Richmond, Scone, Glen Innes, Amberley) (45/49 events)

The majority of these abrupt drying events occurred on days with strong, active southerly changes (pressure troughs) progressing northwards along the NSW coast, often with a trailing easterly trough a little inland and parallel to the coast. There is almost always cross-range flow ahead of the trough, and usually a period of southwesterly flow following the change, so the influence of the topography in generating downslope winds or enhanced mixing in the lee of the ranges is a potential contributor to the abrupt drying events. In such situations upstream blocking of low-level air by the mountain barrier can also lead to drier air from ridgetop levels or above reaching the surface in the lee of the ranges (Sharples et al. 2007).

Fig. 10 **Cross-sections through the 0.05° meso-LAPS forecast shown in Fig. 9. Upper panel shows in red contours of potential temperature with a contour interval of 2K, and in black contours of vertical motion (hPa h^{-1}), with negative values (ascent) dashed, a contour interval of 20, and the zero contour is not shown. The lower panel shows mixing ratio, with a contour interval of 1 g kg^{-1}. Contours are blanked below model topography.**

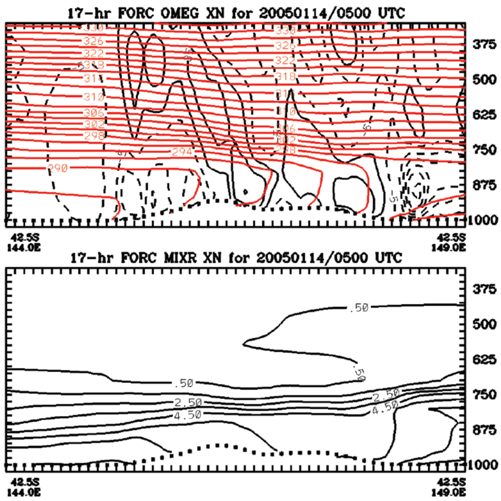
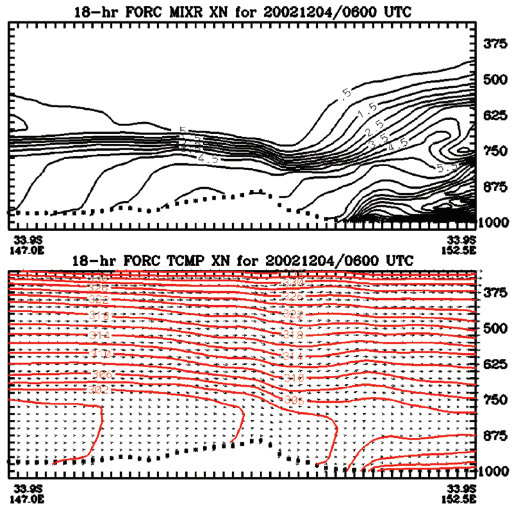


Fig. 11 **East-west cross-section through the latitude of Richmond, and crossing the Great Dividing Range. Upper panel shows mixing ratio, with a contour interval of 0.5 g kg^{-1}. The lower panel shows potential temperature with a contour interval of 2K, and the arrows show the vector representation of the component of the horizontal (pressure level) flow in the plane of the cross-section versus the vertical motion. Contours are blanked below model topography.**



Some evidence for such wave activity is seen in Fig. 4(k), where wave structures are seen in the WVI (circled). A cross-section (Fig. 11) through the ranges and at the latitude of Richmond (YSRI), where the drying event occurred on that day, shows wave structures in the westerly flow across the ranges, and dry air being advected downwards immediately downstream of the crest of the Great Dividing Range.

