Verification of Mesoscale NWP Forecasts of Abrupt Cold Frontal Wind Changes

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ABSTRACT

During a wildfire, a sharp wind change can lead to an abrupt increase in fire activity and change the rate of spread, endangering firefighters working on what had been the flank of the fire. In southeastern Australia, routine forecast of cold-frontal wind change arrival times is a critical component of the fire weather forecasting service, and mesoscale NWP model predictions are integral to this forecast process. An event-based verification method has been developed in order to verify these mesoscale NWP model forecasts of wind changes. The approach is based on fuzzy-rule techniques and objectively determines the timing of significant (fire weather) wind changes from time series of observations at a single surface station.

In this paper these rules are applied to observational and NWP model forecast time series at observation locations over five fire seasons to determine objective "observed wind change times" and "forecast wind change times" for significant frontal wind changes in southeastern Australia. These forecast wind change times are compared with those observed, and also with those determined subjectively by forecasters at the Victorian Regional Forecast Centre. This provides an objective verification of NWP wind change forecasts and a measure of contemporary NWP model skill against which future model improvements may be measured. Case studies of two wind change events at selected stations are also presented to demonstrate some of the strengths, weaknesses, and characteristics of this verification technique.

1. Introduction

The dry summertime "cool change" of southeastern Australia has significant impacts on the consciousness of the population of the region and has a long history in the literature (e.g., Loewe 1945; Berson et al. 1957, 1959; Clarke 1961; Reeder and Smith 1987; Physick 1988; Garratt et al. 1989; Mills 2002, 2005a,b). While cool changes are often depicted on synoptic-scale surface analyses as cold fronts, many of these studies have demonstrated the significant effects of land–sea heating contrasts and topographic blocking on the evolving morphology of these cool changes. For the general public the interest lies in the fact that the cooler and more humid conditions following the change bring abrupt relief from strong, hot northerly winds. These cool changes also have a major impact on wildfire behavior and preventive operations. Before the change, extreme fire dangers are often experienced, with temperatures frequently near or above 40°C, relative humidities below 10%, and mean wind speeds greater than 20 kt. Exacerbating these prefrontal conditions, the abrupt wind direction change with the frontal passage can turn the flank of an existing fire into a long head-fire, putting firefighters in this region at risk (Cheney et al. 2001). This situation is exacerbated if postfrontal
winds are strong. Such situations occurred on Ash
Wednesday, 16 February 1983, when 75 lives were lost in
the fires (Bureau of Meteorology 1984; Mills 2005a);
during the Lower Eyre Peninsula fires on 11 January
2005, when 11 lives were lost (Bureau of Meteorology
2005); and most recently in Victoria on 7 February 2009,
when 173 lives were lost.

The impacts of these wind changes on firefighting
operations has led to the practice of issuing a “wind
change forecast chart” (Fig. 1) by the Victorian Regional
Forecast Centre (VRFC) of the Australian Bureau of
Meteorology (the Bureau) “on days when a significant
(e.g. frontal) wind change is expected and the fire danger
is expected to be Very High or Extreme” (Bureau of
Meteorology 2007). To enhance this graphical infor-
mation, forecasters routinely add comments describing
a change as being shallow or deep, abrupt or gradual, etc.,
and arrows indicate the predominant wind directions
before and after the change. At the end of the fire season
these forecasts are verified at selected stations in Vic-
toria with the verifying wind change times based on the
spatial and temporal consistencies of the meteorological
observations and analyses and relying on the expertise
of experienced meteorologists. Results have been re-
ported by Van Zetten et al. (2001), Morgan (2002), and
Bureau of Meteorology (2008). In the remainder of this
paper we will refer to this method as subjective verifi-
cation. While very effective, it is a time-consuming task.

An increasingly important form of guidance used by
forecasters in preparing their wind change forecasts are
the mesoscale NWP forecasts from the finest-mesh (ap-
proximately 5 km) version of the Bureau’s operational
limited-area NWP suite. These forecasts have been
shown to provide high-quality forecasts of frontal timing
in a number of fire-weather events and, perhaps even
more importantly, accurately forecast the wind structures
before and after the front (e.g., Mills 2002; Mills and
Pendlebury 2003; Mills 2005a,b, 2007). Hitherto, how-
ever, there has not been a systematic, objective verifica-
tion of these NWP model forecasts of cool change timing.

Most NWP verification methods use measures-oriented
statistical measures (Brooks and Doswell 1996) that are
not well suited to the verification of strong temporal or
spatial gradients. Case et al. (2004), Rife and Davis
(2005), and Colle et al. (2001) argue the advantages of
using event-based verification techniques. Each defines

\[ \text{Fig. 1. Example of a wind change forecast chart issued to fire authorities by the VRFC.} \]
their verification “event” to suit their particular application. Both Rife and Davis (2005) and Colle et al. (2001) interpolated their NWP forecasts to the locations of their verifying observations, while Case et al. (2004) used spatial patterns, assisted by the very high density of observations available over their study area, but they first interpolated their model forecasts to observation points before reinterpolating both observations and forecast data onto the same verification grid. In this study an event-based verification process based on time series of automatic weather station (AWS) observations and of mesoscale NWP forecasts interpolated to the observation locations is described. The verification method was developed to be compatible with the VRFC forecast and verification procedures so that not only an objective verification of NWP forecasts may be obtained, and also to automate the VRFC verification procedures.

