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Abstract

In bush fire events, wind changes can cause abrupt changes in fire behaviour and activity, thus endangering fire fighters. Predicting the timing of wind changes is therefore an important aspect of fire weather forecasts. While subjective forecasts of wind change times have been subjectively verified for some years now, there is a need to verify mesoscale NWP forecasts of wind changes as these forecasts provide significant guidance to operational forecasters. Previous studies have proposed fuzzy-logic methods to objectively determine fire weather wind changes from observations at a single surface observation station. These methods are comprised of algorithms that diagnose the timing and the strength of the wind changes from time series of wind direction, speed, gust, and of surface temperature, dewpoint and pressure.

In this report, these methods are applied to both observation and NWP model forecast time series to provide an objective verification of forecast wind change timing based on a five-year fire season data-set over selected stations in Victoria. It is concluded that 70% of wind changes identified with the method from model forecast are within 2.5 hours of independent subjective wind change estimations issued from Victoria Regional Forecasting Centre, while 93% of the subjective wind changes fall within the objective wind change periods. Within 87% of the objectively determined major pressure trough passages, wind change are identified from both observations and the model forecasts.

Case studies are discussed for the wind changes identified with the method under transitional trough/cold front situations in Victoria, demonstrating the behaviour of the algorithms in a range of situations, and also the complexities and uncertainties of determining a single wind change time.

1 Introduction

Wind change prediction is a crucial component of fire weather forecast services. For a burning bush fire, a sudden wind change can turn a long fire flank into a wide fire front, and rapidly spread the fire over a much larger area. Most dangerously, an unexpected wind change could cause the new wide fire front to engulf the fire fighters if they are working at what had been the previous fire flank. Fatalities have been reported on these days, and this has led Cheney et al. (2001) to term this the "dead man zone".

The importance of wind change forecasts to fire managers has led to the routine issuing of a "Wind Change Forecast Chart" by weather forecast offices such as the Victorian Regional Forecast Centre (VRFC) of the 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 2006). These forecasts have been verified at the end of the fire season for recent years at selected stations in Victoria and the results reported by Van Zetten et al. (2001) and Morgan (2002). The method used to determine the time at which the wind change occurs relies on the skills of experienced meteorologists and is based on spatial and temporal consistency of meteorological observations and analyses. In the remainder of this report we will refer to this method as *subjective identification*. While very effective, it is a time-consuming task.

Wind changes are caused by many meteorological processes occurring on different temporal and spatial scales. Thus there are slow and rapid, small and large, fluctuating and persistent wind direction changes, along with a range of speed, temperature and humidity variations. This large range of possible change structures make the development of objective rules to identify a unique wind change time extremely challenging, yet there are obvious benefits in being able to perform such a task. Huang and Mills (2006, 2007) (hereafter HM06 and HM07) developed fuzzy-logic methods to determine wind change timings at a location from single-station time-series of meteorological observations. While the initial, and primary, aim of this algorithm was to provide a single time of maximum wind change to be used in verification studies, it was found useful to also develop measures of start time and end time of a wind change period, and also various measures of the strength of the wind change. These studies showed that for some 85 percent of the wind change forecasts issued by the VRFC, the objective and subjective wind change timings were within 2.5 hours, and that for more than 95 percent of these changes the VRFC wind change timing fell within the objective wind change period (HM06). Given the differences in the two methodologies, this was considered to be a level of performance sufficient for the objective timings to be incorporated into the VRFC verification practice for the 2005-6 and later fire seasons (Bureau of Meteorology 2008).

When applied to time series of data for all days in the fire season, rather than just the VRFC wind change days, HM06 showed that many more wind change events were identified, and suggested that some means of stratification of wind change days might prove beneficial if these algorithms were to be used operationally. In southeast Australia wind changes are closely linked with cold frontal passages. Such systems and their impact on the weather and fire weather in southeast Australia have been extensively studied (Mills 2007; Mills 2005a, b; Mills and Morgan 2006; Physick 1988; Reeder, 1986; Garratt et al. 1989). In Western Australia, studies have shown that the transitional trough line of the Australian west coast trough often alters the wind direction over the region in the summer, affecting sea breezes or causing further weather change (Watson 1984; Ma and Lyons 2000). In addition, easterly troughs extending southwards from inland Australia can interact with mid-latitude synoptic scale troughs to bring wind changes as pre-frontal troughs (Hanstrum et al., 1990). These associations led HM07 to develop a fuzzy-logic algorithm to identify phases of a synoptic pressure cycle in order to stratify the objective wind changes identified using the methods in HM06 into those occurring within synoptic-scale trough or ridge passages, as it was found that most of the VRFC wind changes occur during synoptic-scale trough passages (pressure minima). The combination of the HM06 and HM07 fuzzy-logic algorithms will be referred to in the remainder of this report as *objective identification*.

To date the methods of HM06 and HM07 have only been applied to observation time series. However, mesoscale numerical weather prediction (NWP) model forecasts are an integral component of the forecast guidance used in preparing wind change forecasts, and thus a systematic verification of the wind change forecasts from these models is of interest to both model developers and to forecasters. As one of a series reports, following HM06 and HM07, this report first summarises the methodologies of objective and subjective wind change timing, and then describes how HM06 and HM07 can be applied to mesoscale NWP model forecasts to generate forecast wind change timings. Comparisons of objective wind change identifications from model forecasts with the VRFC subjective identifications, and with the objective identifications from the observations are presented to provide objective verification of the operational mesoscale NWP model forecasts of wind change times on the VRFC wind change days. Using only the VRFC wind change forecast days is a restrictive, yet useful validation of the model forecasts, as it is on these days that forecasters predicted significant wind changes to occur. However, it is also of interest to validate a wider range of forecast wind changes. Using all model forecasts for several fire seasons various other selection or stratification methodologies are employed to provide a more general perspective on the accuracy of the NWP model wind change forecasts. Finally, a number of case studies are presented to illustrate characteristics of objective wind change identifications from model and observation time series, and provide a context for the interpretation of the verification statistics.

2 Wind Change Identification Algorithms

In this section, we briefly describe all the wind change identification methods that were used to generate the data upon which the verifications in this report are based.

2.1 VRFC subjective wind changes

The genesis of this project was based on the desire to verify NWP model forecasts of wind changes on days when the VRFC issued Wind Change Forecast Charts. These are issued 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, 2006). An example of such a wind change forecast chart is shown in Fig. 1. At the end of each fire season these forecasts are verified using a combination of observation and analysis time series, and these data are referred to in this report as subjective wind change verification times. Details of this verification process have been given in Van Zetten et al. (2001), Morgan (2002), and Bureau of Meteorology (2006).

The VRFC subjective wind change provides only a single wind change time (t_{RFC}) and it is assumed that the wind change occurs instantly. It is recognised that some wind changes are slower than are others, and that on a given day there may be more than one significant wind change. In this case the most significant change, which is often considered to be the final establishment of steady southwesterly post-frontal winds, will be selected as the wind change time (Bureau of Meteorology 2006). It is routine practice for forecasters to add comments describing the change as being shallow or deep, abrupt or gradual, etc (Kevin Parkyn, personal communication).

2.2 Objective identification

Objective identifications use the fuzzy-logic techniques described in detail in HM06 and HM07. There are several components of these that are described below. Using time series of observed wind direction and speed at a single station, measures of wind change duration and time of maximum wind change are determined, while similar approaches using wind direction, speed, gust, and dewpoint depression are used to quantify the "strength" of the change. Finally, applying fuzzy-logic methods to pressure time series defines phases of the synoptic pressure cycle which allows wind changes identified with the first set of algorithms to be classified into those occurring with major pressure trough passages etc. The first set of timing algorithms provide an objective wind change time data set, while the measures of strength and pressure cycle phase provide ways to select particular classes or types of wind change.

2.2.1 Objective wind change timing and intensity

a. Wind change time

The objective timing algorithms are based on the simple conceptual model of a wind change shown in Fig. 2. Wind direction is defined to exist in one of four states: calm, steady, transition, and change states (HM06). A typical wind change is defined to commence with a change from a steady to a transition state, with a starting time t_{sc}, to pass into a change state at time t_{ds}, pass back from change state to transition state at time t_{de} and then to a final steady state at t_{ec}. The "change time" (t_{mx}) is defined to occur at the time between t_{ds} and t_{de} at which a Wind Change Rate Index (WCRI, see below) is a maximum. This "objective maximum wind change timing" (t_{mx}) is that which will be compared with the VRFC subjective wind change time. A comprehensive description of the way in which WCRI , t_{mx}, t_{sc} and t_{ec} are determined is found in HM06.

b. Wind change intensity

b1. Wind Change Rate Index

The WCRI is used to quantify the instantaneous wind change intensity at a given time t.

Even on those days when a frontal wind change is forecast, a range of behaviour is observed. This makes it difficult to select a single set of direction, speed or dewpoint depression parameter thresholds that will uniquely determine the occurrence or timing of any cold-frontal wind change. Accordingly HM06 developed fuzzy logic functions to determine the change timing and strength. The basic idea of fuzzy logic is that instead of a yes/no answer being based on whether a parameter is above or below a threshold value, a continuous function is used to estimate the likelihood that a threshold is exceeded. Such fuzzy rule-based methods have been used in meteorology, for example, by Bardossy et al. (1995) to classify atmospheric circulation patterns and by Keenan (2003) in hydrometeor classification.

Using fuzzy functions, WCRI is calculated from the wind direction change rate (r_d), the wind speed change rate (r_u) and gust wind speed (g_u). Included in this index is a component that allows for a direction change being more significant if the mean/gust speed (g_u) is greater, and that for some changes there is a significant speed change at the "wind change time", and that this can aid the discrimination of the most significant wind change time. The Wind Direction Rate Index (WDRI) and Wind Speed Rate Index (WURI) are first defined as

$$WDRI = \begin{cases} 100 & WDRI > 100 \\ 100 \times [w_g f_z(r_d) + f_z(g_u)]/(1 + w_g) & \\ 0 & WDRI < 0 \end{cases}$$

and

$$WURI = \begin{cases} 100 & WURI > 100 \\ 100 \times [w_g f_z(r_u) + f_z(g_u)]/(1 + w_g) & \\ 0 & WURI < 0 \end{cases}$$

where the weighting parameter w_g (w_g=2.0 in this application) gives greater weight to r_d (r_u) than g_u in the calculation of WDRI (WURI). When both r_d (r_u) and g_u are very high, the WDRI (WURI) is close to 100. The fuzzy function f_z is fully described in HM06. To reduce the effects of the different wind speed sampling times between METAR (the scheduled observation data archive) and SPECI (the special observation data archive), the gust speed (g_u) is used instead of wind speed to determine WDRI and WURI.

The WCRI at a given time t is then defined as

$$WCRI(t) = max\{WDRI(t), WURI(t)\} \tag{1}$$

and so incorporates the effects of both speed and direction change. Values of gust speed $g_u \sim 6\ ms^{-1}$ and wind direction change $r_d \sim 60$ degree hr^{-1} will lead to a WCRI of ~ 36.

b2. Wind Change Strength Index

The WCRI, a measure of "instantaneous" wind change strength is used to define the "change time" for wind changes, and also defines the transition points in Fig. 2. While appropriate for its application, it does not differentiate between what a meteorologist might term synoptically weaker or stronger wind changes. A function that represents the "wind change strength" over 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 dewpoint depression change across the whole change period is the Wind Change Strength Index (WCSI, HM06). This function is intended to lead to 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, and is fully described in HM06. WCSI is estimated from

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

b3. 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 VRFC Fire Weather Directive (Bureau of Meteorology 2006), and which calls for the identification of a "significant" frontal wind change. Since the aim of this project 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", HM06 proposed a Wind Change Danger Index (WCDI) that combines the WCSI and WCRI into a single index, as shown in the schematic in Fig. 3. 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". The formulation on which Fig. 3 is based is presented in Appendix D of HM06.