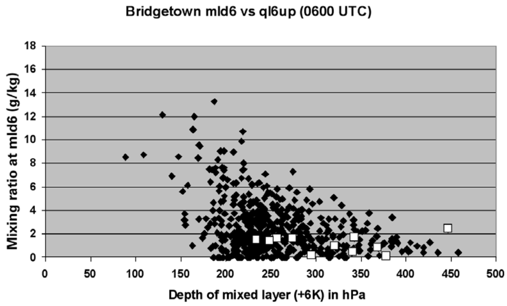
Stability environments

The case studies of the Canberra and the Wangary fire events hypothesised that dry convective mixing was sufficient to explain the connection between the dry mid-tropospheric air visible in the WV imagery and the surface, with scaling arguments following Stull (1988) indicating that an abrupt lowering of humidity at and just above the entrainment layer would affect the entire mixed layer in less than an hour (Mills 2005a, 2007, 2008). In addition Fig. 2 indicates that the majority of abrupt surface drying events occur during the afternoon, when mixed layers would be at their deepest. Further, the radiosonde observations at Wanga on 18 January 2003 (Mills 2005a) and at Adelaide Airport on 11 January 2005 (Bureau of Meteorology 2005) both showed very deep mixed layers with only relatively weak increases in stability above that mixed layer. Such vertical temperature profiles might be considered typical of a situation in which deep dry convective mixing entrains dry air from above the mixed layer to cause an abrupt surface drying event.

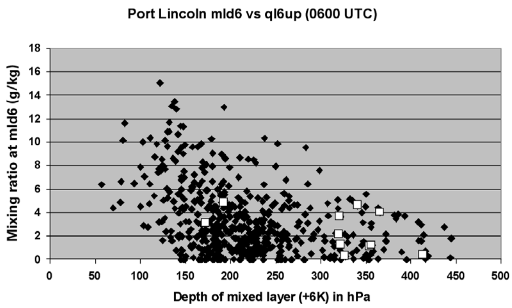
There are essentially no observations available to validate this hypothesis, as there are no radiosonde observations near most of the stations chosen for study in this paper, and certainly none during the time of the daytime heating maximum. An alternative approach is to use assimilated analyses from an operational NWP system to diagnose vertical temperature and humidity structure, both for the 232 abrupt drying events, and for each day of the six fire seasons studied. This then constitutes a climatology of vertical temperature profiles at these station locations. As archived LAPS numerical model output is available at three-hourly intervals, for each station, at each of 0300, 0600 and 0900 UTC (one hour earlier prior to 2001 when the base-time of the operational NWP models changed) a vertical temperature and humidity profile was extract-

Fig. 12 **Scatterplots of the mixing ratio (g kg-1, ordinate) at the model level above the layer less than 6K warmer than the surface virtual potential temperature versus the depth of that layer (hPa, abscissa) at 0600 UTC for all days during the fire seasons studied (diamonds), and for days on which a daytime abrupt surface drying event was determined to have occurred (white squares). Stations are (a) Bridgetown, (b) Port Lincoln, (c) Horsham, (d) Canberra and (e) Glen Innes.**

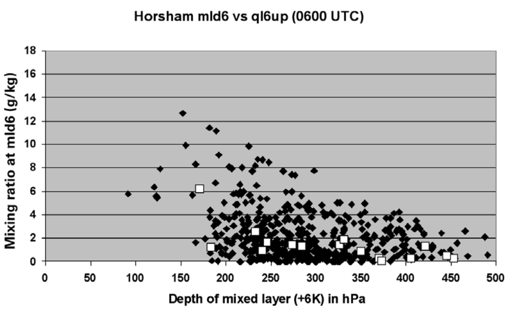
(a)



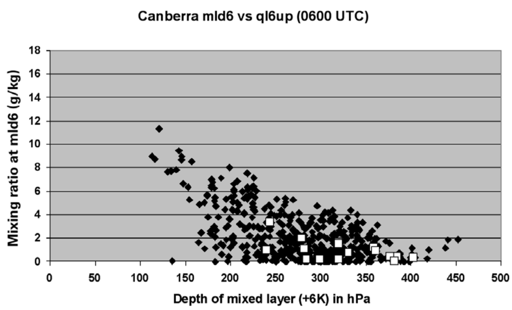
(b)



