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Objective identification of wind change timing from single station observations Part 2: towards the concept of a wind change climatology

Xinmei Huang
Bureau of Meteorology Research Centre, Australia
and Bushfire Cooperative Research Centre, Australia
and
Graham A. Mills
Bureau of Meteorology Research Centre, Australia

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Fuzzy logic functions of time series of METAR and SPECI data were used in a companion paper to identify 'timing' of frontal wind changes on days that the Victorian Regional Forecast Centre of the Australian Bureau of Meteorology had issued a 'Wind Change Forecast', and the results compared with subjective wind change timings for these same events. In this paper the same algorithms are applied to the full METAR and SPECI database, and additional measures designed to quantify the 'strength' or 'significance' of the changes so identified are developed. It is shown that the algorithms identify many more changes than simply those that occur on the VRFC wind change days, and that the number of wind changes resolved varies with different screening thresholds, thus generating a wind change climatology at each observation site. Examples of potentially useful wind change climatology products are presented, and it is shown how the objective methods can identify significant change types other than those associated with strong, dry cold fronts.

Introduction

Wind changes, and particularly wind changes that are associated with dry cold fronts, have profound effects on fire behaviour and fire-fighting operations (e.g. Cheney et al. 2001). Huang and Mills (2006b) (hereafter Part 1) have reported on the first stage of a larger scale project that aims to improve the understanding and prediction of wind changes in Australia. In Part 1 a method of objectively identifying the 'change time' at an observing station on a day when a significant frontal wind change was forecast by the Victorian Regional Forecast Centre (VRFC) of the Australian Bureau of Meteorology (the Bureau) was described. The method uses fuzzy logic based on time series of METAR and SPECI observations from a single station, and was shown to have comparable performance to subjective methods based on space-time continuity of synoptic analyses. The objective method also produces start time and end time of the change period, rather than just a single 'change time', as well as the interval during the change period where the 'Wind Change Rate Index' (WCRI) exceeds a specified threshold.

Corresponding author address: X. Huang, Bureau of Meteorology Research Centre, PO Box 1289, Melbourne, Vic. 3001, Australia. Email: x.huang@bom.gov.au

The algorithms described in Part 1 were only applied to METAR and SPECI time series on the VRFC wind change days in the first instance, since it is only on those days that comparative subjective change timings were available. However, considerable case-to-case and station-to-station variability was seen in Part 1, and so an obvious next step is to apply the algorithms to the full METAR and SPECI record to see if the algorithms can identify useful information about systematic differences in change structures across a State. The purpose of this paper is to present the results of doing this at the seven VRFC verification stations used in Part 1.

In Part 1 the WCRI was introduced as a means of identifying the change time – the time within the change period at which WCRI was highest. As defined, the WCRI has a unique value at each observation time. However, wind changes can be short, sharp transitions, or long, slow transitions; and may have greater or lesser degrees of difference in the basic change parameters (wind speed/gust, wind direction and dew-point depression) across the whole change period (quantified for VRFC changes in Part 1). In order to make possible some objective stratification of the changes identified in this paper, we develop a Wind Change Strength Index (WCSI), which again uses fuzzy logic to define an index of synoptic strength of the change as measured by the difference between the change parameters at the beginning and end of the change period. It is not difficult to envisage circumstances where WCRI may be large and WCSI small, or vice versa, yet it is those cases where both WCRI and WCSI are large that are perhaps closest to the synoptic paradigm encapsulated in the Victoria Fire Weather Directive quoted in Part 1, and which calls for the identification of a 'significant' frontal wind change. Since our aim is to develop a system whereby some form of discrimination of change 'significance' can be achieved without resorting to a subjective synoptic typing paradigm, while still encompassing the essential components of the synoptic paradigm of the southeastern Australian 'cool change', we will also describe a Wind Change Danger Index (WCDI) that combines the WCSI and WCRI into a single index. The first section of this paper describes these WCSI and WCDI algorithms.

We then apply the timing algorithms to the full METAR and SPECI database for the seven verification stations for the four fire season's data used in Part 1, show that many more objective changes than VRFC changes are identified, and that this ratio is dependent on the value of the WCDI used to stratify the data. As one of the criteria for a VRFC wind change chart to be issued is that the Forest Fire Danger Index (FFDI, Luke and McArthur (1978)) is expected to be very high or extreme (FFDI ≥ 24), we also compare the effects of stratifying the objective changes by FFDI rather than WCDI. Distributions of change time by time of day and change duration at each of the verification stations are presented, as are examples of significant non-frontal change types identified by the objective timing algorithms. Finally, some implications for the future directions of this type of analysis are discussed.

Measures of change intensity

The Wind Change Strength Index

The WCRI, a measure of 'instantaneous' wind change strength, was described in Part 1 and used to define the 'change time' for frontal wind changes. While appropriate for its application, it does not differentiate between what a meteorologist might term synoptically weaker or stronger wind changes. However, it was shown in Part 1 that the VRFC wind changes generally were associated with large direction, speed and dew-point depression changes, and also with significant wind speeds. In this section we develop a measure of the 'wind change strength' that represents the entire change period – that is, the degree of change from the start time to the end time of the wind change period, based on a combination of direction range, wind speed change, wind speed and dew-point depression change across the whole change period. This function is intended to lead to a means of objectively stratifying the 'significance' of wind changes using the time series of observations from a station rather than using a subjective synoptic classification.

Using the schematic model of a wind change presented in Fig. 10 of Part 1, and the terminology used in that figure, we first define parameters, which we will term change parameters, representing:

- the wind speed during the wind change period (x_u), designed to take into account the mean speed through the change period, the speed at the time of the maximum WCRI, and the speeds before and after the change period;
- change in wind direction (x_{dd}), defined as the difference between the directions at the start and end of the change period;
- change in wind speed (x_{du}), defined as the difference between the speed at the beginning and end of the change period;
- change in gust wind (x_{dg}), defined as the difference between the average gust speed through the change period and a gust threshold;
- change in dew-point depression (x_{dpd}), defined as the maximum hourly dew-point depression change during the change period.

These change parameters are fully described in the Appendix. A generic fuzzy function, $f_z(x)$, is defined as

$$f_z(x) = \begin{cases} y1 & x < x_{c1} \\ y1 + \dfrac{(y2 - y1)}{(x_{c2} - x_{c1})}(x - x_{c1}) & x_{c1} \le x < x_{c2} \\ y2 + \dfrac{(y3 - y2)}{(x_{c3} - x_{c2})}(x - x_{c2}) & x_{c2} \le x < x_{c3} \\ y3 & x_c \ge x_{c3} \end{cases} \quad ...1$$

where separate values of the thresholds (x_{c1}, x_{c2} and x_{c3}) and the constants $y1$, $y2$ and $y3$ are defined for each of the change parameters above, and are described in the Appendix.