2.2.2 Pressure cycle identifications

In HM07, the synoptic pressure cycle, which in the mid-latitudes might be represented in its simplest form by a cosine function of single-station pressure observation time series that corresponds to the passage from a high pressure system through low pressure minimum and back to high pressure, is classified objectively using fuzzy logic. Using this approach, the general pressure cycle can be objectively classified into 6 phases: falling pressure, local minima, major minima (trough/low passage), rising pressure, local maxima, and major maxima (high pressure system passage) (Fig. 4). Fuzzy-logic algebra applied to the time series of surface pressure at single station leads to the classification of any period as falling within one of these 6 phases of the synoptic pressure cycle, with full details described in HM07.

HM07 applied the method to two fire seasons at selected surface station in Victoria and found that the overwhelming majority of VRFC wind changes occur in either Stage 3 (63%) or Stage 2 (24%) of the pressure cycle - that is, during trough passages. This is consistent with the VRFC policy that wind change forecast charts will be issued on days when a significant (frontal) wind change is expected, together with very high or extreme fire danger index.

2.3 Meso-LAPS05 model wind changes

Meso-LAPS05 model wind changes are determined in basically the same way as objective wind changes. Meso-LAPS05 is a mesoscale version of Bureau of Meteorology's regional atmospheric prognostic system at horizontal grid spacing of 0.05 degree. As the model usually predicts wind speeds lower than observations, 20% is added the forecast speeds to produce the WCRI and WCDI. In addition the model time series, available hourly, is notably smoother than the observation time series so the algorithms are simplified and the dependence of model forecast WCRI on rate of change of direction for different speed ranges is shown in Fig. 5

A benefit of mesoscale NWP forecast fields is their spatial resolution and consistency, and applying the WCRI algorithm to each model gridpoint allows the wind change rate index, overlaid on forecast wind barbs, to be presented to forecasters as a single frame, or as an animated loop, as shown for example in Fig. 6. Interpolated to the observation sites, these time series then allow comparison of forecast and observed WCRI.

3 Data and Verification Methods

3.1 Data

3.1.1 Observations

The observations used in this study are extracted from the Australian Data Archive for Meteorology (ADAM) database maintained by the Bureau. The observation time, surface pressure, wind speed, wind direction, gust speed, screen level temperature, and dewpoint are extracted from the METAR and SPECI database. The METAR data are observed at half-hourly intervals at the stations used in this study, and special observations (SPECI) are recorded when the weather conditions meet specified criteria. The wind speed and wind direction are normally 10-minute averages for METAR and 2-minute averages for SPECI observations. The gust is the maximum wind speed in the 10 minutes preceding the observation time. Both METAR and SPECI data are used in this study. In the analysis to follow no differentiation is made between METAR and SPECI data, in spite of the potential inhomogeneities due to the difference in averaging periods used in the two data types. This is to take advantage of the higher time resolution afforded by the use of the SPECI data. The use of gust speed rather than wind speed ameliorates some of the consequences of this choice. It is also important to note that if there has been a SPECI issued shortly before a routine METAR is scheduled, then that METAR will not be sent, thus significantly reducing the time resolution of the observation series at a critical time if SPECI observations are not included.

3.1.2 Numerical model data

The Bureau's operational high-resolution mesoscale NWP model (Meso-LAPS05) is used for this study. The Meso-LAPS05 model is nested within the Limited Area Prediction System (LAPS375) model which itself is nested within the Global Assimilation and Prediction System (GASP). The LAPS375 model has 0.375-degree horizontal grid spacing and produces 0-72 hour numerical forecasts over the Australian region. A detailed description of the LAPS model and its physical processes can be found in Puri et al. (1998).

The Meso-LAPS05 model has 0.05-degree horizontal resolution, 29 vertical sigma levels, and output is generated each hour. Meso-LAPS05 models run twice daily, initialised at 0000 UTC and 1200 UTC, on a number of domains to 36 hours, including over Victoria. The wind speed and wind direction at a height of 10 m, screen level temperature and dew point from Meso-LAPS05 are used to diagnose model forecast wind change timings and strengths.

The LAPS375 and Meso-LAPS05 models underwent a major upgrade at the start of the year 2000 and hence only Meso-LAPS05 model outputs for the 2001-2002 to 2005-2006 fire seasons were used in this study. The Meso-LAPS05 model base times were 2300 UTC and 1100 UTC before 18 March 2002, and 0000 UTC and 1200 UTC after that time. For convenience in this report reference to a model base time of 0000 UTC includes the 2300 UTC base time for the earlier period and a model base time of 1200 UTC includes 1100 UTC. Only forecasts between 6 and 36 hours of the forecast time are used, in order to exclude the effects of model spin-up in the early hours of the forecast.

3.1.3 Verification stations

The VRFC has subjectively verified the wind change forecasts at selected Automatic Weather Stations (AWS) for days on which wind change forecasts were issued (Van Zetten et al. 2001; Morgan 2002). The objective and subjective wind change verification times at these selected stations are used to verify Meso-LAPS05 forecast wind changes in this study. The Meso-LAPS05 forecast fields, available hourly, are interpolated to a station location to provide time series of model parameters at that location, and the objective wind change forecast times are determined from these time series. The locations of these stations and the topography of southeastern Australia are shown in Fig. 7 and listed in Table 1. Among the AWS stations, Albury (YMAY) only had half hourly data during the 2002-2003 fire season, and no subjective wind changes were recorded there during that season, while only one wind change was identified during the 2003-2004 fire season at Mt Hotham (HOTH) (Morgan (2002) discusses the difficulties of identifying change passages across the higher elevations of eastern Victoria). Accordingly these two stations are not included in this study. Hence, seven stations in Victoria, Port Fairy (PTFA), Horsham (YHSM), Latrobe Valley (YLTV), East Sale (YMES), Mildura (YMIA), Melbourne Airport (YMML) and Shepparton (YSHT) are selected to verify the wind changes. Table 1 lists the full names and locations of the stations.

The Victorian fire weather season generally commences in late Austral spring and ends in early to mid autumn. Data from 9 November to 1 April for the five fire weather seasons from 2001/2002 to 2005/2006 are selected for verification in this report.

All times used in this report are local time, which is either Australian Eastern Standard Time (AEST) or Australian Eastern Daylight Time (AEDT), depending on the date in the season.

3.2 Objective verification comparisons

Two sets of verifications are presented in Section 4 of this report. The first is the verification of Meso-LAPS05 wind change forecasts for those days on which VRFC wind change forecasts were issued. In each case, a match between the wind changes identified by the observations and those from the NWP model forecasts is needed. We first describe the specific problems of matching forecast wind changes and VRFC changes, and then discuss the more general problem of matching observed and forecast objective wind changes for all changes identified.

3.2.1 Matching VRFC changes with NWP model forecast changes

VRFC wind changes are issued during cold front passages in the Victorian region, and the majority of these occur during stage 3 of the synoptic pressure cycle (HM07). In order to simplify the change-matching decisions, the subset of the VRFC changes that occurred during pressure cycle stage 3 are selected for verification, subject to the additional condition that the objective wind change period overlaps the stage 3 pressure cycle.

As described in Section 2, the objective identification provides a wind change period and a maximum wind change time, while the VRFC subjective identification provides only a wind change time. To make a comparison between the two wind change identifications, we define two parameters, the *wind change period coverage* and the *wind change timing error*, or simply as the coverage and the timing error.

a. The coverage

This metric is designed to demonstrate the proportion of VRFC wind changes for which a wind change period is forecast to overlap the VRFC wind change. We first select those objective wind change periods that might be considered significant changes, using both the WCDI and the WCRI. A change is considered a candidate for verification if, for the observations, both the conditions of $WCDI > 35$ and $WCRI > 35$ are satisfied, and, for the NWP model forecast time series, either of $WCDI > 35$ or $WCRI > 35$ is satisfied. The conditions for the observation time series are more stringent because the observation data contain more small scale or turbulent variations which cause greater fluctuations in $WCRI$, while such variations are mostly smoothed out in the model forecast outputs.

Defining N as the total number of stage 3 pressure cycles for which both VRFC and objective wind changes are identified, and N_c as the number of stage 3 pressure cycles for which the VRFC wind change time (t_{RFC}) is within what we will term the 2.5 hours extended objective wind change period ($t_{sc} - 2.5 < t_{RFC} < t_{ec} + 2.5$) the coverage R_c can be defined as

$$R_c = \frac{N_c}{N} \tag{2}$$

R_c thus represents the proportion of VRFC wind changes for which either an observed or forecast objective wind change period can be identified when a VRFC wind change forecast verification time is also available. As such it can perhaps be considered a hit rate for the change events.

b. Timing error

For the stage 3 pressure cycles where both VRFC and objective wind changes are available, the timing error is defined as the time difference between the VRFC subjective wind change time (t_{RFC}) and the objective maximum wind change time (t_{mx}) selected from one or more objective wind change periods. Conditions to choose the ONE maximum wind change are:

1. If there is any wind change period for which $WCDI \geq 35\%$, the objective maximum wind change time (t_{mx}) that is nearest to the VRFC wind change time (t_{RFC}) is chosen;

2. If condition 1 is NOT valid, the wind change with maximum WCRI is chosen.

Condition 1 treats all the wind changes with the WCDI being greater than 35 as equally dangerous fire weather wind changes. If condition 1 is not satisfied, then condition 2 sequentially selects the most significant of the weaker objective change periods.

3.2.2 Matching forecast wind changes to observation wind changes

In the previous section we described our methods of verifying wind change forecasts when events are selected subject to a VRFC wind change forecast having been issued, and verification timing for that forecast having been produced. However, there can be more than one wind change during a cold frontal passage as found, for example, in Mills (2005a, b). In addition, sea breeze and local effects can also cause significant wind changes (HM06). In order to verify all model predicted objective wind changes, we match them against objective identifications from observations. However, this approach does identify a very large number of wind changes, and in order to simplify the interpretation we group these wind changes according to the pressure cycle stages following HM07. We further focus primarily on those wind changes occurring during stage 3 (major pressure trough) of the pressure cycle, as the majority of frontal wind changes occur during this stage of the synoptic pressure cycle, including 63% of VRFC wind changes (HM07).

A stage 3 pressure cycle is treated as wind change sub-cycle when one or more objective wind change periods occur either within, or overlap, the stage 3 sub-cycle period. When objective wind change periods are identified from both observations and model forecasts within a stage 3 pressure sub-cycle identified from the observations, the model and observed objective wind changes closest in time within that sub-cycle are selected as being a verification pair. This assumes that the mesoscale NWP model is forecasting the same wind change as is identified in the observation time series, and is not necessarily always valid, but is based on the subjective forecaster impressions that realistic change structures are regularly forecast by the Meso-LAPS model. This assumption is not necessarily true for all verified changes, but it does provide an objective selection rule. Examples of changes that illustrate the consequences of this assumption are presented in the Case Studies section later in this report.

Many of the results to be presented are in terms of contingency tables, where forecasts are defined in terms of a *hit*, a *false alarm*, a *missed forecast* and a *correct rejection*, with a hit being a forecast that predicts an observed wind change, a missed forecast is an observed wind change that is not forecast, a false alarm is a forecast wind change that is not observed, and a correct rejection represents a stage 3 pressure sub-cycle for which neither a forecast or an observed wind change is identified. These terms are summarised in Table 2.

4 Verification Results

Table 3 shows the number of stage 3 pressure cycles identified at each verification station and for each year, and in the same format the number of VRFC wind change forecasts issued. There are around 20 major trough passages at each station per fire season, and around half that number of VRFC wind change verifications at each station.

Applying the objective wind change identification algorithms to both observation and model time series for the entire fire seasons identifies very many more changes (Table 4) - around 400 per season - although average numbers per station range from an average of 275 at Mildura to 446 at Melbourne. Gratifyingly, very similar numbers are identified in model time series from both 0000 UTC and 1200 UTC base times. If these changes are selected on the basis that the change period overlaps a stage 3 pressure cycle, then this number per station per season reduces to some 75 (Table 5), and still with nearly a factor of two between the stations with the smallest (Mildura) and the largest (Melbourne) number of changes.

Table 6 shows the number of wind changes during stage 3 pressure cycles when the VRFC validations are available. The number of observed changes per year per station then ranges from 20 at Mildura to 33 at Melbourne, with the number of modelled changes being some 50% greater, although with similar station to station variation.