Huang and Mills (2006a,b, hereafter HM06) developed a set of “fuzzy rules” (Bardossy et al. 1995; Keenan 2003) that were used to objectively determine a wind change time from a time series of single-station AWS observations. As well as an instantaneous wind change time, these algorithms also provide measures of a wind change period, with a start time and an end time, together with a measure of the strength of the overall wind change. In this paper the same approach is applied to mesoscale NWP forecast time series, and the resulting forecast wind change times (FWCs) are verified against those from the observation time series. We first summarize the methods used by the VRFC to issue and verify their wind change forecast charts, and review the methods of HM06. The way in which these algorithms are applied to NWP model output and how NWP model wind change times are matched with those from observation time series are described, and verification statistics for the NWP model forecasts for five (summer) fire seasons are presented. Two cases studies follow to demonstrate the characteristics of the objective timing algorithms and to assist with the interpretation of the statistical measures of forecast performance.

2. Data

a. Observations

The VRFC routinely verifies their wind change forecasts at selected AWS locations (Van Zetten et al. 2001; Morgan 2002). The stations selected are Port Fairy (PTFA), Horsham (YHSM), Latrobe Valley (YLTU), East Sale (YSHT), Mildura (YMIA), Melbourne Airport (YMML), and Shepparton (YSHT), all of which are located in Victoria (Fig. 1). The Victorian fire weather season generally commences in late austral spring and ends in early to midautumn. Data from 9 November to 1 April for the five fire weather seasons from 2001–02 to 2005–06 were selected for verification in this paper. All times used in this report are local times: Australian eastern standard time (AEST) or Australian eastern daylight savings time (AEDT).

The observation time, surface pressure, wind speed, wind direction, gust speed, and screen-level temperature and dewpoint are extracted from the aviation routine weather report (METAR) and special observations.
(SPECI) database in the Bureau’s Australian Data Archive for Meteorology (ADAM). The METAR data are reported half-hourly at the stations used in this study, and SPECI data are reported when the weather conditions meet specified criteria. The wind speed and wind direction are normally 10-min averages for METAR and 2-min averages for SPECI observations. The gust is the maximum wind speed recorded in the 10 min preceding the observation time. Both METAR and SPECI data are used in the analysis to follow, partly to take advantage of the higher time resolution afforded by the use of the SPECI data, and partly because a routine METAR is not necessarily reported if there has been a SPECI in the 5 min prior to the hour or half-hour.

b. Numerical model data

NWP data come from the Bureau’s operational high-resolution mesoscale NWP model (MesoLAPS05). The MesoLAPS05 model is nested within the regional Limited Area Prediction System (LAPS375; Puri et al. 1998), which itself is nested within a global NWP model. The MesoLAPS05 model has 0.05° horizontal grid spacing and 29 vertical sigma levels, and three-dimensional fields of temperature, humidity, and wind components are output each hour. MesoLAPS05 models are run twice daily to 36 h on a number of domains including over Victoria.

To have homogeneous data for all years of this study, the MesoLAPS05 model outputs for the five seasons from 2001–02 to 2005–06 were used. Base times for the numerical forecasts were 2300 and 1100 UTC before 18 March 2002 and 0000 and 1200 UTC after that time. Hereafter, reference to a model base time of 0000 (1200) UTC includes the 2300 (1100) UTC base time for the earlier period. Only forecasts between 6 and 36 h after the initialization time are used, in order to exclude the effects of model spinup in the early hours of the forecast.

3. Indices determining the timing of wind changes

a. Subjective VRFC wind change verification times

The VRFC subjective wind change verification time provides only a single wind change time, $t_{rfc}$, as its purpose is to verify the wind change forecast charts (Fig. 1). This perhaps implies that the wind change occurs instantly. In practice it is recognized that wind changes occur over varying periods of time, and that on a given day there may be more than one significant wind change. In such cases the VRFC wind change time indicates the most significant change and, in the absence of any more pressing criterion, the final establishment of steady southwesterly post-frontal winds is selected as the wind change time (Bureau of Meteorology 2007). Hereafter, these wind change times are termed VRFC wind change times (VWCs).

b. Objective observed wind change verification times

HM06 developed fuzzy rules based on the conceptual model of a wind change shown in Fig. 3. In developing these algorithms, the aim was to identify wind changes that are consistent with those identified by the VRFC, and that have a high success rate. In this model, the wind direction is defined to exist in one of three states: steady, transition, and in change (although in practice, we must also allow for the possibility of calm conditions). A typical

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1 UTC is 10 h earlier that AEST, and 11 h earlier than AEDT.
wind change commences with a change from a directionally steady (DirS) to a transition state (DirT), with a starting time, \( t_{sc} \), to pass into a change state (DirC) at time \( t_{dc} \), pass back from a change state to a transition state at time \( t_{tc} \), and then to a final steady state at \( t_{ec} \). The **objective observed wind change time** (OWC), \( t_{mx} \), is defined to occur at the time between \( t_{dc} \) and \( t_{tc} \) at which the rate of change of the wind direction, subject to some secondary criteria based on the gust speed, is a maximum.