Combining the three fuzzy functions of x_{dd}, x_u and x_{dpd}, the wind direction change strength function f_{ds} from t_{sc} to t_{ec} (the start time and the end time of the change period, see Fig. 10 of Part 1) is expressed as

$$f_{ds} = \begin{cases} 0 & f_{ds} < 0 \\ f_z(x_{dd}) + f_z(x_u) + w_m f_z(x_{dpd}) & f_{ds} \ge 0 \end{cases} \quad ...2$$

where w_m is a weight factor for x_{dpd}, giving the change in dew-point depression less weight than wind speed and wind direction in the calculation of f_{ds} (w_m = 0.5 is used in this study). With the values selected for $y1$-$y3$ in this study, the wind change strength function f_{ds} can range from 0 to 3.5.

The wind speed change strength function f_{us} (t_{sc}, t_{ec}) is expressed as

$$f_{us} = \begin{cases} 0 & f_{us} < 0 \\ f_z(x_{du}) + f_z(x_u) + w_m f_z(x_{dpd}) & f_{us} \ge 0 \end{cases} \quad ...3$$

The wind change strength function f_{ws} from t_{sc} to t_{ec} is then evaluated as

$$f_{ws}(t_{sc}, t_{ec}) = \begin{cases} f_{ds} & f_{us} \le 1.1 f_{ds} \\ f_{us} & f_{us} > 1.1 f_{ds} \end{cases} \quad ...4$$

If f_{us} is less than 1.1 f_{ds}, a wind change may be classed as primarily a wind direction change. Otherwise it is regarded as a wind speed change.

The wind change strength function f_{ws} can then be scaled to produce a normalised wind change strength index (WCSI),

$$WCSI = 100 \times \left[\frac{f_{ws}(t_{sc}, t_{ec})}{WSmx} \right]^2 \quad ...5$$

where $WSmx$ = 3.5 is the maximum value that f_{ws} can reach, and the WCSI can consequently range from 0 to 100.

Wind Change Danger Index

It is not difficult to envisage circumstances where WCRI may be large and WCSI small, or vice versa, yet it is those cases where both WCRI and WCSI are large that are perhaps closest to the synoptic paradigm encapsulated in the Fire Weather Directive (Bureau of Meteorology 2004), and which calls for the identification of a 'significant' frontal wind change. Since our aim is to develop a system whereby some form of determination of change 'significance' can be achieved without resorting to a subjective synoptic typing paradigm, while still encompassing the essential components of the synoptic paradigm of the southeastern Australian 'cool change', accordingly, we propose a Wind Change Danger Index (WCDI) that combines the WCSI and WCRI into a single index, as shown in the schematic in Fig. 1. In Area 1 of that diagram either the WCRI or the WCSI is small and the change is regarded as 'weak'; Area 2 has either moderate to large WCSI or moderate to large WCRI, and so the WCDI increases with increasing WCSI and WCRI; while in Area 3 both WCSI and WCRI are large and the change is classed as 'very significant'. An algebraic description of Fig. 1 is presented in Appendix D of Huang and Mills (2006a) (hereafter HM06).

WCDI distribution on VRFC wind change days

Having proposed an index of wind change strength to act as a potential identifier of significant frontal wind changes, we first assess the frequency distribution of WCDI on the VRFC wind change days, and this is shown in Fig. 2. There is little difference between the distributions in the development (2001-02 and 2002-03) and independent (2000-01 and 2003-04) fire seasons, with some 50-55 per cent of changes having a WCDI of 100, and about 80 per cent of changes having a WCDI greater than 50. These results suggest that on most of the days the VRFC expected a significant wind change to progress through the State; the objective technique also identified a change of significant strength at most of the verification stations. There are, however, some 10 per cent of changes for which the WCDI is less than 30, indicating that only a very weak change was identified by the objective technique. This is less a deficiency in either technique than a consequence of the difference in methodologies used. Two examples where the objective technique identified a wind change on a VRFC wind change day, but with a very low WCDI, are presented in Figs 23 and 24 of HM06.

Fig. 1 **Schematic showing the relation between WCRI, WCSI and WCDI.**

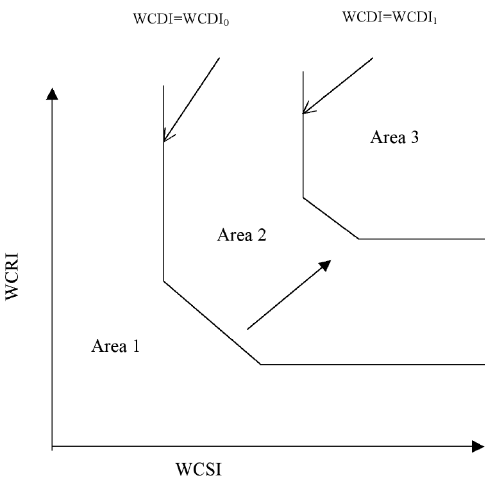
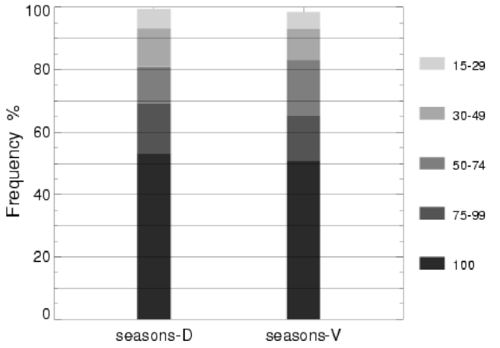


Fig. 2 **Frequency of VRFC wind changes with different WCDI thresholds for development (D) and for independent (V) seasons.**



An objective change climatology

Ratio of objective to subjective changes

It was shown in the preceding section that the objective method identifies wind changes on most of the station days that the VRFC issued wind change forecast charts, and that a large proportion of these changes have a high value of WCDI. Applying the objective change identification method to the full METAR and SPECI archive for the seven verification stations for the four seasons used in this study, many more changes were identified than were included in the VRFC data. Plotting the ratio of the number of objective changes to the number of subjective changes (R_{os}) for various WCDI thresholds (Fig. 3) shows that for the strongest changes the objective method identifies three times as many changes as were forecast by the VRFC. This ratio increases to something like six for a WCDI threshold of 50, and even more quickly as the WCDI threshold decreases. This result, combined with individual case studies, indicates there are a number of meteorological events other than simple frontal changes during which significant changes in wind direction, speed, temperature and moisture content may have a fire weather impact.

The frequency distribution of all objective wind changes for different WCDI thresholds is shown in Fig. 4. In contrast to the VRFC wind changes (Fig. 2), the frequency of objective wind changes with high a WCDI is very low. Around 10 per cent of the objective wind direction changes have a WCDI of 100, and about 35 per cent have a WCDI of 50 or greater. The frequency of VRFC wind changes with high WCDI (Fig. 2) is much larger than for those evaluated by the objective method. As about 80 per cent VRFC wind changes have a WCDI of 50 or greater, an objective wind change with WCDI of 50 or greater will be defined as a significant wind change for the remainder of this study. A consequence of this definition is that some five times as many objective wind changes are identified compared to the VRFC forecasts. Figure 5 shows the ratio of the number of objective to subjective wind changes for different WCDI thresholds for each of the verification stations.