In order to present the verification results in some context, we will focus on the changes that occur during stage 3, first comparing the VRFC verification times with those of the objective verification times, and then verifying the model forecasts for those dates. Second, all model forecast changes that occurred during stage 3 will be verified.

4.1 Model wind changes on VRFC wind change days

Figure 8 shows, in the upper pair of panels, the comparison between the VRFC verification times and the objective verification times, sorted by verification station and by verification season. Well over 90 % of the VRFC wind changes occur within the extended wind change coverage period as defined in Section 3.2, and around 80 % of objective wind change times within 2.5 hours of the VRFC verification time, with some station-to-station variation. Mildura show the lowest proportion of verification times within 2.5 hours of each other, possibly due to the longer wind change periods common at the more inland stations (HM06, Mills 2005a). There are also some year-to-year variations in the proportions of extended wind change period coverage, and of 2.5 hour differences. It is hard to attribute reasons for this, as the VRFC practice may have been subtly different from year to year due to personnel changes or subtle changes in practice. The objective verification data was used by the VRFC in their verification for the 2005-6 season, and it may not be coincidental that the highest proportion of matches are seen in that season. It is, of course, also entirely possible that year to year variations in circulation patterns may mean that changes have different characteristics from year to year.

A significant point, though, is that there are inherent degrees of uncertainty in the definition of a unique change time, and this uncertainty must be remembered when the model forecast verifications are presented below.

In the second row of Fig. 8 the comparison of the model forecasts with the VRFC wind change times is presented, sorted according to station (left) and year (right). Overall, around 70 % of the model forecast maximum wind change times are within 2.5 hours of the VRFC wind change time, while around 93 % of VRFC wind change times lie within the mesoscale NWP model forecast extended wind change period. The highest proportion of forecast changes within 2.5 hours is at Port Fairy, while the lowest is at Shepparton.

Finally, in the third row of Fig. 8 the comparison of model forecast and verifying objective wind change times is given. In this case a third comparison is presented, as both sets of forecast and observed objective times determine wind change periods as well as the maximum wind change time. The black bars show that the forecast and observed wind change periods overlap on some $65-95$ % of occasions, with Port Fairy showing the lowest rate of overlap, or hit rate, while the greatest hit rate is at East Sale. The percentage of forecast wind change times within the extended objective wind change verification period ranges from $85-99$ % (green bars) depending on station, and the proportion of wind changes that are forecast within 2.5 hours of the objective wind change time ranges from 70 % (Mildura) to 90 % (Horsham) (red bars). There is some interannual variability, but less than the station to station variability. It is also notable that at several stations (Horsham, East Sale and Shepparton in particular) a considerably larger proportion of forecasts are within 2.5 hours of the objective wind change timings than they are of the subjective wind change times. This perhaps reflects the different definitions of a wind change time used in determining these times, but with the model and the observation objective wind change times using similar processes, then apparently improved model performance is achieved. The apparent anomaly between the smaller percentage of overlapping forecast and observed wind change periods than the other two metrics in these verifications is due to the number of occasions when the objective wind change period is short, producing a lower hit rate for the event than might be interpreted from the comparison of the objective wind change times.

In Fig. 9 we present the forecast errors in a manner similar to that presented by Morgan (2002), with a scatterplot of forecast wind change timing error versus model lead time in the upper panel, and mean and standard deviation of the forecast error versus lead time in the lower panel. There is only a very weak trend in mean error with time, and almost no trend in standard deviation of that error. Thus the numerical model forecasts for the VRFC wind changes are essentially unbiased as far as timing error is concerned. While the standard deviation of the forecasts is around 3 hours, these statistics are dominated by the few large errors, a component of which is an artefact of our verification methodology rather than what a forecaster might interpret subjectively as a model error. These aspects will be discussed in the Case Studies section later in this report.

4.2 Model forecasts versus observations

In the preceding section the NWP model forecast wind changes were verified against the objective timings from observations only for those days on which VRFC wind change forecasts were issued. Applying the objective wind change algorithms to the full observational record for each fire season identifies a very large number of wind changes, and in principle verification statistics for all these changes could be produced. However, the long duration of some stages of the pressure cycles in which local effects dominate can allow for multiple wind changes and long wind change periods within those stages, thus creating ambiguity in matching observed and forecast wind changes.As the majority of frontal wind changes occur during stage 3 (major trough passage) of thesynoptic pressure cycle, and because the shorter duration of these stages (see HM07) makes the interpretation of the verification matchupssimpler for these events, in this section we present a verification of NWP forecasts for all objective wind changes that occur within stage 3 of the pressure cycle during the fire season.

Based on the stratifications described in Tables 4-6 above, an average of approximately 75 observed wind change periods per year occur within stage 3 of the synoptic pressure cycle at each station, and approximately similar numbers from the NWP forecasts. A requirement of the verification is that there be an overlap of the observed and forecast wind change periods. Fig. 10 shows the contingency table matching observed and forecast wind change events, stratified again by verification station and by season. Overall 86.9% of all pressure cycle stage 3 periods are identified with both an observed and forecast wind change period, or *hit* as defined in section 3.2.2. Some 5.4% of the stage 3 periods include an observed wind change period, but not a forecast wind change, or a *missing forecast*. 4.9% periods include a forecast wind change, but not one from the observations (a *false alarm*). The stage 3 periods that contained no objective wind change identifications from either the observation or the model forecast account for 2.7%, and are classed as *correct rejection*. The total rate for a correctly forecast wind change events during stage 3 of the pressure cycle is the sum of hit and correct rejection rates of 90%.

The lowest proportion of "hits" occurs at Mildura, but the number of "correct rejections" is largest at this station. In addition the number of stage 3 pressure cycles is also lowest of all the stations at Mildura, where HM06 noted that wind changes tended to be weaker and of longer duration, and HM07 showed had a greater number of stage 2 relative to stage 3 pressure cycles. As it is also seen that Mildura has the greatest number of missed forecasts, the implication is that the weaker changes experienced well inland (Mills 2005a) are both harder to identify and harder to forecast correctly. The other six stations show similar performances in most criteria, but Port Fairy 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 the seasons being easier to forecast is unclear. These two years show the smallest and the largest number of pressure cycles of the five verification years, so perhaps in themselves the synoptic circulations are not similar for those two years.

Wind change timing errors for those forecasts identified as hits in Fig. 10, are shown in Fig. 11. Overall some 78% of stage 3 pressure cycles have an overlapping forecast and observed wind change period, although this ranges from 68% (Port Fairy) to 94% (East Sale), 90% of forecast wind changes lie within the extended observed wind change period, and some 75% of forecast times are within 2.5 hours of the observed time. Again, while Port Fairy shows the lowest percentage of overlapping wind change periods, it also has the highest proportion of forecast wind changes within 2.5 hours of observed. Year-to-year variations show, as for the VRFC wind change events, that the model skill was highest for the latter two years verified.

Fig. 12 shows the scatterplot of timing error versus model forecast lead time for all stage 3 significant wind changes through the five verification seasons, together with the mean error and standard deviation of that error in the lower panel. Changes with errors greater than 18 hours have been excluded from the calculations of mean and standard deviation as by the definitions made to match forecast and observed wind changes these must be associated with extremely long wind change periods, and are probably not those a forecaster would compare. While there is a slightly greater scatter than seen in the scatterplot for the VRFC wind changes, as would be expected from the statistics shown in Fig. 10, there is again a strong clustering around zero error, and mean and standard deviation of the errors shows only a very slow trend towards a slow bias with time, and essentially no trend in the variance of the forecast error.

5 Case Studies

There are two issues not addressed in the preceding sections. The first lies in the complexity of the observation time series in many of the events for which wind change times are determined (see the examples in HM06 and HM07), and the way in which these structures affect the wind change times determined by the fuzzy functions described earlier. The second issue is the relationship between these structures and the synoptic meteorology of the event. The statistical verifications presented in the preceding sections were intentionally independent of any synoptic classification, partly because the difficulty of objectively matching forecast and observed patterns led HM06 to use single-station time series of observed and forecast wind temperature and humidity data to identify the wind change times at those points. In this section we present a number of case studies that illustrate different aspects of the wind change timing algorithm, particularly illustrating how subtle variations in the observation time series can affect the selection of the maximum wind change time for simple and more complex wind change structures. It is intended that these examples aid the interpretation and understanding of our wind change verification.

Most of the examples to be presented are associated with dry cool changes associated with eastward propagating pressure troughs in the westerly wind flow south of the Australian continent. While many of these are depicted on synoptic-scale surface analyses as cold fronts, a large number of studies (Reeder, 1986; Reeder and Smith, 1987; Physick, 1988; Garratt et al., 1989; Mills, 2002, 2005a, 2005b, 2007; Mills and Morgan, 2006) have shown that effects of land-sea heating contrast and of topographic blocking of flows have a major effect on the exact morphology of a particular cool change. There are other paradigms that differ from the simple cold frontal conceptual model, and one widely used in southeastern Australia is that of the pre-frontal trough (Hanstrum et al. 1990) where a trough associated with the pool of hot air over the continent interacts with the pre-frontal airflow to generate a front, and this marks the first change from hot northerly to cooler westerly winds, while the original front marks the final establishment of cooler maritime air. In such situations a longer change time and multiple wind change periods can be identified. There can also be considerable fluctuation in wind speed through a cool change transition, with stronger winds before and after the wind change, but a period of lighter winds during the trough transition when the pressure gradient can be weak (Ma and Lyons 2000).

For each case study we present conventional synoptic-scale MSLP analyses, Meso-LAPS05 forecasts of MSLP and low-level wind, and separately, the corresponding surface potential temperature and wind speed forecasts. (Mills (2002, 2005b) has discussed the intimate dynamic relationship between thermal gradient discontinuities and wind changes). In addition, we present in each case study for several of the verification stations meteograms of observed and forecast pressure, temperature and dewpoint, and wind speed and direction. Overlaid on these 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 made, and so present a powerful set of examples of the strengths, weaknesses, and complexity of the objective verification methodology.

5.1 Case 1: single cold front passage

Figure 13 shows the synoptic-scale mean sea level pressure (MSLP) analyses at 1200 UTC 10 March, and 0000 and 1200 UTC 11 March 2002. This is a typical synoptic sequence for an abrupt dry cool change through Victoria in late summer, with a heat trough over central Australia extending southwards, a mid-latitude cold front extending northwards, and the two systems moving through southeast Australia in the cool region between two ridges.

In this case, single objective wind changes were identified at Latrobe Valley, East Sale and Mildura in both the observational and the forecast time series (Figs. 14 and 15). At other stations multiple objective wind changes were identified, either or both from the observations or the forecasts.

The wind change reached Port Fairy and Horsham relatively early in the day. At Port Fairy (Fig. 15) the first observed wind change was identified at around 0730 EDST, the same time as selected by the VRFC, and coinciding with an abrupt backing of the wind and an increase in dewpoint. The observed wind change period was quite short. The forecast wind change period was rather longer, although its start-time was the same as that observed, and the time of maximum wind change was forecast at 0900 EDST, at the time when the rate of change of wind direction was the greatest. At Horsham (Fig. 14), the subjective (VRFC), objective, and second forecast wind change times were all around 1030-1100 EDST, towards the end of the objective wind change period. The forecast wind change period was slightly longer than the observed, but essentially unbiased, with the forecast maximum wind change time at 1100 EDST. In contrast to the meteogram at Port Fairy, the wind direction backed relatively slowly. From the forecast model fields at 2300 UTC (1000 EDST) (Fig. 16) it can be inferred that the change at Port Fairy was associated with the developing coast-parallel temperature gradient seen around longitudes 142-143E (Fig. 16b2), and the sharp wind direction change across this gradient, while inland the portion of the change that affected Horsham had a weaker temperature gradient and a smoother backing of the wind. These patterns bear a striking resemblance to the structures of the change diagnosed in Mills (2002), and physical arguments explaining these different structures are discussed in that paper.