HM06 discuss in detail the complexity of wind change structures that are observed during a season, or even a single day, and so a range of measures are calculated to assist in the selection of the OWC. The \( t_{mx} \) is primarily determined by a wind change range index (WCRI, defined below), but this decision is conditioned by measures of the overall strength of the total wind change between \( t_{sc} \) and \( t_{ec} \) [the wind change strength index (WCSI) and the wind change danger index (WCDI)], and measures of whether the wind change occurs during the passage of synoptic-scale troughs or ridges. Brief descriptions of these algorithms are presented below, and full details and a number of examples can be found in HM06, Huang and Mills (2007, hereafter HM07), and Huang et al. (2008, hereafter H08).

1) **THE WIND CHANGE RANGE INDEX (WCRI)**

To calculate the WCRI, a wind direction rate index (WDRI), and a wind speed rate index (WURI) are first defined as

\[
WDRI = \begin{cases} 
100 & \text{WDRI} > 100 \\
100 \times \left[ w_g f_{\zeta}(r_d) + f_{\zeta}(g_u) \right] / (1 + w_g) & \text{WDRI} < 0 \\
0 & \text{WURI > 100} \\
100 \times \left[ w_g f_{\zeta}(r_d) + f_{\zeta}(g_u) \right] / (1 + w_g) & \text{WURI < 0}, 
\end{cases}
\]

where \( r_d \), \( r_u \), and \( g_u \) indicate the wind direction change rate, wind speed change rate, and gust speed, respectively. Speed is included in the formulation of WDRI as a direction change is considered more significant if the wind speed is greater, while the weighting factor \( w_g \) (\( w_g = 2 \) in this application) gives greater weight to the direction than to the speed component. Further, during development it was found that some VRFC wind changes were better discriminated by speed change, and this inclusion improved the success rate in matching VWC with OWC. Examples are shown in HM06. To reduce the effects of the different wind speed averaging times between the METAR and SPECI observations, the gust speed is used instead of the mean wind speed to determine WDRI and WURI. When both \( r_d \) and \( g_u \) are very high, the WDRI (WURI) is close to 100. The fuzzy function \( f_{\zeta} \) is fully described in HM06, and for each variable increases linearly from 0 for values below a lower threshold to 1 for values above an upper threshold. Individual thresholds are specified for the change rates of each of the wind direction, wind speed, gust wind speed, and dewpoint depression. These thresholds are listed in appendix C of HM06.

The WCRI at a given time \( t \) is then defined as

\[
WCRI(t) = \max[WDRI(t), WURI(t)]
\]

and so incorporates the effects of both speed and direction change. Values of gust speed \( g_u \sim 6 \text{ m s}^{-1} \) and wind direction change rate \( r_d \sim 60^\circ \text{ h}^{-1} \) will lead to a WCRI of \( \sim 36 \).

2) **THE WIND CHANGE STRENGTH INDEX**

The WCRI is a measure of “instantaneous” wind change strength and defines the OWC and also the transition points in Fig. 3. It does not, however, differentiate what a meteorologist might term a synoptically stronger wind change that might have larger total direction and speed changes, as well as significant changes in temperature and humidity due to a change in an air mass. A function that represents the wind change strength over the entire change period—that is, the degree of change from the start time \( t_{sc} \) to the end time \( t_{tc} \) of the wind change period—is the WCSI (full details in HM06), which is estimated from

- the wind speed during the wind change period;
- the change in wind direction–speed, defined as the difference between the directions–speeds at the start and end of the change period; and
- the change in dewpoint depression, defined as the maximum hourly dewpoint depression change during the change period.

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FIG. 5. Examples of the forecast wind direction change rate index from the MesoLAPS05 NWP model, overlaid on the 10-m wind forecast. Shown are (a) 0500, (b) 0900, and (c) 1300 UTC (1600, 2000, and 2400 EDST) 30 Nov 2006. Definition of wind barb here and in Figs. 13 and 16 follows meteorological conventions.
This function is intended to assist the objective determination of the “significance” of wind changes from time series of observations rather than using a subjective synoptic classification.

3) THE WIND CHANGE DANGER INDEX

There are circumstances where the WCRI may be large and the WCSI small, or vice versa; yet, those cases when both WCRI and WCSI are large are perhaps closest to the synoptic paradigm implicit in the VRFC Fire Weather Directive (Bureau of Meteorology 2007). Accordingly, HM06 proposed a WCDI that combines the WCSI and WCRI into a single index. This index is formulated so that it has low values if either the WCRI or the WCSI is small, and increases with increasing WCSI and WCRI. This is shown graphically later (see Fig. 12) and algebraically in appendix D of HM06.

c. Mesoscale NWP forecast wind change times

MesosLAPS05 model wind changes are determined in the same way as are the objective wind changes, but with simplified algorithms as the hourly model time series is notably smoother than the more frequent observation time series. In addition, the forecast wind speeds have a 20% bias correction applied before the calculation of the WCRI and WCDI. The dependence of a model forecast WDRI on the rate of change of direction for different (bias corrected) speed ranges is shown in Fig. 4.