Fig. 3 **Ratio of number of objective wind direction changes identified to number of subjective wind direction changes with changing WCDI threshold for development (D) and for independent (V) seasons.**

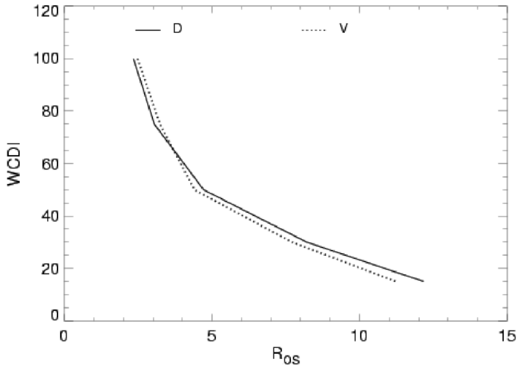


Fig. 4 **Frequency of objective wind wind changes with different WCDI thresholds for development (D) and for independent (V) seasons.**

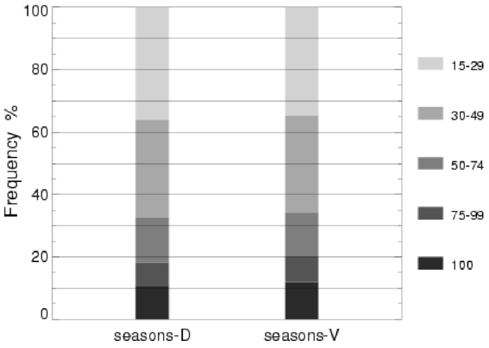
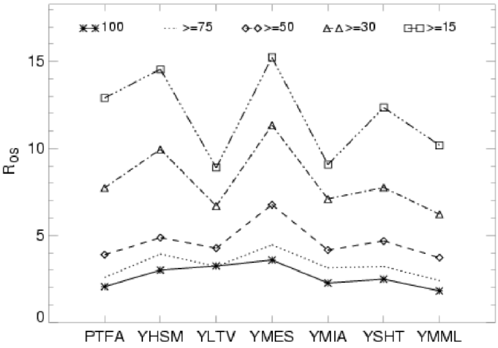


Fig. 5 **Ratio of number of objective wind changes to number of subjective wind changes for each verification station with different WCDI thresholds for the objective changes. The four fire season's data are used. Station identifiers: PTFA Port Fairy; YHSM Horsham; YLTV Laverton; YMES East Sale; YMIA Mildura; YSHT Shepparton; YMML Melbourne Airport.**



At the highest threshold, there is little difference between the stations. However, there is more variability between stations when lower WCDI thresholds are used, with East Sale having the highest ratio, but Latrobe Valley (quite close to East Sale), Melbourne and Mildura having a significantly lower proportion of weaker changes than the other stations.

There are a number of factors that might contribute to the higher number of changes determined by the objective method. Clearly the method is not constrained to a single synoptic paradigm, as is the VRFC method, and so local effects such as sea-breezes, upslope and downslope winds in areas of significant topographic relief, and local boundary-layer development can all have an influence. In addition, the VRFC only selects one change time for a given event, but the objective method can determine more than one time on a given day.

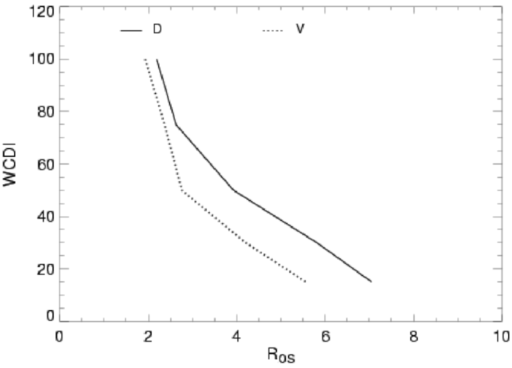
Fire danger index and objective change frequency

Given that the VRFC wind change forecasts are only issued if it is expected that the McArthur Forest Fire Danger Index (FFDI) (McArthur 1967; Luke and McArthur 1978; Griffiths 1998) will be very high or extreme (i.e. FFDI > 24), and that the objective wind change timing does not explicitly consider the fire danger at the time of the wind change, it is of interest to compare the number of objective changes that occur with the FFDI greater than 24. We follow the VRFC in calculating the FFDI according to the formula of Noble et al. (1980),

$$FFDI = 2\times\exp(-0.45 + 0.987\ln(DF) - 0.0345RH + 0.0338T_a + 0.0234U) \qquad ...6$$

where RH is relative humidity (%), T_a is air temperature (°C), U is wind speed (km h^{-1}), and DF is the Drought Factor (see Griffiths 1998) that ranges from 0 to 10. Using the highest FFDI at the station on the day of the objective wind change, we can determine the number of 'objective' and 'VRFC' wind changes that occur with FFDI above a certain threshold. Figure 6 shows the ratio of the number of objective to VRFC changes for objective changes when the FFDI

Fig. 6 **Ratio of number of objective wind direction changes identified to number of subjective wind direction changes with changing WCDI threshold for development (D) and for independent seasons (V), but only including objective changes for which FFDI ≥ 24.**



is 24 or greater for varying values of WCDI. While the ratio is still significantly greater than one, it is much less than the values shown in Fig. 3. For the strongest changes, the objective method identifies 2 to 2.5 times as many changes as were forecast by the VRFC. This ratio increases to something like 3 to 5 for a WCDI threshold of 50. The R_{os} for the independent seasons (2003-04 and 2000-01) is less than for the development datasets. This could be caused by the higher DF observed at many of these stations during the 2002-03 fire season (Bureau of Meteorology 2003).

The climate of wind change times

It is instructive to group the change times by time-of-day for the objective 'significant' wind changes and the VRFC changes; these plots are shown for each of the verification stations in Fig. 7. There are a number of interesting features seen in these plots.

- For most stations the VRFC change times tend to be in the mid-afternoon through to the evening, although Port Fairy shows a significant number of VRFC changes in the earlier part of the day, and East Sale and Latrobe Valley show steady increases in numbers from the mid-morning to broad maxima in the late afternoon and early evening, and secondary maxima in the middle of the night.
- The time distribution of the objective 'significant' change times is a little broader than the VRFC distribution, with many more changes identified. However, the same general distributions can be seen, with a tendency for late afternoon and early evening maxima, Port Fairy again showing a distribution biased to earlier in the day. Other differences include a secondary morning peak at Melbourne Airport.