The observed change reached Melbourne at 1600 EDST (Fig. 14d), and the VRFC diagnosed the same time. A very long objective wind change period was determined, chiefly due to the variations in forecast wind speed through that period, with two maximum wind change times diagnosed - the first at 1100 EDST associated with the sharp increase in wind speed at that time, and the second with the abrupt backing of the wind and re-strengthening of the wind at 1700 UTC. It is this latter forecast wind change that was matched with the verifying wind change times. The NWP forecast (Fig. 16) shows that, again with considerable similarity to the Mills (2002) event, the change had surged along the coast between Cape Otway and Melbourne, bringing an abrupt change to this region.

According to the objective and subjective verification the change arrived at Shepparton at 2100 EDST (Fig. 15), when the wind shifted to the south and abruptly increased in speed. The NWP model forecast wind change time was 2 hours earlier, at the time of maximum forecast backing of the wind. Prior to 1700 and after 2100 the forecast and observed wind directions are essentially identical, but during the wind change period the observed winds veer from north to east, and at the same time weaken dramatically, before shifting to the south and strengthening again.

While Latrobe Valley Airport and East Sale are not geographically far apart, the differences in their locations relative to coast and ranges means that the diagnosed change structures are different at the two stations, even though the subjective verification times are only an hour apart. At Latrobe Valley Airport the observed wind change period is from 0900-1730 EDST, while the forecast period is from 1000-1900 EDST. Greater differences are seen the selection of maximum wind change timing. The objective time is at approximately 1330 EDST, when the wind direction shifts sharply from a fluctuating east-northeasterly to the west over the early part of the wind change period. The subjective choice of wind change time is at the end of the objective period, coinciding with a final backing to the southwest, and more importantly, a very sharp increase in wind speed. The forecast maximum change time occurs at 1900 UTC, again associated with an increase in wind speed and a final backing of the wind. In this case verifying the model time against the observed time is harsh, as this would provide an error of 5.5 hours, while a more appropriate error might be the 1.5 hour difference between forecast and subjective times. To demonstrate the complexity of this process, though, if one were to identify the "frontal timing" with the drop in temperature and increase in dewpoint seen at 1500 EDST in the forecast and at 1700 EDST in the observation time series (both within the objective wind change period, and the latter coincident with the subjective timing) then the model forecast would be -2 hours (an early forecast) rather than +1.5 or +5.5 hours (a late forecast). This case was also discussed in HM06, with the early wind change attributed to the breaking of an inversion, and the latter with the passage of the frontal wind change.

The decisions are considerably simpler at East Sale. Both forecast and observed wind change periods are quite short, with the observed and subjective times at 1830 EDST associated with a sharp change from easterly to southwesterly winds. The forecast change is 0.5 hours earlier, and shows very similar characteristics. The wind and temperature patterns (Fig. 16) show a very strong change, with easterly winds along the Gippsland coast, associated with the lee trough pattern typically present in synoptic-scale northwesterly flows, shifting to strong southwesterly as the cool change surges along the coast associated with strong coastal ridging.

At Mildura, smooth wind changes are diagnosed both from the observation and the forecast with the objective method, while a VRFC subjective wind change was not identified, presumably due to the lack of any clearly identifiable trough passage there.

In Fig. 17 the 24-hour forecasts are compared with the initial state for the following 24-hour later model run. While the verifying fields are smoother, as they are interpolated from the 0.375^o LAPS analysis, the phase and structure of the MSLP, wind, and thermal patterns are quite similar.

5.2 Case 2: multiple cold front/trough passages

This case is less extreme than that described in Case 1, as a trough had passed through Victoria the previous day (see the analysis for 1200 UTC 1 November 2004 in Fig. 18), and a second change, associated with a developing low pressure system in western Bass Strait, passed through southern Victoria during the morning of 2 November 2004. Because of the previous day's change there was not as much thermal contrast across this front as in many cases, and so some of the characteristics of the change are different to the case above. In addition VRFC wind change timings were not determined for this case.

Meteograms are shown in Figs. 19 and 20. The change arrived earliest at Port Fairy, with a sharp backing of the wind at about 0730 EDST. Only a very short observed wind change period was diagnosed, but a much longer forecast wind change period due to the varying wind direction coupled with varying wind speed. The diagnosed forecast wind change time is at 0800 EDST. At Horsham two observed maximum wind change times were diagnosed, at 1000 and 1300 EDST, both within the single wind change period, while the single modelled maximum wind change time at 1200 EDST lay between the two observed wind change times. The Meso-LAPS05 forecast fields (Fig. 21) are atypical for summertime cool changes due to the effect of the previous day's change, with the wind change more clearly associated with the pressure trough than the discontinuity in thermal gradient.

At Melbourne two observed wind change times, both around 1300 EDST, are diagnosed, within a very short wind change period. The numerical model-diagnosed wind change period is quite long, with three maximum wind change times diagnosed. The first, at 0800 EDST is more associated with the increase in forecast wind speed there. The second at 1400 EDST is linked with the backing of the wind at that time, and the third at 1500 EDST with the forecast strong increase in wind speed then. The association of the second forecast change with a decrease in temperature and increase in dewpoint at that time suggests that the matching by the verification decisions of this change with the observed change is the correct choice.

At Shepparton three observed and two forecast wind change times are diagnosed. There is a difference in timing of approximately 2 hours between the first observed and forecast changes, while the second pair is considerably closer. However, it could be argued from inspection of the temperature and dewpoint time-series that the correct verification pairing should be the first observed change with the second forecast change, which would increase the forecast error to 2.5 hours.

At Latrobe Valley a long forecast wind change period is diagnosed, with the maximum wind change time diagnosed at 1000, the start of the forecast wind change period. The observed wind change is diagnosed at 1515 EDST, chiefly on the basis of a sharp increase in wind speed at that time. However, the forecast wind change time appears to be more associated with the inversion breaking mechanism discussed earlier, and inspection of the temperature and dewpoint traces suggests that the frontal wind change time is 1 hour later than the observed. While there is a small backing of the forecast wind direction trace at the same time, the amplitude was insufficient to diagnose a wind change time at this point, although it is within the forecast wind change period. In this case the verification has imposed a harsh judgement on the numerical model.

At Mildura overlapping observed and forecast wind change periods were diagnosed, but the variation of the forecast variables is so small that this diagnosis is moot.

5.3 Case 3: transitional trough

The wind changes that affected Victorian stations on 26 January 2006 were complex and weakly forced synoptically. The synoptic scale MSLP analyses (Fig. 22) show a very weak easterly trough extending southwards from the interior of the continent, and a weak trough in the westerlies. During the afternoon of 26 January, Victoria was essentially in the weak pressure gradient region between two high pressure systems. Thus the land-sea heating contrast produced a local pressure gradient along the Victorian coast, and the effects on the wind flow can be seen in Fig. 23, where the NWP model forecasts show a trough just inland from the coast, with convergent winds across this trough line, and only weak inland penetration of the wind change in the west of the state.

The meteograms (Figs. 24 and 25) show long wind change periods in both the observation and the model forecast time series, with multiple change times. The extremely variable time series plots make unambiguous attribution of model and observed maximum wind change timings difficult.

At Port Fairy long wind change periods with multiple wind change times are diagnosed. The first observed change time is associated with a sharp backing of the wind and a temperature fall/dewpoint rise at around 1630 EDST. The second model wind change at 1600 EDST marks the same change, and so a forecast error of -30 mins is diagnosed.

At Horsham very long wind change periods are again diagnosed, with multiple wind change times. The observed wind change near the start of the second observed wind change period is matched with the third maximum wind change time from the forecast. The later wind change time from the VRFC matches the second drop in temperature/rise in dewpoint seen in the observed time series, and while there is also a marked backing of the wind in the hour before that time the observed speed is very low, causing this wind direction shift not to be objectively identified. Whether the objective or the subjective timing is correct in this case is unclear, but the objective timings are associated with the stronger wind speeds. This case at Horsham is one where a "wind change period" might be a better product than a "wind change time".

At Melbourne the first objective and the subjective wind changes are associated with an increase in wind speed together with a small directional fluctuation, and second order discontinuities in temperature and dewpoint, and so this pairing for verification purposes is probably correct and also indicates a very accurate forecast.

East Sale and Latrobe Valley show the major observed wind change times at 1800 UTC and 2000 UTC respectively, associated with a shift from westerly to easterly winds as the trough line moves inland (Latrobe Valley is further from the coast). In each case the model forecasts are 1 hour early and correct verification decisions were made.

A pressure cycle stage 3 is not diagnosed at Shepparton and Mildura, both of which are inland.

5.4 Case 4: distinguishable trough and cold front passages

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 associate a single wind change time determined from an observation time series with that determined from a NWP model forecast time series. In this section we discuss such a case, which was first discussed in HM06 addressing the lee trough effect in the Latrobe valley (HM06, section 6.6.1). In this discussion we describe the change over all verification stations from a model wind change verification perspective. The case is categorised to occur during stage 2 of the pressure cycle (Fig. 4), in contrast to the previous three case studies which all occurred during stage 3.

The synoptic MSLP analyses (Fig. 26) show a low and associated cold front moving eastward south of southeast Australia, and a trough line passing through Victoria ahead of this front. During the afternoon pressures fell significantly over western Victoria (see 0600 UTC analysis), but this was followed by strong coastal ridging, and the wind changes experienced at the different stations occurred under rapidly evolving pressure patterns. Thus the coastal stations further east (Melbourne, East Sale and Latrobe Valley) show a very sharp pressure rise following minimum pressure in their observational time series (Fig. 27 and 28) while the other stations show a more symmetric fall/rise sequence.

The mesoscale structures predicted by the Meso-LAPS05 model (Fig. 29) show a coastal temperature gradient developing along the length of the Victorian coast at 2300 UTC. By 0200 UTC a low had formed over western Victoria and a coastal wind change was developing (c.f. Mills 2002), while east of Melbourne a strong lee pressure trough dominated, with sharp shear from northwest (inland) to easterly (offshore) winds. In the far west of the domain cool-air advection was occurring west of a weak pre-frontal trough of the type described by Hanstrum et al. (1990). By 0500 UTC the change had moved inland and intensified, indicated by the stronger thermal gradient and wind shear at its forward edge, while the coastal wind surge had reached Wilsons Promontory and coastal ridging was developing west of Melbourne. In the final time shown in this sequence, at 1100 UTC, the southwesterly change had reached the west Gippsland stations, with a marked coastal pressure ridge simulated.

Wind changes are identified at all stations except Mildura (farthest from the coast) between 2200 EDST 28 December to 1000 EDST 29 December 2001 (Figs. 27 and 28). A particular feature of this event is the long period of relatively steady backing of the wind associated with the development and movement across the state of the low pressure system which led to long diagnosed wind change periods at all stations except East Sale and Latrobe Valley. At these locations the effects of the coastal ridging resulted in marked changes later in the day.

At Port Fairy three short observed wind change periods are seen, with the second coinciding with the VRFC wind change time. Because of the slow backing of the wind, and the strong post-change wind speeds, a very long forecast wind change period is diagnosed, but with only one maximum wind change time 30 mins earlier than the observed time.

The change is very clearly marked at Melbourne in the observation and model time series, although the objective wind change time from the model is 2 hours after both that of the VRFC and of that observed. Inspection of the temperature and dewpoint meteograms, though, indicates much closer agreement between observed and modelled air mass change.

At Horsham the model and the observation time series indicate overlapping wind change periods, with that of the model 1 hour later than that from the VRFC. The observations, though, indicate the maximum wind change time at the beginning of the period, while from the model that time is at the end of the period. Thus the verification process used gives a harsh assessment of the model forecast of 4 hours late. The VRFC time is at the end of the observed maximum change time, and so is only 1 hour earlier than the model time. At Shepparton both observations and VRFC identify the wind change time at 2300 EDST, almost at the end of a very long wind change period. However the model forecast suggests a shorter wind change period, although within that diagnosed from observations, with a maximum wind change time some 1 hour earlier than the verification times.