One of the strengths of the mesoscale NWP forecast fields is their spatial resolution and temporal consistency. Applying the WCRI algorithm to each model grid point allows the WCRI, overlaid on forecast wind barbs, to be presented to forecasters for a single forecast time, or as an animated loop, as shown in Fig. 5. The evolving structures of the change are clear, with the prefrontal trough (inland part of the change) intensifying between 0500 and 0900 UTC (1600 and 2000 AEDT), and then weakening again, while the coastal part of the change surges eastward. This presentation shows not only frontal changes, but also wind changes due to topographic or coastal forcing, such as the band between YMES and ORBT in Fig. 5b. This output is now routinely used by forecasters in assessing the strength of wind changes and in preparing the wind change forecast chart (e.g., Fig. 1). Interpolated to the observation sites, the time series of the forecast WCRI can be compared with observed values.

4. Selection of wind changes for verification

Applying the WCRI algorithm [Eq. (3)] to our observation dataset results in about 400 changes per station per fire season being identified (Table 1, column b1), although the average numbers range from 275 at YMIA to 446 at YMML. This is far in excess of the number of VRFC wind change days (Table 1, column a2), as all types of wind changes, including weak diurnal changes, are included in this first classification, and is consistent with the results of HM06 and HM07. Very similar numbers are identified in NWP model time series from both 0000 UTC (column b2) and 1200 UTC (column b3) forecast base times.

Choosing only those changes that occur on VRFC wind change days provides a simple subjective selection, and this leads to one of the verifications in the next section. It is, though, desirable from the perspective of NWP model performance assessment to have a more general, and objective, selection method. Noting that VRFC wind changes are issued when “significant” and “frontal” wind changes are expected, then developing criteria based on, first, frontal characteristics and, second, a strength criterion, would be expected to select a subset of OWC or FWC that show frequencies more similar to those of the VRFC wind changes.

<table>
<thead>
<tr>
<th>Station</th>
<th>Trgh</th>
<th>VWC</th>
<th>Obs NWP 00</th>
<th>NWP 12</th>
<th>Obs NWP 00</th>
<th>NWP 12</th>
<th>Obs NWP 00</th>
<th>NWP 12</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTFA</td>
<td>20.6</td>
<td>8.6</td>
<td>357.6</td>
<td>432.8</td>
<td>437.6</td>
<td>78.8</td>
<td>90.8</td>
<td>86.6</td>
</tr>
<tr>
<td>YHSM</td>
<td>19.6</td>
<td>11.6</td>
<td>414.4</td>
<td>328.6</td>
<td>300.8</td>
<td>79.4</td>
<td>83.2</td>
<td>67</td>
</tr>
<tr>
<td>YLTIV</td>
<td>22</td>
<td>11.6</td>
<td>398.4</td>
<td>394</td>
<td>337.6</td>
<td>83.6</td>
<td>84.4</td>
<td>66.4</td>
</tr>
<tr>
<td>YMES</td>
<td>21.8</td>
<td>9</td>
<td>436.2</td>
<td>483</td>
<td>421.4</td>
<td>75.6</td>
<td>85.8</td>
<td>69.6</td>
</tr>
<tr>
<td>YMIA</td>
<td>18.8</td>
<td>10.8</td>
<td>275</td>
<td>235.2</td>
<td>216.8</td>
<td>54.2</td>
<td>58</td>
<td>46.6</td>
</tr>
<tr>
<td>YSHT</td>
<td>19.2</td>
<td>9.8</td>
<td>403.6</td>
<td>422.8</td>
<td>406</td>
<td>59.8</td>
<td>80</td>
<td>72.4</td>
</tr>
<tr>
<td>YMML</td>
<td>21.8</td>
<td>12.6</td>
<td>446.6</td>
<td>475.2</td>
<td>450.6</td>
<td>95</td>
<td>91</td>
<td>77.8</td>
</tr>
<tr>
<td>Average</td>
<td>20.5</td>
<td>10.6</td>
<td>390.3</td>
<td>395.9</td>
<td>367.3</td>
<td>75.2</td>
<td>81.9</td>
<td>69.5</td>
</tr>
</tbody>
</table>

Table 1. Five-year-average fire-season wind change statistics. Column a shows the number of major pressure trough passages (trgh) and the number of subjective wind changes (VWC). Column b shows the numbers of OWCs (obs) and FWCs from NWP model forecasts based at 0000 UTC (NWP00) and 1200 UTC (NWP12). Column c is similar to column b but restricted to the pressure trough cases listed in column a. Column d is similar to column b but restricted to the pressure trough cases when the change strength criteria described in the text are met.
Frontal passages are usually associated with pressure troughs. HM07 developed an objective method of classifying “phases” of the synoptic pressure cycle, which, in its simplest form conceptualized the surface pressure time series at a point as a cosine wave, with an initial maximum as an anticyclone moved over a point, a minimum as this was replaced by a trough, and then another maximum as the subsequent anticyclone approaches. In practice, of course, the anticyclonic phases tend to last longer than the trough passages, and secondary minima and maxima do occur, but using fuzzy rules HM07 objectively classified six phases of the synoptic pressure cycle, and showed that 63% of the VRFC wind changes occurred during major pressure trough passages, while an additional 24% occurred during minor trough passages. Accordingly, the “frontal” selection criterion can be satisfied by selecting only those wind changes that occurred during the trough passage phases of the synoptic pressure cycle.