In the next section we will present examples of non-frontal (non-VRFC) changes at these stations that provide some insight into the climatological analysis presented in Fig. 7, and also indicate how a climatological change analysis can indicate significant sub-synoptic change paradigms different from the dry cold front synoptic paradigm.

As described in Part 1, the objective timing algorithm provides a start time and an end time for the change period, and also the duration during which the WCRI exceeds a given threshold, termed the accumulated High Wind Change Rate Time (HCRT) or significant change period. Figure 8 shows the distribution of wind change periods for Port Fairy, Melbourne Airport and Horsham, and HCRT for all objective wind changes for the four seasons of fire data used in this study, subject to the WCDI associated with those changes being 15 or greater and 50 or greater. There are clear differences in the duration of change climatology at these three stations. For example:

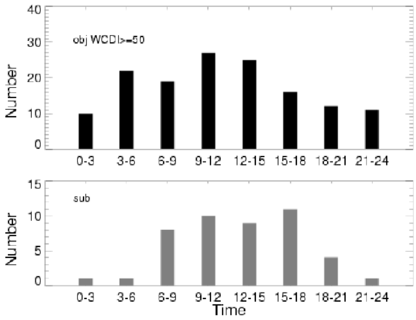
- at Port Fairy and Melbourne a significant proportion of strong changes have a change period of an hour or less, while at Horsham much larger proportion of wind changes have a very long (over four hours) change period;
- Port Fairy has the highest proportion of changes with a significant change period of less than two hours, and relatively few changes with significant change periods of greater than three hours;
- the distribution of significant change periods is a little broader for Melbourne Airport, although still strongly biased to the shorter periods. However, at Horsham a much broader distribution is seen, with a smaller proportion of short significant change periods – that is moderate or higher WCRI conditions are likely to last longer at Horsham (typical of the inland stations) than at Melbourne or Port Fairy.

Non-frontal wind changes in the Latrobe Valley

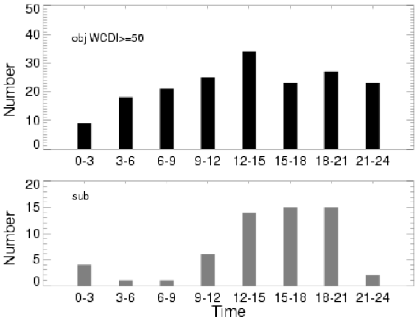
The higher R_{os} at East Sale than at the other stations encourages the hypothesis that local circulation features at East Sale, be they valley or sea-breeze circulations, are more significant at this location than at some others. Ludwig et al. (2004) (amongst many others) have noted that the wind vector has greater variance at day-night transitions in mountain valleys, while Physick and Abbs (1992) have shown examples of the complex diurnally varying flows in the Latrobe Valley. It was seen in Fig. 7 that VRFC forecast wind changes occur more frequently at East Sale in the late afternoon, but with secondary maxima just after midnight and in the morning. There are many more significant (WCDI>50) objective wind changes at East Sale and also a steady increase in number of changes through the middle of the day, with the maximum number occurring between 1200 and 1800 Australian Eastern Daylight Saving Time (AEDT). The increased number of changes in the late morning and early afternoon might be hypothesised as being due to the breaking of a valley inversion, while some of the peak in the afternoon and evening changes may be due to the arrival of the sea-breeze. The significant numbers of both VRFC and objective changes after 1800 AEDT indicates a slight preference for cold-frontal changes to arrive at this time, and this late evening arrival might be considered consistent with a tendency for daytime frontogenesis on the west coast of Victoria, as postulated by Loewe (1945) and diagnosed in the case described in Mills (2002).

Fig. 7 **Time distribution of wind direction changes. Upper panels (black) are the objective wind direction changes; lower panel (grey) are the VRFC wind direction changes. Objective wind change time is t_{mx}. For the objective changes, number is the number of wind changes with WCDI ≥ 50 for the four fire seasons. Note that the scales used in the ordinates change from station to station.**