Latrobe Valley and East Sale are the stations that show different behaviour here. Each shows a sharp change at around 1230 EDST with the wind shifting from northeast to west-northwest. The numerical model only shows this shift very weakly, and so a forecast wind change period is not diagnosed associated with this change. The associated sharp drop in dewpoint suggests that this change is caused by the erosion of a surface inversion. Each station also shows an observed and a forecast wind change time around 2000 EDST (Latrobe Valley) and 2100 EDST (East Sale) marking the frontal wind change, and in each case the NWP model error is less than 1 hour.

6 Concluding Remarks

The fuzzy-logic methods of objective wind change timing and classification developed by HM06 and HM07 have been applied to numerical model forecasts, and these forecasts verified at seven surface stations in Victoria over five consecutive fire seasons from 2001/2002 to 2005/2006. The objective verification times are compared with the subjective verification times from the VRFC, and then two sets of model forecast wind changes are verified against both sets of verification times.

For the VRFC wind change days, 70% of the forecast objective wind change times are within ± 2.5 hours of the VRFC wind change time, and 93% of the VRFC wind change times fall within the extended wind change period. That is, while the maximum wind change time may differ from the VRFC wind change time, on the majority of occasions the model forecasts a wind change period that covers the time of the VRFC wind change. This is a consequence of the wide range of morphologies of wind changes - the “instantaneous” wind change of, say, Ash Wednesday at Melbourne (see P60 of Bureau of Meteorology 1984) is not the norm, with many changes being considerable more gradual.

Stratifying objective wind changes by the various stages of the synoptic pressure cycle indicates that, during the pressure cycle stage three when cold front passage wind changes are most likely to happen, 86.9% are identified with wind changes both from the observations and the forecasts, or a *hit*. 5.4% sub-cycles are identified with changes from the observations but not from the forecast, or a *missing forecast*. 4.9% sub-cycles are identified with changes from the forecasts but not from the observations, or a *false alarm*. Those sub-cycles that do not contain identifications from either the observations or the forecast, or *correct rejections*, account for 2.7%.

During the pressure cycle stage three when both observation and forecast objective wind changes are identified, around 78% of the sub-cycles contained overlapping wind change periods both from the observation and the forecast, with clear differences in behaviour between coastal and inland stations. For these cases, and for the cases of objective observed and forecast changes on the VRFC wind change days, there is little bias in the forecast timing, and little trend in either bias or error with forecast lead time between 6 and 36 hours, with around 75 percent of forecast times within 2.5 hours of the verification time.

Case studies show that the method is capable of tackling complex wind changes during transitional trough/cold front episodes in Victoria. In clearly-defined cases the method produces verification matches with observations that agree closely with subjective verifications. There are examples, however, where in more complex change types the objective decisions may match the "wrong" changes, although examples were presented where this may act to either increase or decrease the forecast error, and so perhaps "averages out" in the longer term statistics. Most of these cases occur with rather longer change periods, and it is perhaps moot whether a "wind change time" is the most appropriate verification in these events.

Overall this study shows that the fuzzy-logic methods can be applied to objective wind change forecast verification of NWP model forecasts, and that the operational MesoLAPS05 NWP model used in Australia shows a very sound level of accuracy, with little timing bias. Further, the examples show the difficulty of defining a unique wind change time to many of the southeast Australian cool changes, and so while it is not invalid to verify such forecasts, the error statistics so generated must be interpreted in that light, and also with consideration of the verification algorithms.

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List of Tables

Station Abbreviation	Station name	Latitude	Longitude
PTFA	Port Fairy	-38.3933	142.2317
YLTV	Latrobe Valley Airport	-38.2094	146.475
YMES	East Sale Airport	-38.1083	147.1300
YMML	Melbourne Airport	-37.675	144.8422
YHSM	Horsham Aerodrome	-36.6711	142.1719
YSHT	Shepparton Airport	-36.4303	145.3936
YMIA	Mildura Airport	-34.2306	142.0839

Table 1: Names and locations of Automatic Weather Stations used in this study.

		Wind Change	Observed
		Yes	No
Wind Change	Yes	Hits	False Alarm
Forecasted	No	Missing	Correct Rejection

Table 2: Defination of Contingency Table

a						
Season	01/02	02/03	03/04	04/05	05/06	Average
PTFA	20	20	23	17	23	20.6
YHSM	20	18	20	16	24	19.6
YLTV	21	22	22	19	26	22.0
YMES	21	22	21	19	26	21.8
YMIA	21	18	18	17	20	18.8
YSHT	22	17	18	17	22	19.2
YMML	21	22	22	18	26	21.8
Average	20.9	19.9	20.6	17.6	23.9	20.5
b						
Season	01/02	02/03	03/04	04/05	05/06	Average
PTFA	9	8	8	8	10	8.6
YHSM	12	9	12	12	13	11.6
YLTV	14	11	11	10	12	11.6
YMES	13	8	10	9	5	9.0
YMIA	13	9	11	9	12	10.8
YSHT	15	11	8	6	9	9.8
YMML	16	10	12	12	13	12.6
Average	13.1	9.4	10.3	9.4	10.6	10.6

Table 3: Numbers of stage 3 of the pressure cycles (a), the number of subjective wind changes during these cycles (b).

a						
Season	01/02	02/03	03/04	04/05	05/06	Average
PTFA	367	322	342	367	390	357.6
YHSM	373	467	340	435	457	414.4
YLTV	387	416	387	371	431	398.4
YMES	394	471	407	431	478	436.2
YMIA	251	283	250	278	313	275.0
YSHT	406	472	366	382	392	403.6
YMML	420	432	409	468	504	446.6
Average	371.1	409.0	357.3	390.3	423.6	390.3

b1						
Season	01/02	02/03	03/04	04/05	05/06	Average
PTFA	340	380	389	531	524	432.8
YHSM	302	294	309	358	380	328.6
YLTV	254	224	409	528	555	394.0
YMES	395	410	500	548	562	483.0
YMIA	183	167	261	277	288	235.2
YSHT	383	383	400	470	478	422.8
YMML	440	413	477	522	524	475.2
Average	328.1	324.4	392.1	462.0	473.0	395.9

b2						
Season	01/02	02/03	03/04	04/05	05/06	Average
PTFA	377	392	404	512	503	437.6
YHSM	272	288	258	339	347	300.8
YLTV	231	227	374	420	436	337.6
YMES	356	389	432	455	475	421.4
YMIA	149	157	219	277	282	216.8
YSHT	384	367	371	462	446	406.0
YMML	436	423	449	473	472	450.6
Average	315.0	320.4	358.1	419.7	423.0	367.3

Table 4: Numbers of objective wind changes during the whole fire season over selected stations. a is referred to the observation identifications and b is referred to forecasts from 00UTC (b1) and 12UTC (b2).

a						
Season	01/02	02/03	03/04	04/05	05/06	Average
PTFA	79	73	86	71	85	78.8
YHSM	85	78	67	67	100	79.4
YLTV	82	88	88	69	91	83.6
YMES	67	79	79	53	100	75.6
YMIA	51	53	48	52	67	54.2
YSHT	70	59	51	52	67	59.8
YMML	104	90	77	84	120	95.0
Average	76.9	74.3	70.9	64.0	90.0	75.2

b1						
Season	01/02	02/03	03/04	04/05	05/06	Average
PTFA	73	88	91	87	115	90.8
YHSM	85	70	76	73	112	83.2
YLTV	59	61	81	92	129	84.4
YMES	71	85	90	78	105	85.8
YMIA	63	41	52	60	74	58.0
YSHT	83	53	72	81	111	80.0
YMML	87	78	85	88	117	91.0
Average	74.4	68.0	78.1	79.9	109.0	81.9

b2						
Season	01/02	02/03	03/04	04/05	05/06	Average
PTFA	79	84	96	76	98	86.6
YHSM	70	64	52	58	91	67.0
YLTV	44	52	62	78	96	66.4
YMES	54	66	64	79	85	69.6
YMIA	46	41	36	51	59	46.6
YSHT	85	56	58	70	93	72.4
YMML	73	77	71	71	97	77.8
Average	64.4	62.9	62.7	69.0	88.4	69.5

Table 5: Same as Table 4 but restricted to periods of the pressure cycles listed in Table 3.

a

Season	01/02	02/03	03/04	04/05	05/06	Average
PTFA	16	15	24	24	29	21.6
YHSM	25	17	19	23	37	24.2
YLTV	31	29	36	27	34	31.4
YMES	28	33	35	27	47	34.0
YMIA	22	21	15	20	23	20.2
YSHT	27	21	15	21	24	21.6
YMML	37	33	31	29	37	33.4
Average	26.6	24.1	25.0	24.4	33.0	26.6

b1

Season	01/02	02/03	03/04	04/05	05/06	Average
PTFA	43	42	53	57	83	55.6
YHSM	43	40	30	46	64	44.6
YLTV	31	26	39	61	85	48.4
YMES	41	31	48	46	61	45.4
YMIA	20	21	19	30	26	23.2
YSHT	43	25	29	40	71	41.6
YMML	46	36	46	61	82	54.2
Average	38.1	31.6	37.7	48.7	67.4	44.7

b2

Season	01/02	02/03	03/04	04/05	05/06	Average
PTFA	46	42	60	48	62	51.6
YHSM	38	31	27	35	59	38.0
YLTV	26	25	36	49	62	39.6
YMES	30	21	29	47	53	36.0
YMIA	17	14	13	31	27	20.4
YSHT	36	22	24	36	58	35.2
YMML	30	43	38	47	69	45.4
	31.9	28.3	32.4	41.9	55.7	38.0

Table 6: Same as Table 4 but restricted to periods of the pressure cycles listed in Table 3 when VRFC wind change validations are available.

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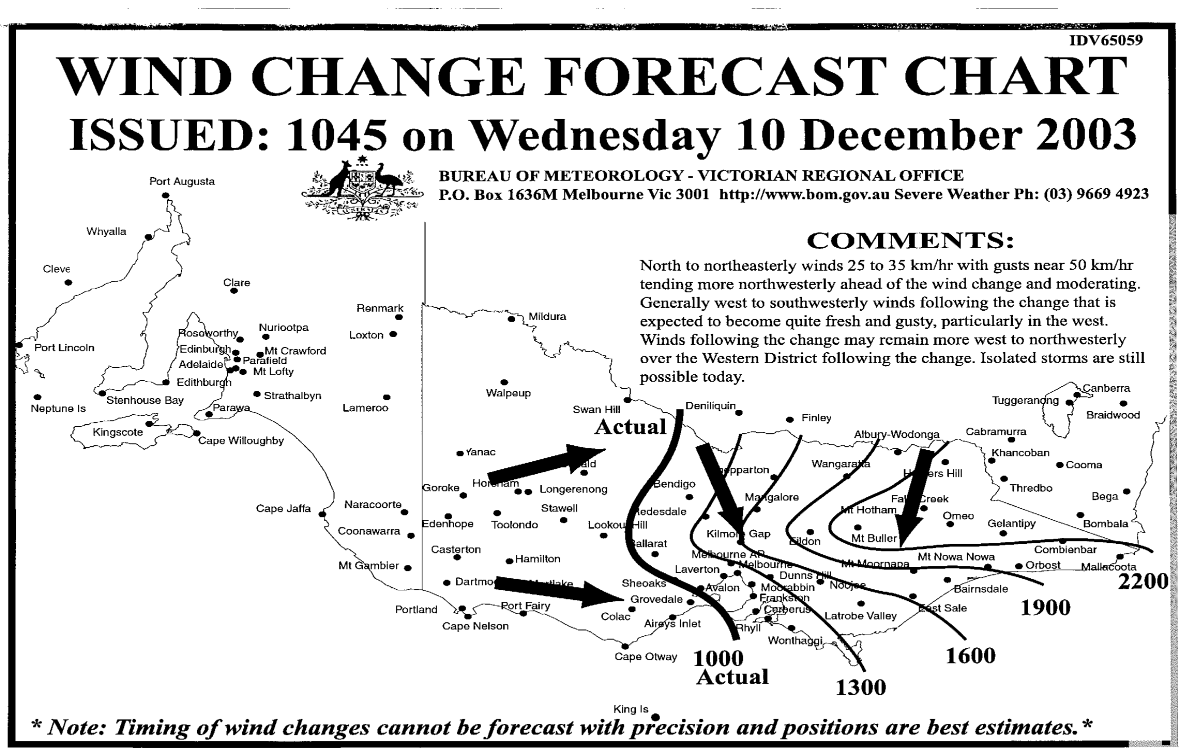


Figure 1: Example of wind change chart issued by the Victoria Regional Forecast Center (From Kevin Parkyn, VRFC, personal communication).