Applying the pressure-cycle classification to our dataset shows that there are some 20 major trough passages per station per fire season (Table 1, column a1), and that VRFC wind change forecasts were issued for approximately 50% of these (Table 1, column a2) and account for ~60% of total VRFC wind changes. Applying this selection to the full set of changes in column b of Table 1 results in an average of about 75 observed changes per station per season (column c1), with similar numbers of FWC for each of the two base times (columns c2 and c3).

While the WCRI provides a measure of the “sharpness” of the wind change, the WCDI provides a measure of the synoptic “strength” of the wind change. Selection of changes based on threshold magnitudes of both WCRI and WCDI results in a set of sharp, strong wind changes. Probability density functions (PDFs) for WCRI and WCDI are shown in Fig. 6a for the observation and the NWP forecast time series. Both the observed and forecast distributions show peaks in WCRI at around 35,
and around 25 for WCDI, although the forecast distribution is rather broader, particularly for the WCDI. The forecast distribution also shows a larger number of weaker changes and a smaller number of stronger changes compared to the observed distribution. Part of this is likely due to the time resolution of the forecast data being hourly rather than half-hourly (and the use of SPECI observations), but other aspects of the model may also contribute. These differences are more apparent in the cumulative density functions (CDFs) for WCRI and WCDI, accumulated from the maximum to the minimum values (Fig. 6b). These CDFs provide a basis from which to choose threshold values of forecast WCRI and WCDI, by requiring forecast thresholds to match the same cumulative density as the observed thresholds. The requirement that the majority of VRFC wind changes be selected led us to consider a change to be a candidate for verification if, in addition to occurring during a major pressure trough passage, both the conditions of WCDI $> 50$ and WCRI $> 50$ are satisfied for the observation time series. From Fig. 6b, the equivalent thresholds for a forecast wind change are the conditions that WCDI $> 40$ and WCRI $> 35$ are satisfied. The conditions for the observed changes are more stringent due to the greater variability in these time series. Applying this additional criterion to the changes selected in column c of Table 1 leads to the numbers shown in column d, with a slightly larger number of observed changes per station than the number of pressure cycles identified in column a1, and also rather more forecast changes.

Two sets of verifications will be presented. The first is a verification of model forecasts on those days when VRFC wind change timings are available, where the FWC can be verified against both the VWC and the OWC. The second is the larger verification set of all FWCs that occur during major pressure trough passages and which satisfy the strength criteria, for which only the FWCs that occur during major pressure trough passages can be used for verification.

5. Results of verifications

a. VRFC wind change days

In this section the comparisons are only for the VRFC wind change days. We first compared the OWC ($t_{mx}$) and the VWC ($t_{sc}$) times, as this demonstrates some of the uncertainty in the determination of a single, instantaneous, wind change time. First, we assess the differences between the two sets of times: since HM06 showed that the average observed wind change period was 261 min, we calculate the proportion of OWCs that are within ±2.5 h of the VWCs. The longer time window selected was chosen to favor a slightly more relaxed matching of wind changes, and noting that the 261 min is itself dependent on the choice of thresholds used in the fuzzy rules of HM06. Second, because the objective timing also provides a measure of the start ($t_{sc}$) and end ($t_{ec}$) times of the change period, a “hit” could be counted if the VWC lies within the observed wind change period. However, a VRFC time that occurred just outside a short observed wind change period would constitute a miss, yet might be considered an excellent match by a meteorologist. Accordingly, following the arguments above, we define an extended wind change period of 2.5 h before and after the observed wind change period, and we count a “hit” if the VWC lies within this extended wind change period.

These comparisons are summarized in the top panels in Fig. 7. Around 78% of the OWC times are within ±2.5 h of the VWC time, with some station-to-station variation, and well over 90% of the VWCs occur within the extended wind change period. YMIA shows the lowest proportion of verification times within ±2.5 h, possibly due to the longer wind change periods and weaker wind change strengths common at the more inland stations (HM06, their Table 6; Mills 2005b). There are also some year-to-year variations in the statistics. It is hard to attribute reasons for this, although slight differences in VRFC practice due to personnel or procedural changes may explain some of this variation. The OWC data were used by the VRFC in their verification for the 2005–06 season, and it may not be coincidental that the highest success rates are seen in that season. Also, year-to-year variations in circulation patterns may result in changes having different characteristics from year to year. The significant result, though, is that despite the inherent degree of uncertainty in the definition of a unique change time, a very good agreement exists between the OWC and VWC maximum wind change times.

A comparison of the FWC with the VWC times is shown in the middle panels of Fig. 7. Nearly 70% of the NWP model FWCs are within ±2.5 h of the VWC wind change time, while over 90% of the VWCs occur within the forecast extended wind change period. The highest proportion of forecast changes within ±2.5 h is at PTFA, while the lowest is at YSHT.