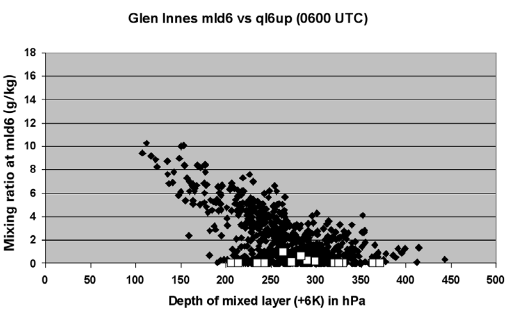
(c)



(d)



(e)



ed. Then, with the premise that abrupt surface drying events might be associated with first, deep mixed layers, second, weak stability above the mixed layer (the entrainment layer), and third, low humidity in the layer above the mixed layer, a means of testing this hypothesis was developed as follows. First, the depth of the mixed layer MLD, defined as the layer through which the virtual potential temperature, θ_v, is less than 1K warmer than the lowest model level θ_v, is determined. Environments with a weaker stability above the mixed layer are characterised by larger depths (lower pressures) at which θ_v is less than the surface value plus a small increase (say 3-9K) in temperature, as weaker stability above the mixed layer would lead to larger increments in extended mixed-layer depth (MLD3, etc., where the numerical suffix refers to the increment in temperature above the lowest level θ_v) for relatively small increases in temperature than would situations of greater stability in the entrainment layer, and the depth to MLD3, MLD6 and MLD9 was also determined. Finally, the mixing ratio (a conservative measure of humidity) at the level of the 3, 6 and 9K extended mixed layer depths was determined, (hereafter ql3up, ql6up, etc.), and these characterise the humidity of the air above the mixed layer.

Figure 12 shows scatterplots of MLD6 vs ql6up for Bridgetown, Port Lincoln, Horsham, Canberra, and Glen Innes at 0600 UTC on all days through the six seasons studied, with the 0600 UTC values for those days on which drying events occurred between 0100 and 0900 UTC (essentially during the daytime) highlighted. Looking firstly at the distribution for all days (diamonds), all stations show broadly what might be expected – the deeper the mixed layer, the lower the humidity above the mixed layer, consistent with the normal decrease in mixing ratio with elevation, but with considerable spread in these scatterplots, and also considerable station-to-station variation. At Bridgetown, Horsham and Glen Innes the event days (white squares) show a strong bias towards low values of mixing ratio, with a lesser tendency to deeper mixed layers. At Port Lincoln, and to a lesser extent Canberra, there is greater spread in the mixing ratio, although still distributed towards the dry end of the distribution, but a strong tendency for events to be associated with deeper mixed layers. These distributions are consistent with the hypotheses developed above, although these phase diagrams do not comprise a unique predictor of such events as there are a large number of 'non-event' days within the phase space of the events. Some of these may have occurred on days when low dew-points occurred, but which did not quite satisfy the criteria required to select an event. It is also possible that on some of those days an ingredient necessary for the event to occur was missing, and, of course, there is some level of uncertainty in the accuracy of the analyses.

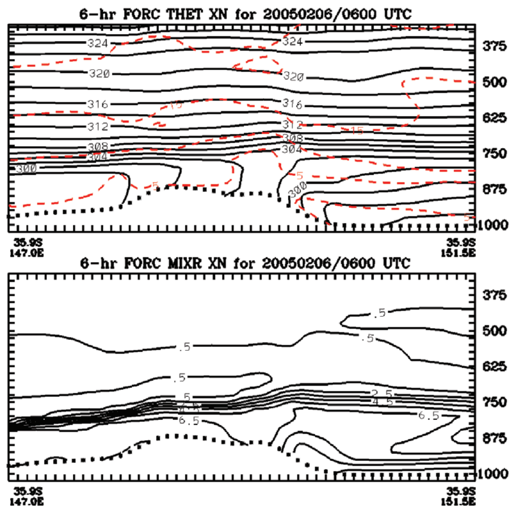
Overnight abrupt drying events

While the majority of the events studied occurred during the afternoon (Fig. 2) there were a number that occurred overnight. As the normal expectation is that relative humidity is lowest during the afternoon, and greatest overnight, these events might well be rather more unexpected, and it is thus worthwhile examining further the circumstances in which they occur. Between 2100 and 0800 LST there were 20 events noted, with an uneven distribution across stations. In order of station frequency:

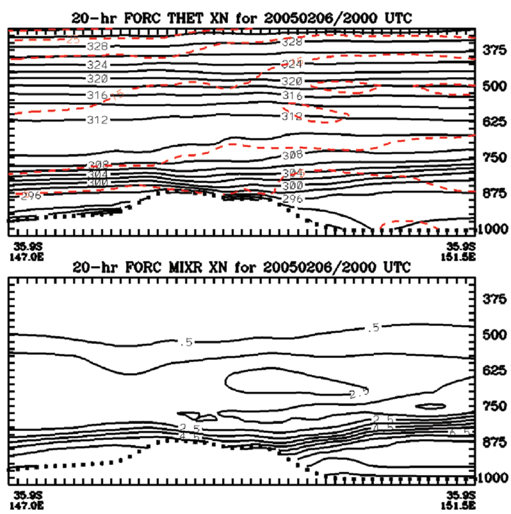
Cabramurra (7 events)
Most of these events occurred with rising temperatures (against an expected trend of nocturnal cooling) and so might be considered to be a result of 'inversion lowering' overnight, although horizontal advection could be a factor (these are not necessarily mutually exclusive). There were cases in which winds were from both the west and the east during these nocturnal drying events, and so a single synoptic model appears unlikely. However, some evidence that lowering of the subsidence inversion contributes to these events is seen in Fig. 13, where cross-sections east-west across the Great Dividing Range, at the latitude of Cabramurra, show a mixed layer extending well above the highest (model) topography during the afternoon (Fig. 13(a)), with a marked stable layer and vertical humidity gradient immediately above the mixed layer. By the early morning hours (Fig. 13(b)) the inversion layer has lowered to the level of the model topography, suggesting that the higher peaks may well penetrate this subsidence inversion.

Fig. 13 East-west cross sections through the Great Dividing Range at the latitude of Cabramurra. Upper pair (a) are valid at 0600 UTC, and the lower pair (b) valid at 0200 UTC, but from the same 0.05° meso-LAPS 'Sydney domain' forecast. In each panel the upper frame shows potential temperature (K, solid contours) and wind speed (dashed, m s^{-1}), and the lower frame shows mixing ratio (g kg-1). Contour intervals are 2 K, 5 m s^{-1}, and 1 g kg^{-1} respectively. Contours are blanked below model topography.

(a)



(b)



Port Lincoln (4 events)
All four cases occurred just before the passage of a strong cold front. In each case the wind speed increased rapidly with a sharp temperature increase and dew-point decrease. Given the particular geography of Port Lincoln, near the tip of Eyre Peninsula, this phenomenon might be ascribed to a shallow marine inversion layer being either 'broken', or advected south of the station by strengthening pre-frontal northerly winds, leading to strong horizontal advection of continental boundary layer air.

Mount Crawford (2 events)
Each occurred in a generally easterly flow, and with a sharp wind change from southeast to northeast. As the station is located in the Mt Lofty ranges, the increased mixing associated with flows similar to the 'gully wind' (Sha et al. 1996) might be the cause.

Hobart (2 events)
Both events occurred with strong winds from the north or northwest, and enhanced vertical mixing in the lee of the Tasmanian topography appears to be a likely contributor to such events, particularly as wave patterns can be seen in satellite imagery during these synoptic sequences.

Mount Gambier (2 events)
Both events occurred just before frontal changes. Increased wind/gust speeds were coincident with the drying, so vertical mixing due to either the increased wind speeds associated with the pre-frontal jet, or enhanced mixing due to the vertical cross-frontal circulation as hypothesised by Mills (2007) may be factors in these cases.

Perth (1 event)
This event occurred as southeasterly winds shifted easterly and strengthened, but the direction did not change dramatically thereafter though the winds continued to increase and the dew-point also increased. The period of low dew-point very much coincided with the period of the wind direction change, and may be associated with topographically induced flows.

Jacup (1 event)
The lowest dew-point was observed in fresh northerly winds prior to a strong trough passage between 0200 and 0400 LST, and appears similar to the nocturnal events at Mt Gambier.