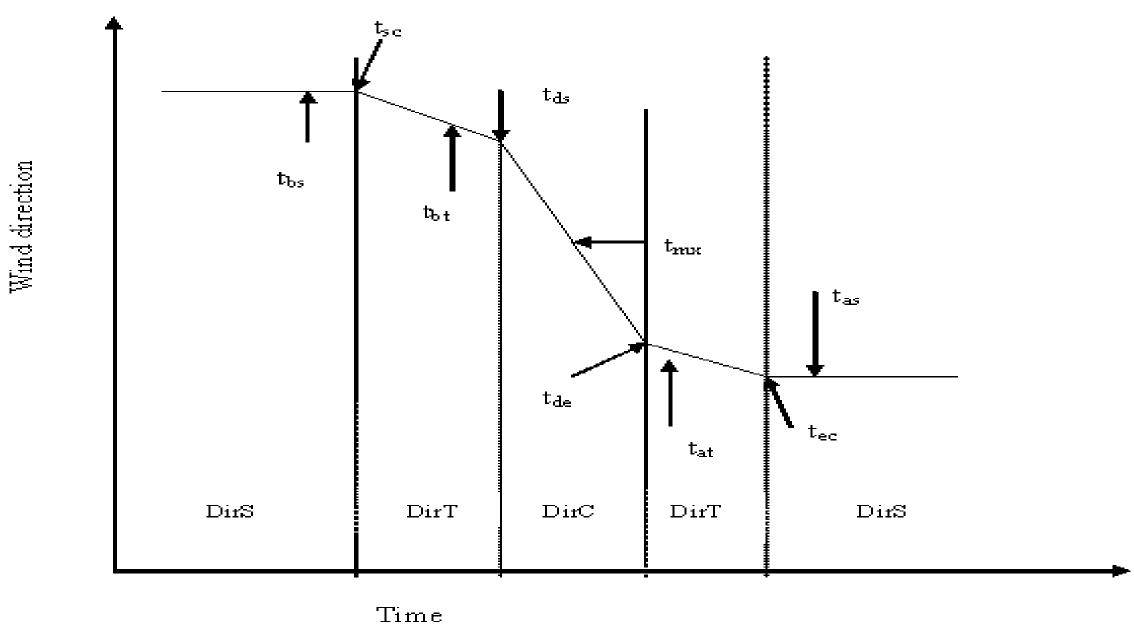


Figure 2: A schematic showing the conceptual structure of the cool change used in the objective timing decisions. t_{sc} is for wind change start time and t_{ec} is for end change time. t_{ds} and t_{de} are the time just before and after change state. t_{mx} is time when WCRI is maximum (after HM06).

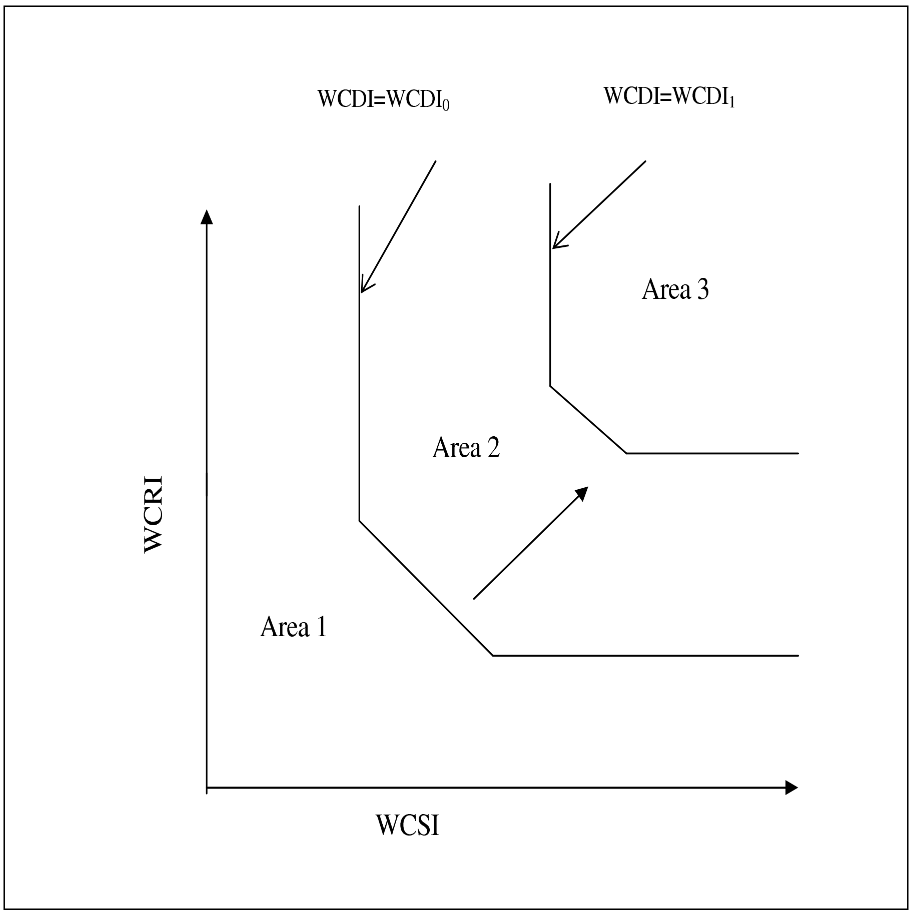


Figure 3: Schematic showing the relationship between WCRI, WCSI, and WCDI (after HM06). The arrow in area 2 indicates the strengthening direction of WCDI

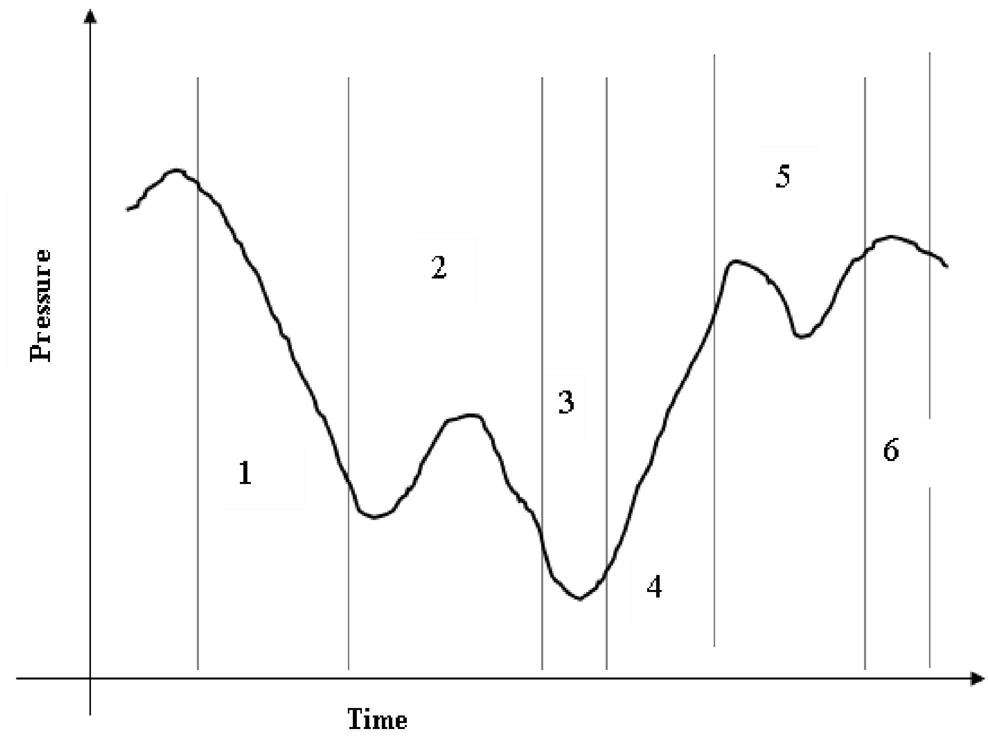


Figure 4: Schematic showing the conceptual model of 6 stages within a major pressure change cycle. Stage 1: after high pressure; Stage 2: sub cycle after low pressure; Stage 3: minimum low passage; Stage 4: rising pressure after the lowest pressure; Stage 5: sub cycle high pressure; Stage 6: under the influence of a major high-pressure system (after Huang and Mills, 2007).

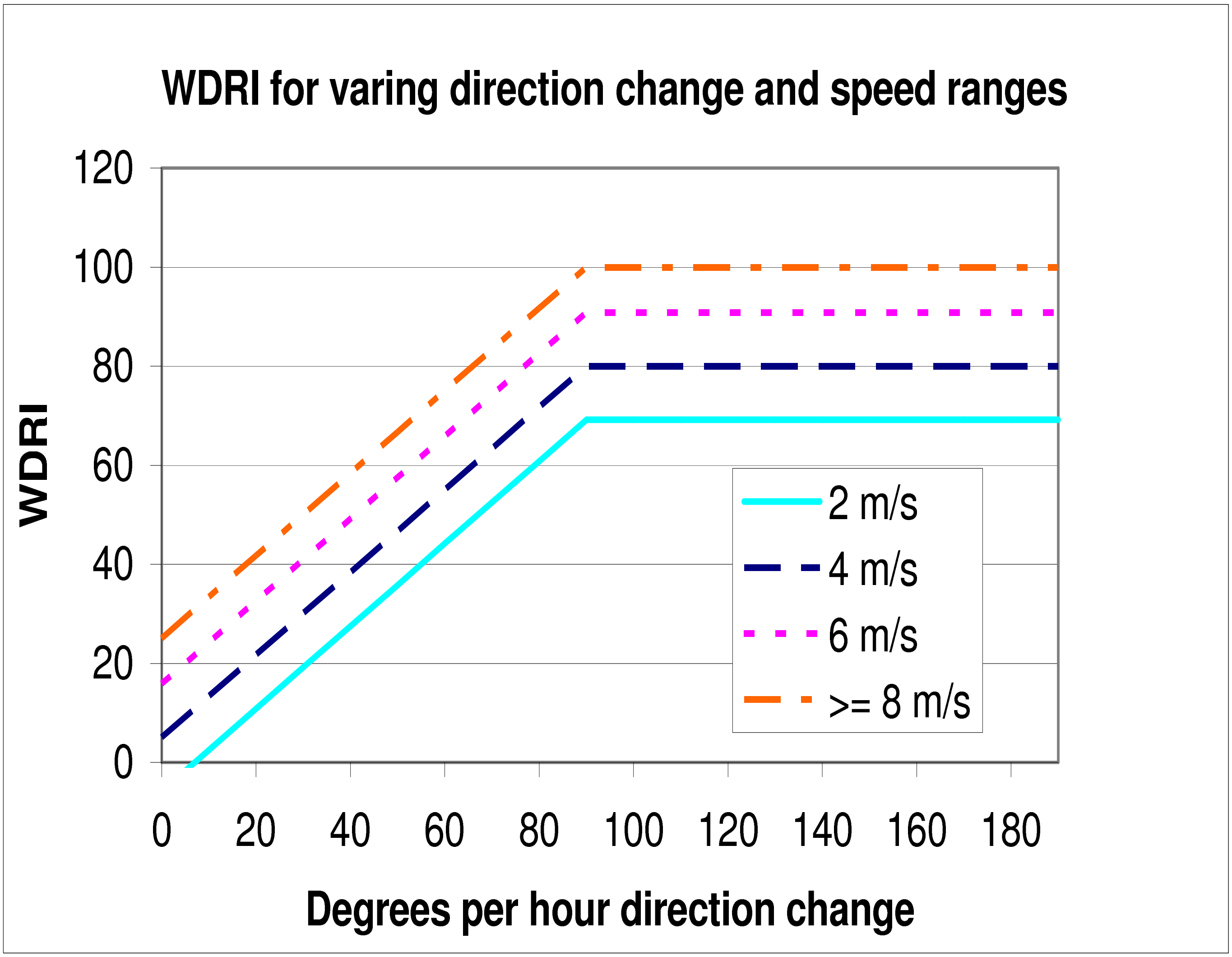


Figure 5: Variations in WCRI with rate of change of direction for various speed ranges, using the functions applied to numerical model data.