In the third row of Fig. 7 the FWCs are compared with the OWCs. The black bars show that the forecast and observed wind change periods overlap on some 69% of the occasions, with PTFA showing the lowest and YMES the greatest rate of overlap, or success rate. The percentages of forecast wind change times that fall within the ±2.5 h extended observed wind change period range from 83% to 98% (hollow bars) depending on station, and the proportion of forecast wind change times that
are within ±2.5 h of the observed time (horizontal hachuring) ranges from 69% (YMIA and YMML) to 82% (PTFA). There is some interannual variability, but less than the station-to-station variability.

It is also notable that at several stations (YSHT, YMES, and PTFA, in particular) a considerably larger proportion of forecasts are within ±2.5 h of the OWC times than the subjective VWC times (Figs. 7c and 7e). This perhaps reflects the different definitions used in determining these times, with the FWCS and OWCs using similar methods. The apparent anomaly between the smaller percentage of overlapping forecast and the observed wind change periods than the other two metrics in these verifications (Fig. 7e) is due to the number of occasions when the observed wind change period is short, producing a lower success rate than might be anticipated from a comparison of the objective wind change times.

b. All changes during major pressure trough passages

On average, approximately 27 OWCs per year occur during major pressure trough passages at each station (Table 1), with slightly greater numbers of FWCs. Comparing the occurrence of forecast and observed change periods during major pressure trough passage in terms of a contingency table (Table 2, first row) shows both forecast and observed major wind change periods, or hits, are identified for 78% of the major trough passages. Some 6% of the major trough passages include an observed wind change period but not a forecast wind change, or a missed forecast, and 11% of these periods include a forecast wind change but not an observed change (a false alarm). The major trough passages that contained no objective wind change identifications from either the observation or the model forecast account for 5% (correct rejections). The proportion correct (PC, the sum of the hit and correct rejection rates) is 77%. The PC is much greater when only those pressure cycles during which VRFC wind changes are considered

### Table 2. Contingency tables (in %) for forecast wind changes satisfying the strength criteria for all pressure trough passages and for only those trough passages when a VRFC wind change forecast was issued (CR stands for correct rejection).

<table>
<thead>
<tr>
<th></th>
<th>Hit</th>
<th>Miss</th>
<th>False alarm</th>
<th>CR</th>
</tr>
</thead>
<tbody>
<tr>
<td>All significant pressure trough changes</td>
<td>67.8</td>
<td>15.8</td>
<td>7.6</td>
<td>8.8</td>
</tr>
<tr>
<td>Only pressure trough changes when VRFC wind changes issued</td>
<td>84.6</td>
<td>9.2</td>
<td>5.6</td>
<td>0.6</td>
</tr>
</tbody>
</table>

![Fig. 7c and 7e](image)

**Fig. 8.** Contingency tables for all major trough passage changes. A hit means that a wind change was diagnosed in both the model and the observations during that pressure cycle stage. A missed forecast is counted if there is an observed but not a forecast wind change, a false alarm is recorded if a change is forecast but not observed, and a correct rejection is noted if no change is either observed or forecast in that trough passage. The numbers to the left of the bar show the total number of trough passages observed, and the numbers to the right indicate the numbers in each classification following the vertical order of the classification distribution.
indicating that the VRFC staff have considerable expertise in identifying those trough passages during which a significant wind change will occur.

Figure 8 presents this information graphically, separated by station and by season. Again there is considerable station-to-station variability, as well as some interannual variability. The lowest proportion of hits occurs at YMIA, but the number of correct rejections is also largest at this station. In addition, the number of trough passages is also the lowest of all the stations at Mildura (Table 1), where HM06 noted that wind changes tended to be weaker and of longer duration, and HM07 showed that Mildura experiences fewer major trough passages than do the other verification stations. As Mildura also has the greatest proportion of missed forecasts, the implication is that the weaker changes experienced well inland (Mills 2005b) are both harder to identify and harder to forecast correctly. The other six stations show similar performances in most criteria, but PTFA does show a larger proportion of false alarms relative to missed forecasts than do the other stations. Year-to-year variations are interesting, with the latter two seasons showing larger hit rates and smaller numbers of missed forecasts than the previous years. Whether this is due to model improvements or to variations in seasonal circulation patterns is unclear. As these two years show the smallest and the largest numbers of pressure cycles during the five verification years, this improved performance is unlikely to be simply due to “easier to forecast” circulation patterns during those two seasons.

Verifications for those forecasts identified as hits in Fig. 8 are shown in Fig. 9. Overall, some 70% of the major pressure troughs have an overlapping forecast and observed wind change period, although this ranges from 56% at PTFA to 82% at YMES. This proportion increases to 86% if the wind change periods are extended

TABLE 3. The effects of varied WCDI thresholds on selected forecast wind changes (in %). All of the other conditions are the same. The numbers of model cases are the average numbers of the 0000 and 1200 UTC model forecasts (CR stands for correct rejection).