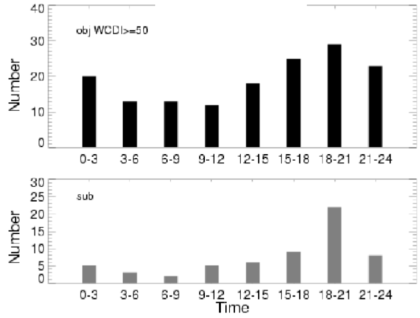
Port Fairy



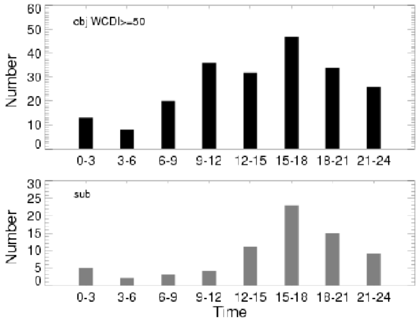
Horsham



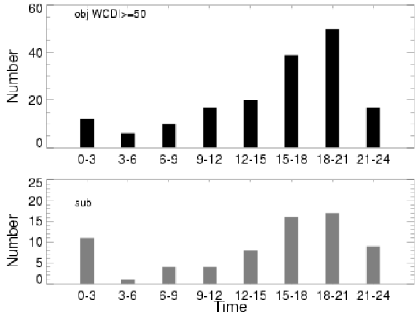
Mildura



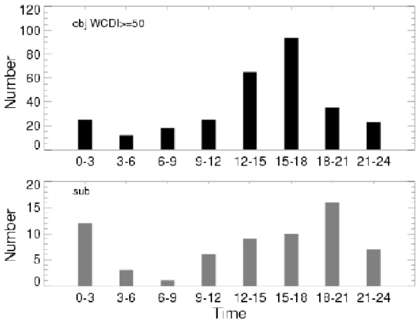
Melbourne Airport



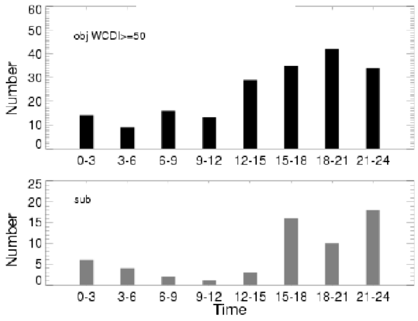
Laverton



East Sale

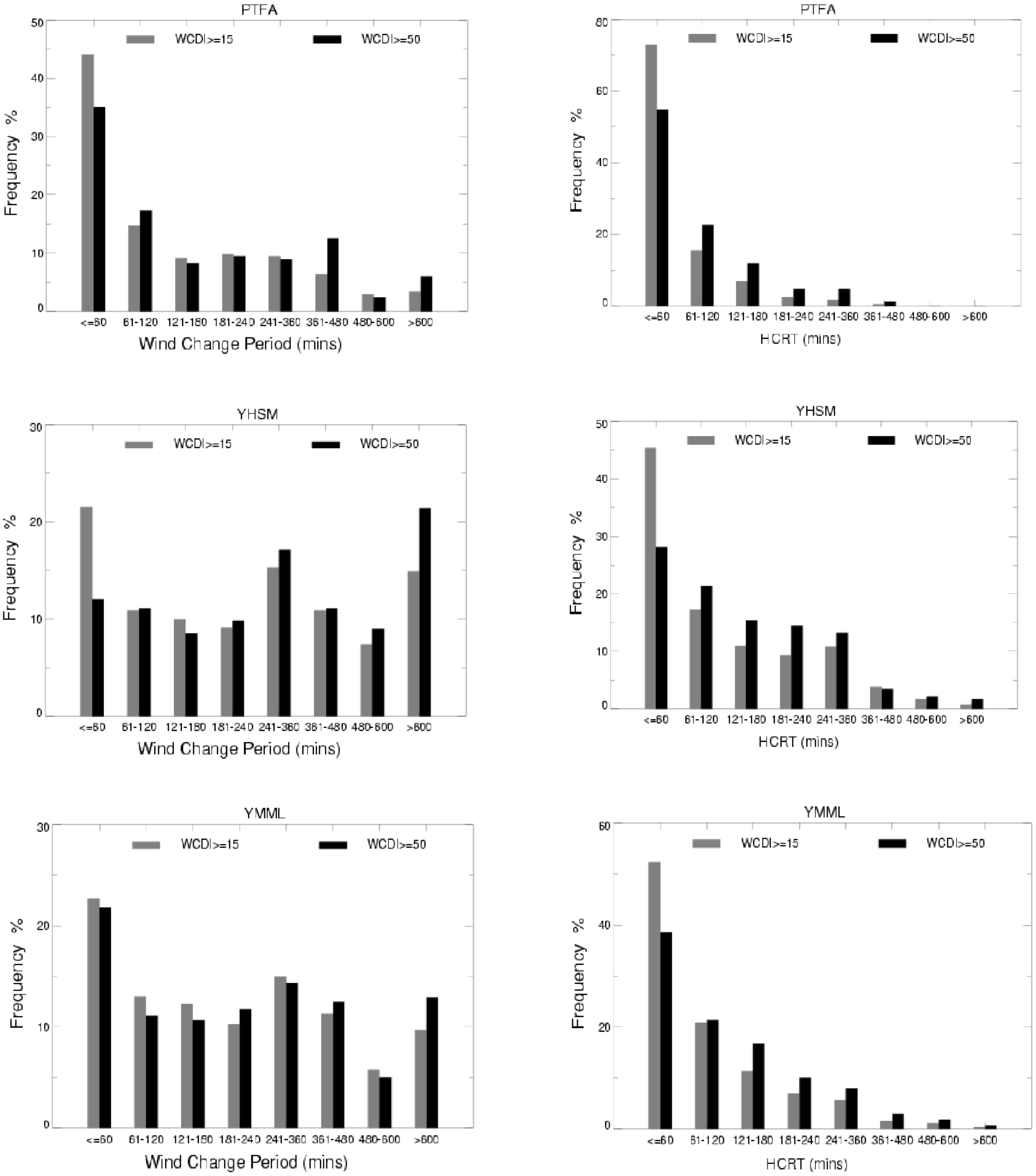


Shepparton



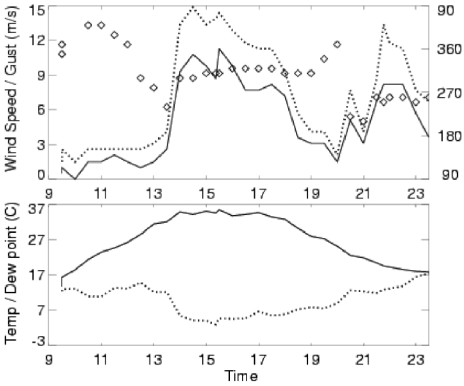
An example of a significant, early afternoon, non-frontal wind change at East Sale is seen in Fig. 9, for the VRFC wind change on 18 March 2002 (this change is shown passing through Port Fairy, Melbourne and Mildura in Figs 4, 5 and 6 of HM06). The objective method identified two wind change periods, the first between 1130 and 1400 AEDT, with t_{mx} (the objective wind change time – the time within

Fig. 8 Frequency distribution of wind change period (left), and accumulated High Wind Change Rate Time (HCRT) (right) for Port Fairy, Horsham and Melbourne Airport for the four fire seasons 2000-01 to 2003-04. Changes with WCDI > 50 (black) and >15 (grey). Note that the time intervals are 1 hour up to 4 hours, then 2-hourly to 10 hours, with the final group >10 hours.



the change period that the maximum WCRI occurs) at 1400 AEDT. During this period the wind backed from northeasterly to northwesterly, but more significantly increased in speed (gust) from 1 (2) m s^{-1} to 10 (14) m s^{-1} in one hour. The second wind direction change period was from 1930 to 2130 AEDT, and both the objective and subjective verifications assessed the time of this wind change at 2030 AEDT. It is this second change that was associated with the cold front on the synoptic-scale analyses for the day. For the first change WCDI was 100 and the second change WCDI was 95. However, during the first change period the

Fig. 9 Meteogram of observations at East Sale for the change of 18 March 2002. The upper panel shows mean wind speed (solid), gust speed (dotted), and wind direction (diamonds), while the lower panel shows temperature (solid) and dew-point (dotted). Times are in hours AEDT.

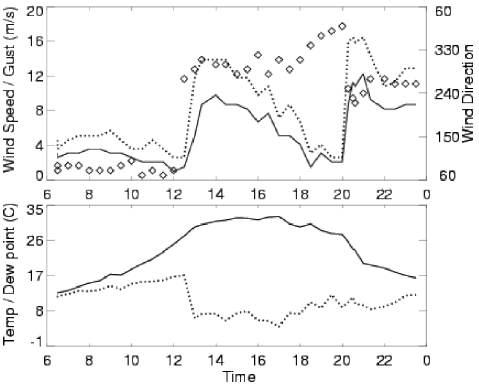


FFDI increased from about 12 at 1300 to about 50 (extreme) at 1400 AEDT, while the lower temperatures and higher dew-points after 2030 AEDT produced a FFDI of less than 10, in spite of the stronger winds at this time.

A similar example at Latrobe Valley Airport is shown in Fig. 10 for the cool change on 29 December 2001. In common with the preceding case, the wind backed from northeast to northwest during the late morning, with an abrupt increase in wind speed during the change period, objectively defined to be between 1200 and 1320 AEDT. A second objective wind change period was defined from 1800 to 2100 AEDT (t_{mx} = 2030 AEDT), associated with the cold front passage. The VRFC verifying change time was 2017 AEDT, when the wind backed to the west and southwest and the speed increased sharply. For both the first and the second wind direction change period the WCDI was 100.