Scone (1 event)
A sharp change was moving northwards along the NSW coast that evening. Winds had backed from northwest to west during the afternoon, and the coincidence of a temperature fall suggests that the cool change passed Scone then. The lowest dew-point occurred some hours after the passage of the front, and coincided with a backing of the winds to the northwest.

Discussion

This paper has described the conditions under which a number of abrupt surface drying events have occurred over six years at a widely dispersed network of stations over southern Australia. The climatological analysis indicates that while not uncommon, such an abrupt surface drying event may only occur at a given location a few times during a fire season, and that there is a weak relationship with antecedent rainfall anomaly. It is proposed that the majority of events require two separate processes to take place, one in the upper half of the troposphere to bring dry upper-tropospheric air to the middle troposphere, and the other a process in the lower half of the troposphere to mix this dry air from aloft to the surface.

The upper-tropospheric descent required to generate this downward advection of dry air is associated with synoptic and subsynoptic trough/ridge and jet stream circulations associated with parcel acceleration. Examples associated with large-scale upper ridges, jet entrance, and jet exit circulations were presented. A particular paradigm was that of overlapping jet entrance and jet exit circulations inducing elongated narrow bands of descending dry air, and such circulation patterns were a feature of the Canberra and the Port Lincoln fire abrupt surface drying events. The presence of these dry areas can be also identified as dark bands in WVI in many cases, supporting the conjecture in Mills (2005a) that WVI may be a useful forecast aid in fire weather forecasting. It must be remembered that this descent occurs over many hours on sloping paths, and thus downward motion in the upper-troposphere at the time of the surface abrupt drying is not a necessary ingredient, although mid-tropopsheric dry air resulting from prior descent may well be.

The lower tropospheric processes that link the mid-tropospheric dry air to the surface are several. A major factor appears to be dry convective mixing in deep, daytime mixed layers, and the stability phase space occupied by the drying events documented in this study, the fact that events occur overwhelmingly during the afternoon heating maximum when mixed layers are typically deepest, and the evidence of the cited case studies all support this hypothesis. There are, however, several other factors regularly seen. The presence of dry cold fronts or troughs appears to be a common factor in some 70 per cent of events. It is less obvious that the front provides a direct mechanism for the vertical exchange of air, but there is evidence that suggests that the pre-frontal updraft may enhance entrainment of mid-tropospheric air immediately before frontal passage, and the pre-frontal jet may either allow mechanical mixing to the surface (in some of the nocturnal events), or have associated with its entrance region a region of lower-tropospheric descent. Of course in much of southern Australia the consequences of high pre-frontal temperatures and southward advection of hot continental air are very deep mixed layers in the pre-frontal air-mass. Finally, the descent on the cool-air side of the frontal system can bring post-frontal dry air from the mid-troposphere to near the surface. The other major low-level process that can link the mid-troposphere with the surface occurs in cross-mountain flows where lee troughs and topographically induced descending flows from ridgetop or above ridgetop level can enhance the downward transport of dry air from aloft. These processes are most commonly seen along the east coast of Australia, including Tasmania, but do appear to have some role near the Mt Lofty Ranges in SA, and the Darling Ranges in WA.

Another effect associated with topography is seen on the higher peaks in southeastern Australia overnight, when lowering of the subsidence inversion can lead to increases in temperature and dramatic lowering of humidity.

Taken in their entirety, the above components are sufficiently diverse that it is difficult to ascribe a small number of typical synoptic conceptual models that can be used as a forecast aid. However, if an ingredients-based view of the process is taken, then carefully assessing the upper troposphere first to identify areas of sustained deep descent that can lead to areas of dry mid-tropospheric air, and second to assess whether there are any of the several lower-level factors present that may allow this air to reach the surface, then some success in forecasting these events might be achievable. This may provide some additional lead-time in warning that an existing wildfire may show enhanced fire activity, with obvious operational benefits. A task for the near future is to assess the ability of operational mesoscale NWP models to accurately forecast such extremely low humidities at the surface.

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