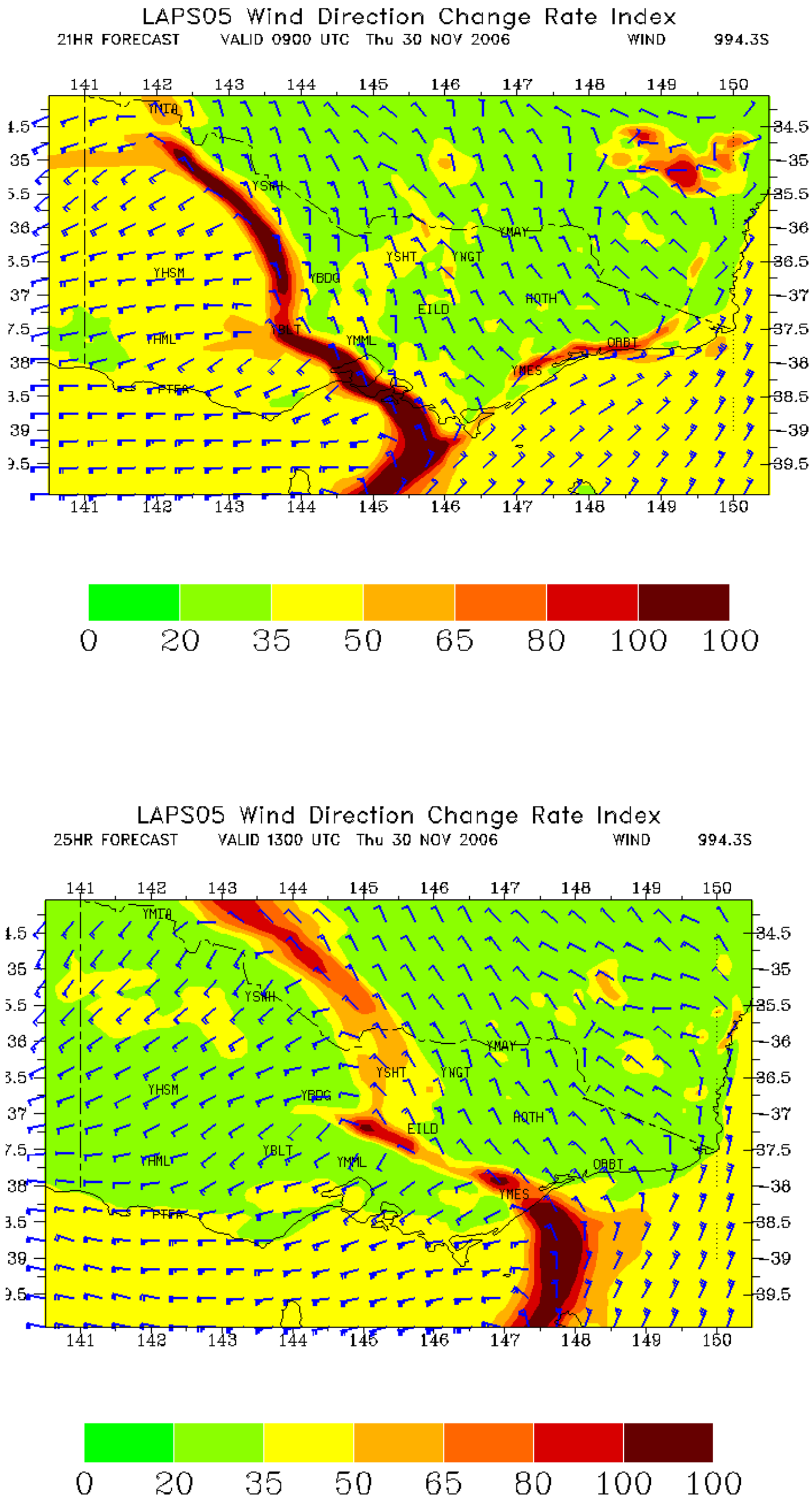


Figure 6: Example of the forecast WCRI, overlaid on the 10 m wind forecast, from the Meso-LAPS05 forecast model.

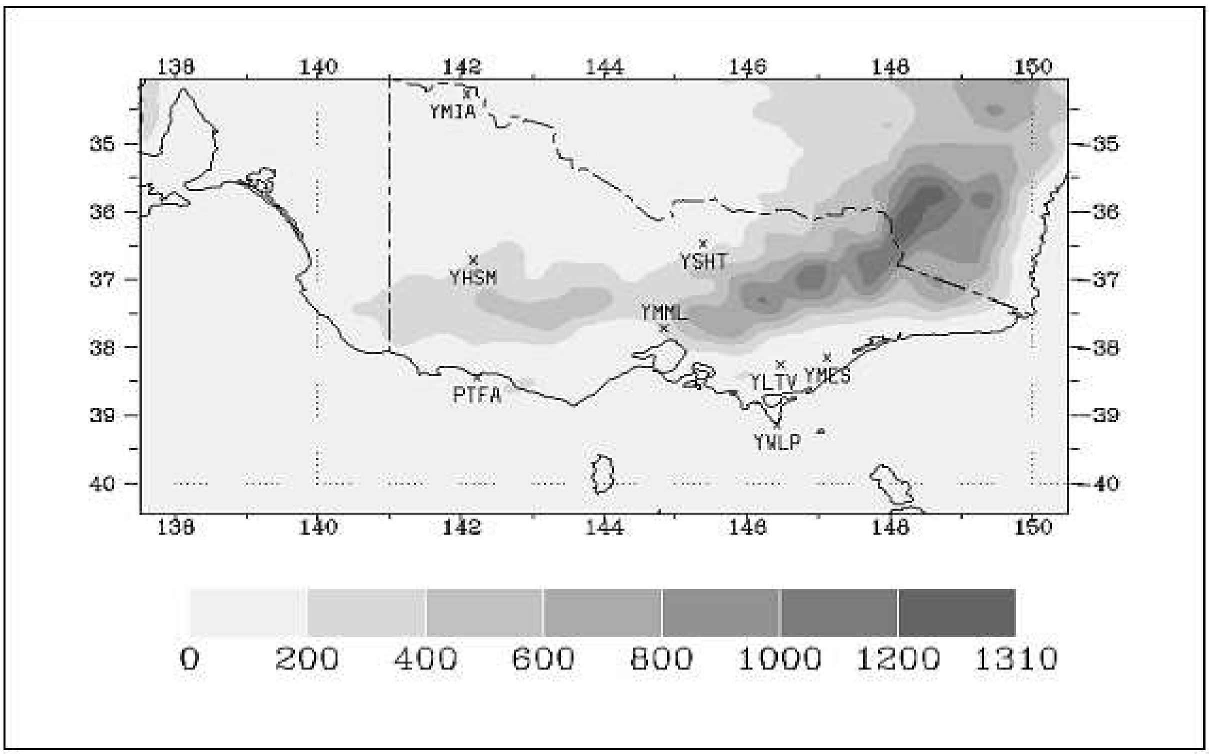


Figure 7: Map showing locations of Automatic Weather Stations in southeastern Australia used in the study. The shading indicates the model topography.

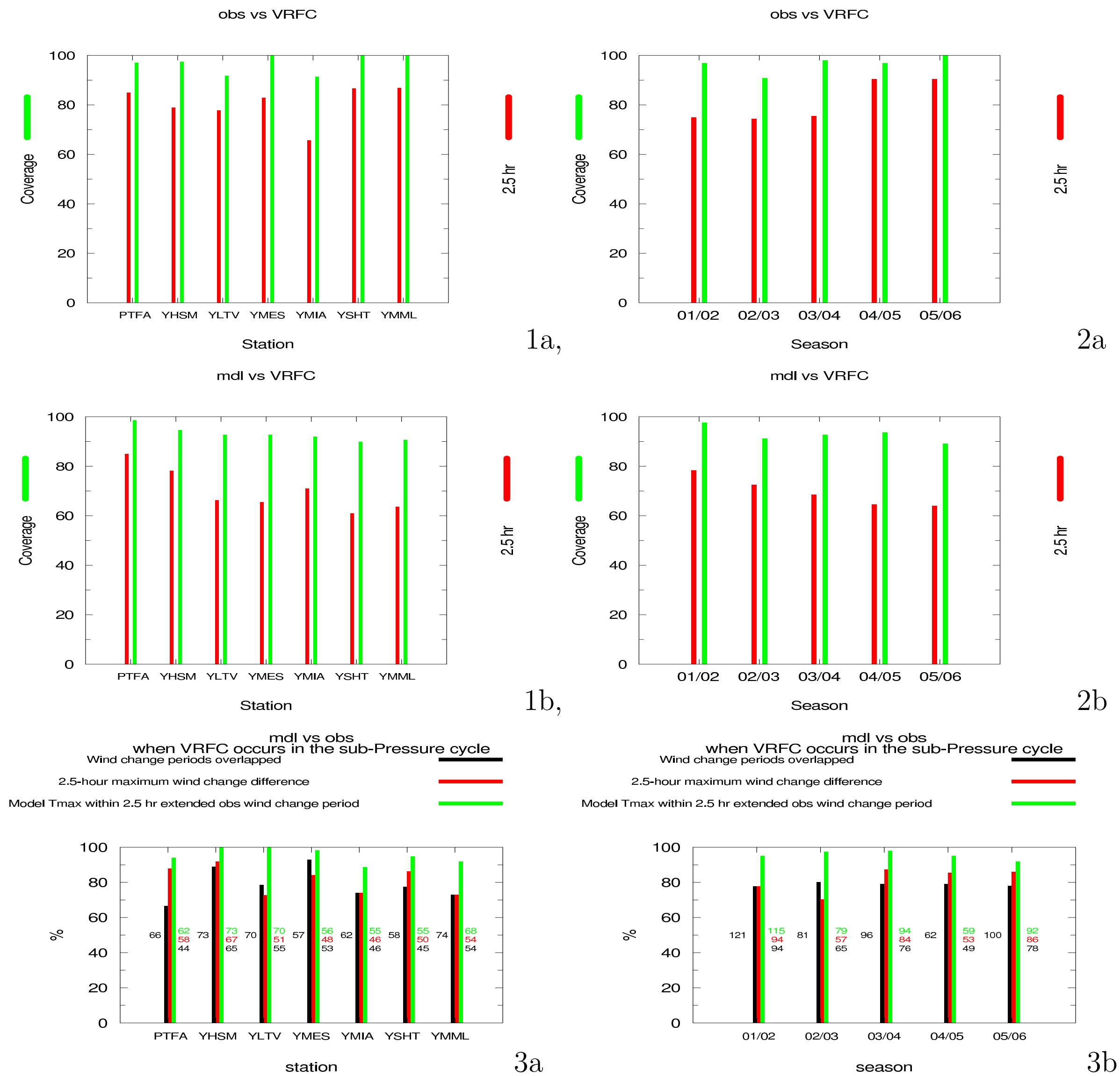


Figure 8: Verification statistics for VRFC wind change days. The left panels stratify the data according to verification station, while the right panels stratify according to fire season. The upper pair compare the observed objective wind change times with the VRFC wind change times, with the green bars showing the percentage of events for which the VRFC time is covered by the extending observed wind change period, while the red bars show the percentage of events for which the observed and subjective times are within 2.5 hours. Middle panels are in the same form, but comparing forecast wind change periods and times with the VRFC times. Lower panels compare model forecast and objective wind change periods and timings. Black bars show the proportion of VRFC wind change days for which observed and forecast wind change periods overlap, red bars show the proportion of forecasts within 2.5 hours of the observed time, and the green bars show the proportion of forecast wind change times that fall within the objective wind change period. The numbers to the left of each set of 3 bars show the number of events, and the sets of three numbers to the right show the number of events in each of the three classes with the same colour codes.