Synoptically, in conditions when there is a front approaching western Victoria in the early part of the day, the northwesterly gradient flow is distorted by the eastern Victorian orography to form a lee trough to the south of the ranges, and produces a northeasterly surface flow over Gippsland and the Latrobe Valley (examples are seen in Mills (2002, 2005)). This lee trough is better defined in the stable conditions of early morning, and so the late morning transitions to northwesterly flow seen in Figs 9 and 10 might be hypothesised to mark the boundary-layer transition to a deeper mixed layer.

Fig. 10 Meteogram of observations at Latrobe Valley for the change of 29 December 2001. The upper panel shows mean wind speed (solid), gust speed (dotted), and wind direction (diamonds), while the lower panel shows temperature (solid) and dewpoint (dotted). Times are in hours AEDT.



An analysis that suggests the conceptual model for a morning wind shift in the Latrobe Valley in pre-frontal conditions has some validity is summarised in Table 1. This shows the number of wind changes identified in the morning at Latrobe Valley Airport and at East Sale on days when VRFC wind changes were forecast. On more than half the VRFC wind change days the objective system identified multiple wind changes with WCDI grater than 50. The average

Table 1. Number of multiple changes from the objective technique on days when VRFC wind changes were forecast at East Sale and Latrobe Valley Airport with t_{rfc} between 1700-2230 AEDT. Objective early changes are t_{mx} between 1000-1400 and WCDI ≥ 50. Objective evening changes are tmx between 1600-2230 and WCDI ≥ 50. Four fire seasons' data used.

	East Sale	*Latrobe Valley*
Number of evening changes	22	21
Number of objective early changes	14	12
Average VRFC change time (AEDT)	1937	1920
Average early changes t_{mx} (AEDT)	1214	1213
Average evening changes t_{mx} (AEDT)	1914	1934
Average early change $WCRI_{mx}$	81	82
Average early change WCDI	86	92
Average evening change $WCRI_{mx}$	86	84
Average evening change WCDI	91	89

t_{mx} is similar at each station with evening changes around 1930 AEDT, but ranging from 1600 to 2230 AEDT, and the early changes between 1000 and 1400 AEDT, with a mean time of 1215 AEDT for the objective changes. The VRFC change times were between 1700 and 2230 AEDT. For both the early and evening changes the WCDI averages 85 to 90 and the average WCRI is greater than 80. While we are not suggesting that the official forecasts are in error, or that forecasters do not understand this phenomenon, this example does indicate a role for this objective change typing technique beyond the sole purpose of objective identification of the time of frontal passage. It should be made clear to the fire agencies that the early non-frontal wind change may have greater impact on their operations than the later 'frontal' wind change.

Wind speed changes

Although it is relatively rare for VRFC wind changes to be forecast during the night at Port Fairy, Mildura and Horsham, the objective method has identified a number of significant wind changes overnight at these stations (Fig. 7). An example of a midnight wind change at Port Fairy is seen in Fig. 11. On 21-22 December 2002 the wind changed from southeasterly to southwesterly, but with relatively low wind speed between 1730 and 2030 AEDT. However, just before midnight (0000 AEDT) the wind backed to southerly and wind speed increased from 1.5 to 8.2 m s^{-1} within one hour. The objective method identified a first wind direction change from 1730 to 2030 AEDT and a second wind speed change from 2200 AEDT 21 December to 0130 AEDT 22 December with WCDI equal to 53. No VRFC wind change was forecast, probably due to the anticipated relatively low overnight FFDI. Synoptic analyses (http://www.bom.gov.au/nmoc/MSL/index.shtml) show the first change was associated with the passage of a trough in easterly flow, while the second change was associated with the passage of a cold front south of Bass Strait that was followed by strong pressure rises through Bass Strait. These pressure rises are clearly seen in Fig. 11 after midnight.

Fig. 11 **Meteogram of observations at Port Fairy of 21-22 December 2002. The upper panel shows mean wind speed (solid), gust speed (dotted), and wind direction (diamonds), while the lower panel shows temperature (solid), dew-point (dotted) and pressure (hPa) (triangles). Times are in hours AEDT.**

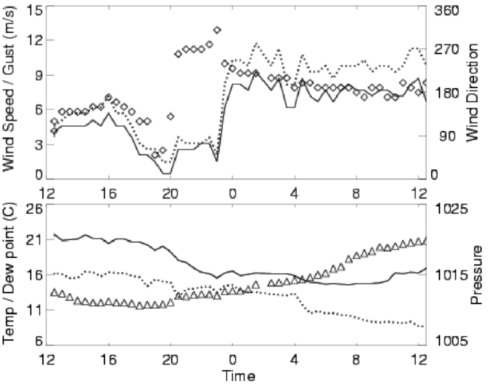
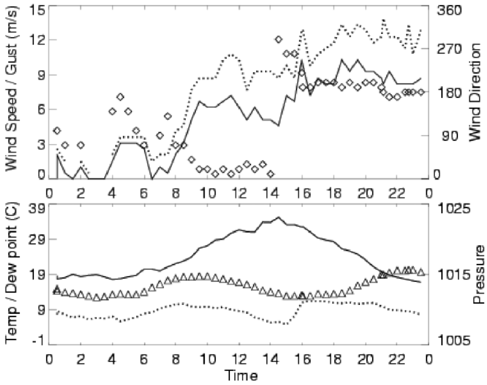


Fig. 12 **Meteogram of observations at Shepparton for the change of 14 January 2003. The upper panel shows mean wind speed (solid), gust speed (dotted), and wind direction (diamonds), while the lower panel shows temperature (solid), dew-point (dotted) and pressure (hPa) (triangles). Times are in hours AEDT.**



For the cool change at Shepparton on 14 January 2003 (Fig. 12), the VRFC timed the change at 0430 AEDT. The objective method did not identify a change around 0430 AEDT, as the wind speed and thus the WCRI were very low at that time. However the objective method identified a wind change period between 0730 and 1000 AEDT with WCDI of 20, and a second wind change period from 1400 to 1558 AEDT, with the WCDI equal to 100. The temperature and dew-point traces also show falls and rises between 1400 and 1550 AEDT, consistent with the model of a wind change used in this study. The Bureau's synoptic analyses (http://www.bom.gov.au/nmoc/MSL/index.shtml) show a frontal position consistent with the VRFC timing. Following the front, though, very strong ridging was observed through western Victoria (see the pressure rises in Fig. 12 after 1600 AEDT), and this led to a rapid increase of the pressure gradient and consequently strengthening southerly winds. It is this synoptic-scale pressure rise that is responsible for the objectively defined wind change in the mid-afternoon.