<table>
<thead>
<tr>
<th>WCDI</th>
<th>No. of model cases</th>
<th>All major pressure trough changes</th>
<th>Only pressure trough changes when VRFC wind changes issued</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Hit</td>
<td>Miss</td>
</tr>
<tr>
<td>30</td>
<td>35.0</td>
<td>69.7</td>
<td>13.9</td>
</tr>
<tr>
<td>40</td>
<td>31.9</td>
<td>67.8</td>
<td>15.8</td>
</tr>
<tr>
<td>50</td>
<td>27.0</td>
<td>63.4</td>
<td>20.2</td>
</tr>
<tr>
<td>60</td>
<td>22.2</td>
<td>56.5</td>
<td>27.1</td>
</tr>
</tbody>
</table>
by ±2.5 h to match the “extended wind change periods” used in the VRFC verification times. Some 66% of the forecast times are within ±2.5 h of the observed time. Again, while Port Fairy shows the lowest percentage of overlapping wind change periods, it also has the highest proportion of FWCs within ±2.5 h of the OWCs due to the relatively large numbers of short observed wind change periods there. Year-to-year variations show, as for the

FIG. 10. (top) Scatterplots of wind change timing error vs forecast lead time and (bottom) graphs of each pair showing the smoothed mean (thin lines) and standard deviation (thick lines) of the error. (a) VRFC wind change forecast days, and (b) all matched wind changes during major pressure troughs.

VRFC wind change events, that these measures of model performance were highest for the latter 2 yr verified.

c. Sensitivity to threshold selection

The selection criteria for the model forecast wind changes obviously affect the statistical evaluations of the method. If we retain all other conditions, but incrementally change the WCDI threshold from 30 to 60, the average number of selected forecast wind change events decreases as the WCDI threshold is increased (Table 3). Hence, the success rate drops and missed forecast rate increases. However, the number of false alarms is slightly reduced and the correct rejection rate is slightly increased. Over all, the PC decreases with increasing magnitude of the WCDI threshold.

d. Timing errors as a function of forecast lead time

In Fig. 10 the differences between the OWCs and the FWCs are presented following Morgan (2002), with a scatterplot of the forecast wind change timing error versus the model lead time in the top panel, and the mean and standard deviation of the forecast error versus the lead time in the bottom panel. The left plots in Fig. 10 are for VRFC wind change days only, while the right-hand plots include all major pressure trough changes. Changes with errors greater than 18 h have been excluded from the calculations of the mean and standard deviation, as by the definitions made to match the forecast and observed wind changes these must be associated with extremely long wind change periods and are probably not those that a forecaster would compare.

There is a somewhat greater scatter in the right-hand panels in Fig. 10, particularly between 6- and 15-h lead times, when the standard deviation of the timing errors for all major pressure trough changes is rather greater than for the VRFC wind change events. However, any trend in the error with increasing lead time is only very slow for both sets of verifications, and the forecasts show relatively low systematic errors for all lead times presented.

These objective verification statistics provide a benchmark for assessing future NWP model performance. The relatively small change in error with increasing lead time is encouraging, as is the clustering of errors near zero. The number of larger errors, though, is a concern, and the sensitivity of the statistics to the various selected thresholds must be remembered when interpreting these results.

6. Case studies

In this section we present a small number of examples of the application of the timing methods to station observation time series for two dry cold frontal events to complement the statistical analyses of the previous
sections. These cases are described at greater length, and for a larger number of stations, in H08.

We present synoptic-scale MSLP analyses, MesoLAPS05 forecasts of surface potential temperature and wind speed [the intimate dynamic relationship between thermal gradient discontinuities and wind changes has been demonstrated in Mills (2002, 2005b)], and for two verification stations meteograms of observed and forecast pressure, temperature and dewpoint, and wind speed and direction. Overlaid on these meteograms are the observed and forecast objective wind change times and periods and, where available, the VRFC wind change time. While these figures are complex, they encapsulate the information on which the verifications are based and, so, demonstrate some of the characteristics of the objective verification methodology.

a. Case 1: Single cold-front passage

A marked cold front moved through southeast Australia during the daylight hours of 11 March 2002 (Fig. 11). This is a typical synoptic pattern for a Victorian late summer dry cool change, with a heat trough over central Australia extending southward, a midlatitude cold front extending northward, and the two systems bringing a cool change to southeast Australia in the cool region between the two anticyclones.

At YMML (Fig. 12a), two OWCs were selected: one at ~0230 AEDT, associated with a sharp increase in wind speed and a small fluctuation in direction, while the second change period of some 4.5 h beginning at 1500 AEDT marks the frontal change. The OWC coincided exactly with the VWC, and the FWC was 1 h later. The wind change period commenced at the same time for both the observed and forecast wind changes, but was shorter for the forecast. At YSHT (Fig. 12b), only one forecast and one observed wind change period were identified. The FWC was 2 h earlier than the OWC, which was again at the same time as the VWC, while the FWC period was longer and started rather earlier than the OWC period. The smoother forecast time series is part of the cause of this difference, and while the forecast period could be reduced with more stringent threshold selection (see section 5c), this would reduce the overall success rate.

Figure 13 shows the different modeled wind change structures at YSHT and YMML. The change through YMML is very sharp, with a strong thermal gradient, as a result of the change surging along the coast southwest of YMML. Inland, diabatic heating has weakened the thermal gradient, making the change more gradual, resulting in the longer wind change period at YSHT than at YMML (Fig. 12).

b. Case 2: Distinct prefrontal trough event

Wind change events associated with long wind change periods, or where multiple wind changes are identified on a given day, can make it difficult to unambiguously
FIG. 14. Case 2: MSLP analyses at (a) 0600 and (b) 1200 UTC 29 Dec 2001.
associate a particular OWC with a FWC. In this section we discuss such a case, which was also discussed in HM06 (section 6.6.1). The case is categorized, following HM07, to occur during a minor trough passage, in contrast to the previous case study, which occurred during a major trough passage.