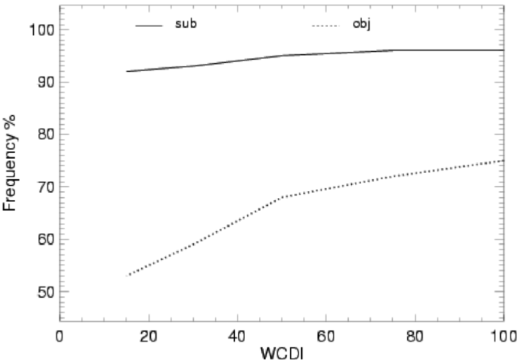
These two cases, and others in HM06, show that the objective technique identifies a class of wind changes as 'speed' changes associated with increasing pressure gradient due to synoptic-scale ridging. It was suggested above (Eqn 4) that changes could be classified primarily as either 'speed' or 'direction' changes. Figure 13 shows the proportion of VRFC changes, and the proportion of all objective changes, that are primarily direction changes, again stratified by WCDI. More than 90 per cent of VRFC changes are primarily direction changes, consistent with the synoptic paradigm used to determine days on which such wind change forecasts are issued, and this proportion does not change significantly with increasing WCDI. For low WCDI thresholds, around 50 per cent of objective wind changes are speed changes, however, as the WCDI threshold is increased, the proportion of direction changes increases to near 70 per cent. Thus even at the highest WCDI, about 30 per cent of objective changes are speed changes.

Discussion

Applying the wind change timing algorithm described in Part 1 to the full METAR and SPECI times series at the VRFC verification stations shows that a large number of wind changes not present in the VRFC wind change days, or at times different to the VRFC wind changes, are identified. The use of the WCDI, a measure of the 'synoptic strength' of the objective changes, allows these changes to be objectively classified. This then allows a climatology of wind change timing, duration, and strength at each verification station to be prepared, and this shows significant station-to-station differences in the wind change climate, even over relatively small areas of southeastern Australia.

Analysis of the objective wind change climate of different groups of stations led to examples of two clear synoptic paradigms of wind changes that are non-frontal in nature – the 'breaking inversion' paradigm in the lee of the eastern Victorian ranges, and the 'synoptic ridging' paradigm whereby increasing pressure gradient associated with pressure rises leads to a sharp increase in wind speed. While we are not suggesting that the strong dry cold-frontal paradigm of a wind change will not remain one of the most critical for fire weather forecasting, given the extreme fire behaviour that can occur near these changes, the other types of change may have significant impacts on fire management operations, especially with the increased emphasis on prescribed (fuel reduction) fires in recent years.

Fig. 13 **Proportion of total number of wind changes that are primarily wind direction changes (see text for details) for VRFC (sub) and all objective wind changes (obj) as a function of WCDI. Four fire season's data have been used.**



It is also shown in HM06 that other non-frontal changes are identified by the objective algorithms, and in that report examples of sea-breeze changes and thunderstorm outflows are presented. Clearly other forms of classification can be used to focus attention on changes of concern in particular applications. For example the thunderstorm outflow changes can generally be filtered by use of the rainfall observations, while benign sea-breeze changes can be filtered using thresholds of fire danger indices. However, given the broad potential of these statistics it is felt that it is better to do this classification at a late stage of the analysis process, rather than including it in the core algorithms. In this way the analysis can focus on a particular feature of interest.

There may well be benefit in applying the objective change algorithms to a wide range of stations in Australia – clearly those states that routinely issue wind change forecasts would find this information beneficial – but it may be instructive in other areas as well. The issue then becomes one of how to present the information, given that it may become quite bulky if a large number of stations were processed. Two options that appear feasible are:

(a) for the current authors to process the raw METAR and SPECI time series and develop a database of wind change statistics (WCRI, WCSI, WCDI, HCRT, start time, end time, duration etc.), and provide some interfaces to allow forecasters or agency staff to browse stations or areas of interest to them;
(b) to provide the software systems to develop a wind change climatology for a given station to the forecast or fire agency staff, and allow them to investigate their regions or stations of interest.

It is not clear at this time what might be the preferred delivery method, but we will be discussing this with interested parties in the near future.

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Appendix

Change parameter for wind direction – x_{dd}

The change period over which the change parameters are calculated covers the period t_{sz} to t_{ez}. These times are close to the times t_{sc} and t_{ec} defined in the conceptual model of a change shown in Fig. 10 of Part 1, and the detailed determination of these times is described in Appendix E of HM06. The wind direction change parameter x_{dd} from t_{sz} to t_{ez} is calculated from both change in mean wind direction through the change period $dD_m(t_{sz}, t_{ez})$ and the direction range through the change period $Rdir(t_{sz}, t_{ez})$ and is expressed as

$$x_{dd} = c1 \times dD_m(t_{sz},t_{ez}) + c2 \times w_{dd} \times Rdir(t_{sz},t_{ez}) \qquad \text{...A1}$$

with

$$c1 = \min\{1.0,\ dD_m(t_{sz},t_{ez}) / Rdir(t_{sz},t_{ez}),\ dD_m(t_{sz},t_{ez})/x_{dc}\} \qquad \text{...A2}$$

$$c2 = 1.0 - c1 \qquad \text{...A3}$$

where w_{dd} is a weight factor, set to be 0.70, and $x_{dc} = 60°$ is used in this study.

Change parameter for wind speed – x_{du}

The change parameter for wind speed is defined as the change in mean speed from the start to the end of the change period. That is,

$$x_{du} = U_m(t_{ez}) - U_m(t_{sz}) \qquad \text{...A4}$$

Change parameter for gust speed – x_{dg}

The change parameter for gust speed x_g from t_{sz} to t_{ez} is evaluated as average gust speed for all observations within the change period. That is,

$$x_{dg} = \left[\sum_{1}^{n} g_u(t_j)\right] / n - x_{gc} \qquad \text{...A5}$$

where $g_u(t_j)$ is gust at time t_j and t_j ranges from t_{sz} to t_{ez} and x_{gc} =10 m s^{-1}.

Wind speed parameter x_u

The wind speed parameter x_u used in the fuzzy function calculation for wind speed from t_{sz} to t_{ez} is determined from the average wind speed during wind change period, the wind speed at t_{mx}, and the mean wind speed at the start and at the end time of the wind change.

We first define the mean speed through the change period as

$$U_{d1} = U_{r1} = \overline{U(t_{sz},t_{ez})} \qquad \text{...A6}$$

a parameter that selects the maximum speed at the beginning and at the end of the change period is defined as

$$U_{d2} = \max\{0.5\times[U_m(t_{sz}) + U_m(t_{ez})],\, w_{uu}U_m(t_{ez})\} \quad \text{...A7}$$

and a speed representative of that at the time of maximum change is defined as

$$U_{r2} = w_{uu}\times U_m(t_{mx}) \quad \text{...A8}$$

with a weighting factor w_{uu} chosen by trial and error to be 0.8. U_m is the two-hour mean wind speed and $\bar{U}$ is the average wind speed.