The synoptic MSLP analyses at 0600 and 1200 UTC 29 December 2001 (Fig. 14) show a low well south of Australia and an associated cold front moving eastward into southeast Australia. A prefrontal trough (Hanstrum et al. 1990) is analyzed through Victoria ahead of this front. During the afternoon, pressures fell significantly over western Victoria (see the 0600 UTC analysis), but strong coastal ridging followed, and the wind change moved through Victoria under a rapidly evolving pressure pattern. Thus, the western and inland stations (e.g., YHSM; see Fig. 15a) show a relatively symmetric fall-rise pressure sequence, while the stations farther east (e.g., YMML; see Fig. 15b) show a very sharp observed pressure rise following minimum pressure.

The MesoLAPS05 model forecasts (Fig. 16) show a coastal temperature gradient developing along the length of the Victorian coast by 0300 UTC. A low had formed over western Victoria and a coastal wind change was developing (cf. Mills 2002), while east of Melbourne a strong lee pressure trough dominated, with sharp shear from northwest (inland) to easterly (off shore) winds. In the far west of the domain cool advection was occurring west of a weak prefrontal trough. By 0700 UTC the prefrontal trough had moved inland and intensified, as indicated by the stronger thermal gradient and backing winds at its forward edge, while the coastal wind surge had reached Wilsons Promontory, Victoria (YWLP). Coastal ridging was developing west of YMML, but there was still a clear wind change associated with the coastal temperature gradient.

At YHSM (Fig. 15a) the observed change period is some 3.5 h, with a OWC at \( \sim 1400 \) AEDT. Because the wind was backing fairly smoothly through this time, the OWC aligns with the fluctuations in wind speed around that time. A much longer forecast change period is diagnosed with an FWC at 1800 AEDT, just 1 h later than the VWC, but 4 h later than the OWC. At this station the long, slow backing of the wind, together with fluctuations in speed over a long period, make for considerable difficulty in determining a unique time of maximum wind change, and so the VRFC has followed their guidelines in selecting the latter phase of the change in such situations.

At YMML (Fig. 15b), three OWCs were selected within a single wind change period. The latter two, very close together and near the end of the 4-h wind change period, align with the VWC. The first OWC can be interpreted as being associated with the passage of the prefrontal trough, and the second with the main change associated with the coastal pressure surge. The forecast wind change period starts at 1900 AEDT and, so, just overlaps with the observed period, with a single FWC 2 h later than the OWC and the VWC. While no FWC is

![Fig. 15](image-url)
selected to match the prefrontal trough passage, the NWP temperature and dewpoint time series do show a suggestion of a change there; however, the specified thresholds do not select an FWC, although there is a period of backing of the wind through that time.

7. Concluding remarks

This study has shown that the fuzzy-rule methods of objective wind change timing and classification developed by HM06 and HM07 can be applied to numerical model forecasts as well as to observation time series and, thus, provide a verification approach for NWP model wind change forecasts. To produce a verification statistic, though, major winnowing of the data is necessary in order to concentrate on just one synoptic archetype of wind change, and in our study we have focused on the strong, dry summertime cool change of southeastern Australia. The result, hitherto unavailable, is an objective verification in terms of the number of changes correctly forecast within a particular time window, and a summary of the mean and variance of the timing error. It is a considerable benefit to forecasters who make decisions based on these NWP forecasts to know that the forecast times are essentially unbiased, while model developers can use these methods to validate NWP model improvements in predictions of a particular meteorological event that has major social consequences.

While the results are sensitive to the particular choices of WCRI and WCDI thresholds used in the event selection, so long as the same thresholds are used, future verifications can be compared with those already established, or other applications can be developed using different thresholds. The error statistics so generated must be interpreted in light of the differences between the VWC and the OWC times, and so some of the scatter in Fig. 10 may be due to uncertainty in the

Fig. 16. Case 2: Forecasts of (left) MSLP and (right) screen-level potential temperature valid at 0300 UTC (top two panels) and 0700 UTC 29 Dec 2001 (bottom two panels) from the operational MesoLAPS05 NWP forecast. In each case, the wind field at the 0.9943 (approx 70 m) sigma level is overlaid.
verification time, rather than being purely a result of model error.

Case studies show that the method is capable of diagnosing complex wind changes during trough–cold front transitions in Victoria. In clearly defined wind change cases, the method produces OWCs that agree well with subjective verifications. However, there are examples of more complex change types where the objective decisions may not necessarily match the change times that might be selected by a subjective assessment of the model and observed time series. Most of these cases occur with rather longer change periods. Given the importance and entrenched role of the wind change forecast chart, this product is likely to be produced and used for some time. The results of this study suggest that there may be considerable benefit to users of these forecasts if information elaborating on the strength and the duration of the wind change pe-

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REFERENCES


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