Then combining these values to define

$$U1_d = \max\{U_{d1}, U_{d2}\} \quad \text{...A9}$$

$$U2_d = 0.5\times U_{d1} + 0.5\times U_{d2} \quad \text{...A10}$$

$$\begin{aligned} U1_r &= \max\{U_{r1}, U_{r2}\} \\ U2_r &= 0.5\times U_{r1} + 0.5\times U_{r2} \end{aligned} \quad \text{...A11}$$

then

$$U_r = \begin{cases} U1_r & t_{ez}-t_{sz}<t_{u1} \\ U1_r + (U2_r - U1_r)\times(t_{ez}-t_{sz}-t_{u1})/(t_{u2}-t_{u1}) & t_{u1}\le t_{ez}-t_{sz}\le t_{u2} \\ U2_r & t_{u2}<t_{ez}-t_{sz} \end{cases} \quad \text{...A12}$$

$$U_d = \begin{cases} U1_d & t_{ez}-t_{sz}<t_{u1} \\ U1_d + (U2_d - U1_d)\times(t_{ez}-t_{sz}-t_{u1})/(t_{u2}-t_{u1}) & t_{u1}\le t_{ez}-t_{sz}\le t_{u2} \\ U2_d & t_{u2}<t_{ez}-t_{sz} \end{cases} \quad \text{...A13}$$

where $t_{u1} = 4$ h and $t_{u2} = 6$ h are times selected to subtly change the speed weightings from the maximum change time for shorter period changes to more weight to the beginning and end times for the longer period changes.

Finally, the wind speed parameter x_u is expressed as

$$x_u = c1\times U_d + c2\times U_r \quad \text{...A14}$$

with the constants $c1$ and $c2$ being the same as used to calculate x_{dd}.

Thresholds and limits for the WCSI fuzzy function

The general form of the fuzzy functions used in calculating WCSI is:

$$f_z(x) = \left\{ \begin{array}{ll} y1 & x < x_{c1} \\ y1 + \dfrac{(y2-y1)}{(x_{c2}-x_{c1})}(x - x_{c1}) & x_{c1} \le x < x_{c2} \\ y2 + \dfrac{(y3-y2)}{(x_{c3}-x_{c2})}(x - x_{c2}) & x_{c2} \le x < x_{c3} \\ y3 & x_c \ge x_{c3} \end{array} \right\} \quad \text{...A15}$$

where x_{c1}, x_{c2} and x_{c3} are thresholds for x.

Constants for direction change parameter

The threshold and scaling constants for x_{dd} are:

x_{ddc1}= 0° h^{-1}, $y1$=-1,

x_{ddc2}= 60° h^{-1} $y2$=1 and ...A16

x_{ddc3}= 90° h^{-1} $y3$=1.5.

Constants for dew-point depression change parameter

The three thresholds for x_{dpd} that are used in the calculation of the fuzzy function for dew-point depression change are:

x_{dpdc1}= 5°C/h, $y1$=0,

x_{dpdc2}= 8.5°C/h, $y2$=0.5, and ...A17

x_{dpdc3}= 12°C/h, $y3$=1

Constants for the wind speed parameter

The three thresholds for x_u that are used in the calculation of the fuzzy function for wind direction change are more complex. The mean wind speed climatologically varies though the diurnal cycle, and also varies from station to station. Accordingly the threshold values for x_u are dependent on the climatological average wind speed (u_{clim}) at the station adjusted by a factor that varies with time of day (u_a).

The function ua is a function of local time, being lower at night than during the day, and is shown schematically in Fig. A1.

The climatological average wind speed, u_{clim}, for each station has been calculated for the five fire seasons 1999-04 for this study, and the speeds for each station used in the verifications are shown in Table A1.

Fig. A1 **Schematic showing the variation of the parameter u_a with local time.**

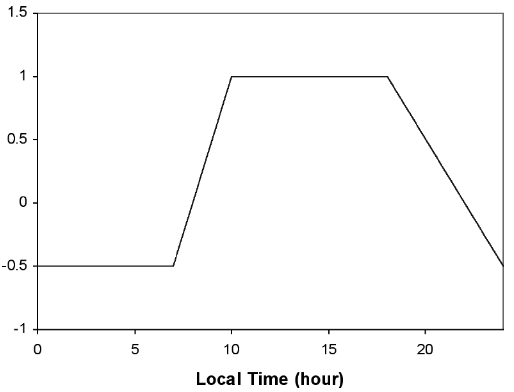

Table A1. Climatological average wind speeds (u_{clim}) used for the verification stations in this study.

Station	u_{clim} *(m s^{-1})*
YSHT	4.2
YMML	5.0
YMIA	3.8
PTFA	6.0
YHSM	5.5
YLTV	4.3
YMES	4.3

Defining

$$u_{ac2} = \min\{[\sum_j u_a(t_j)/(t_{ez} - t_{sz})],\ u_a(t_{mx})\} \qquad \text{...A18}$$

$$u_{cc} = \begin{cases} 4 & u_{c\lim} \le 4 \\ u_{c\lim} & 4 < u_{c\lim} < 5 \\ 5 & u_{c\lim} \ge 5 \end{cases} \qquad \text{...A19}$$

Then the wind speed fuzzy function thresholds become

$$x_{uc1} = 0 \qquad y1 = -0.5 - 1.5/(x_{uc2} - u_1)$$

$$x_{uc2} = u_{ac2} + u_{cc} \qquad \text{y2=1, and} \qquad \text{...A20}$$

$$x_{uc3} = x_{uc2} + u_3 \qquad \text{y3=1.5}$$

with $u_1 = 0.5$ m s^{-1}, $u_3 = 3.0$ m s^{-1}.

Thresholds for wind speed change parameter

The wind speed change parameter x_{du} and gust change parameter x_{dg} are first converted in a manner equivalent to x_{dd} and using the thresholds from equation A16 to calculate the fuzzy functions. The equivalent wind speed change parameter x_{edu} is expressed as

$$x_{edu} = c_u x_{ddc2} + c_u(x_{du} - a_u x_{uc2})(x_{ddc3} - x_{ddc2})/(a_u x_{uc3} - a_u x_{uc2}) \qquad \text{...A21}$$

with $c_u = 0.9$ and $a_u = 1$ h^{-1}.

Similar equivalent gust change parameter x_{eg} is converted as

$$x_{eg} = c_g x_{ddc2} + c_g x_{dg}(x_{ddc3} - x_{ddc2})/(x_{gc3} - x_{gc}) \qquad \text{...A22}$$

with $c_g = 1.0$, and $x_{gc3} = 20$ m s^{-1}.

The final wind speed change fuzzy function is calculated as

$$f_z[x_{du}(t_{sz}, t_{ez})] = \max\{f_z[x_{edu}(t_{sz}, t_{ez})],\ f_z[x_{eg}(t_{sz}, t_{ez})]\} \qquad \text{...A23}$$

Schematic plots of these fuzzy functions, using the different thresholds and constants are shown in Appendix C of HM06.