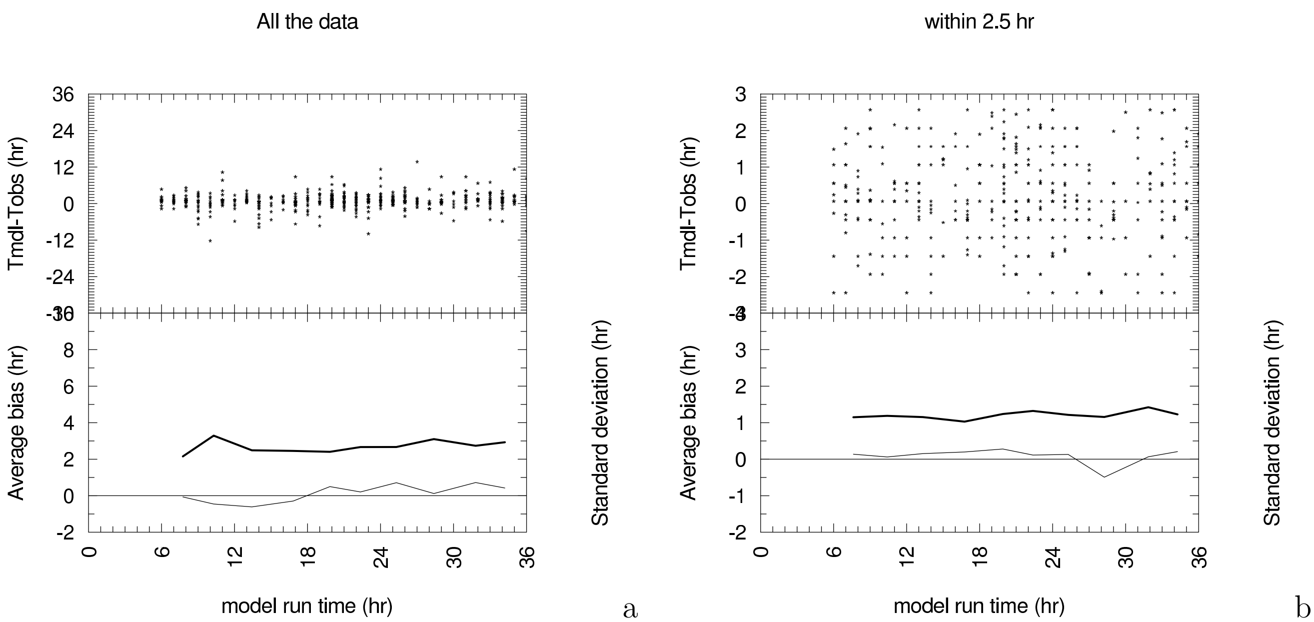


Figure 9: Scatterplots of wind change timing error versus forecast lead time for VRFC wind change days, with the lower panels showing the smoothed mean and standard deviation of error. In the right hand panel only those forecast with errors less than 2.5 hours are shown.

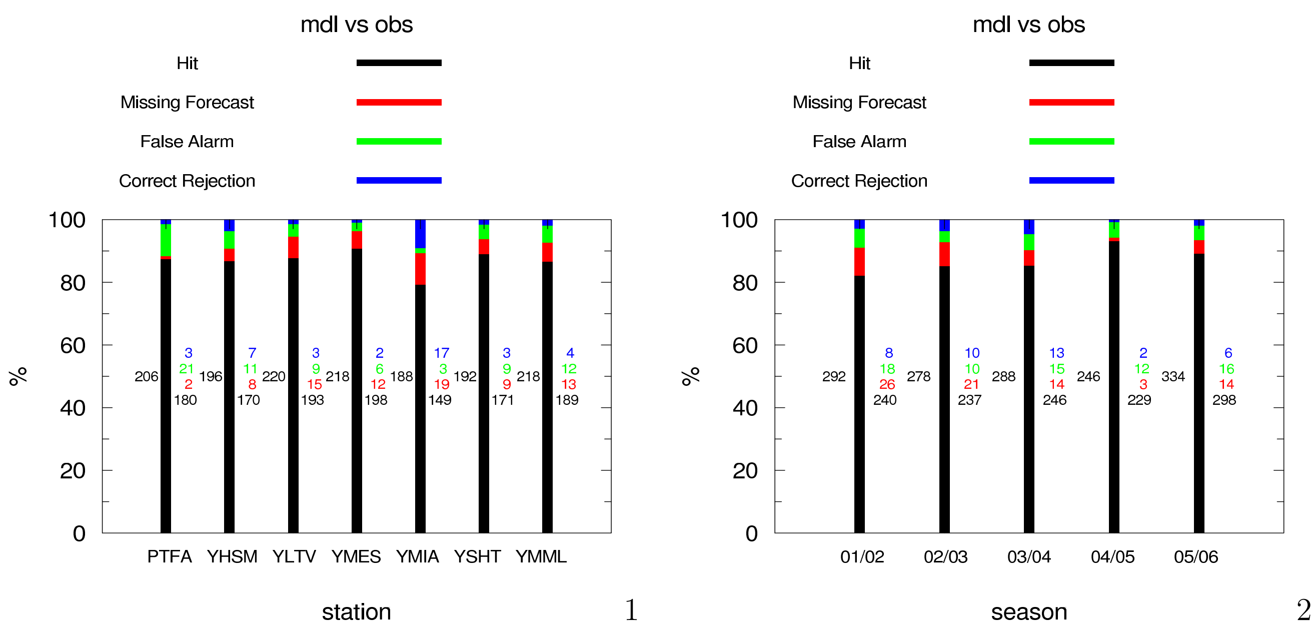


Figure 10: Contingency tables for all stage 3 pressure cycle changes. A hit means that a wind change was diagnosed in both model and observations during that pressure cycle stage. A missed forecast is counted if there is an observed but not a forecast wind change, a false alarm if a change is forecast but not observed, and a correct rejection if no change is either observed or forecast in that stage. The numbers to the left of the bar show the total number of stage 3 pressure cycles observed, and the numbers to the right are colour-coded to indicate the numbers in each classification.

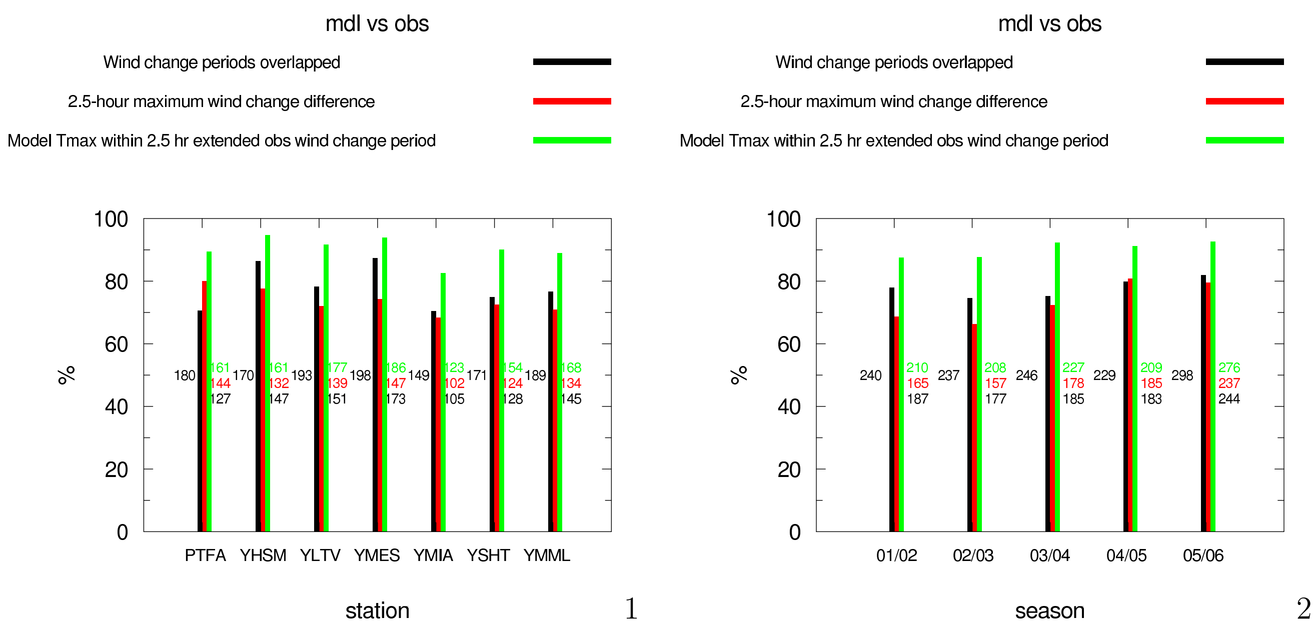


Figure 11: Verification statistics for all matched forecast wind changes in stage 3 of the pressure cycle. Black bars show the proportion of overlapped observation and forecast wind change periods, red bars show the proportion of forecasts within 2.5 hours of the observed time, and the green bars show the proportion of forecast wind change times that fall within the objective wind change period. The numbers to the left of each set of 3 bars show the number of events, and the sets of three numbers to the right show the number of events in each of the three classes with the same colour codes.

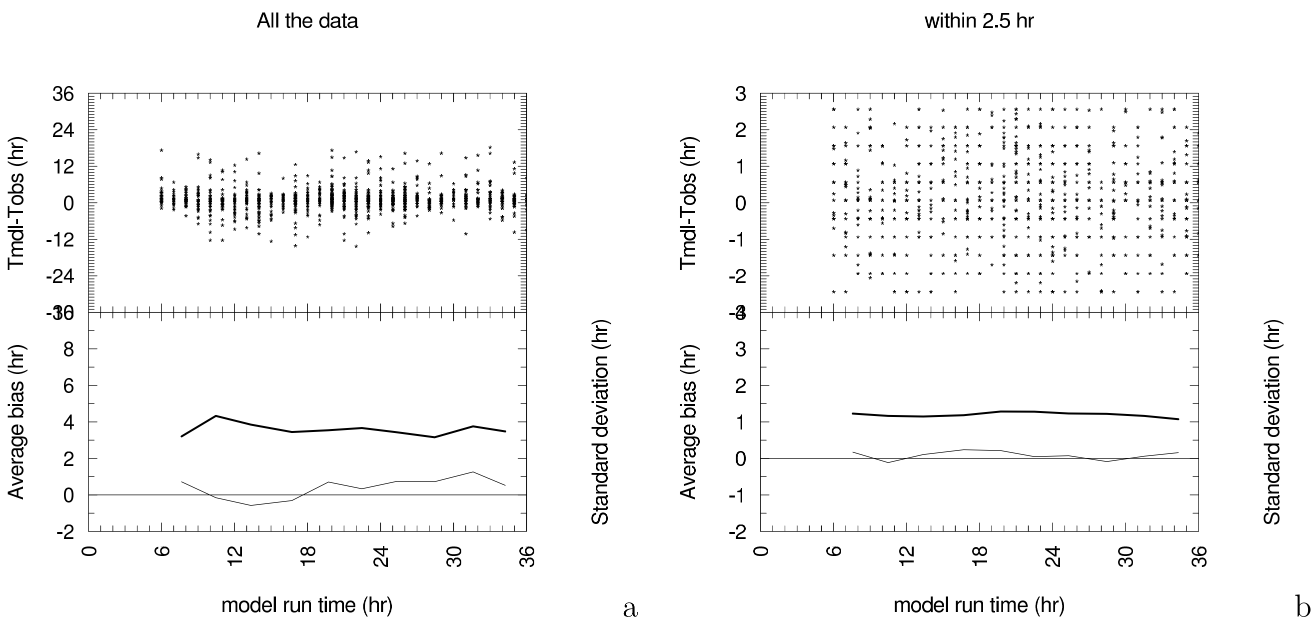


Figure 12: Scatterplot of wind change timing error versus forecast lead time for all matched wind changes occurring in stage 3 pressure cycle phases, with the lower panels showing the smoothed mean and standard deviation of error. In the right hand panel only those forecast with errors less than 2.5 hours are shown.

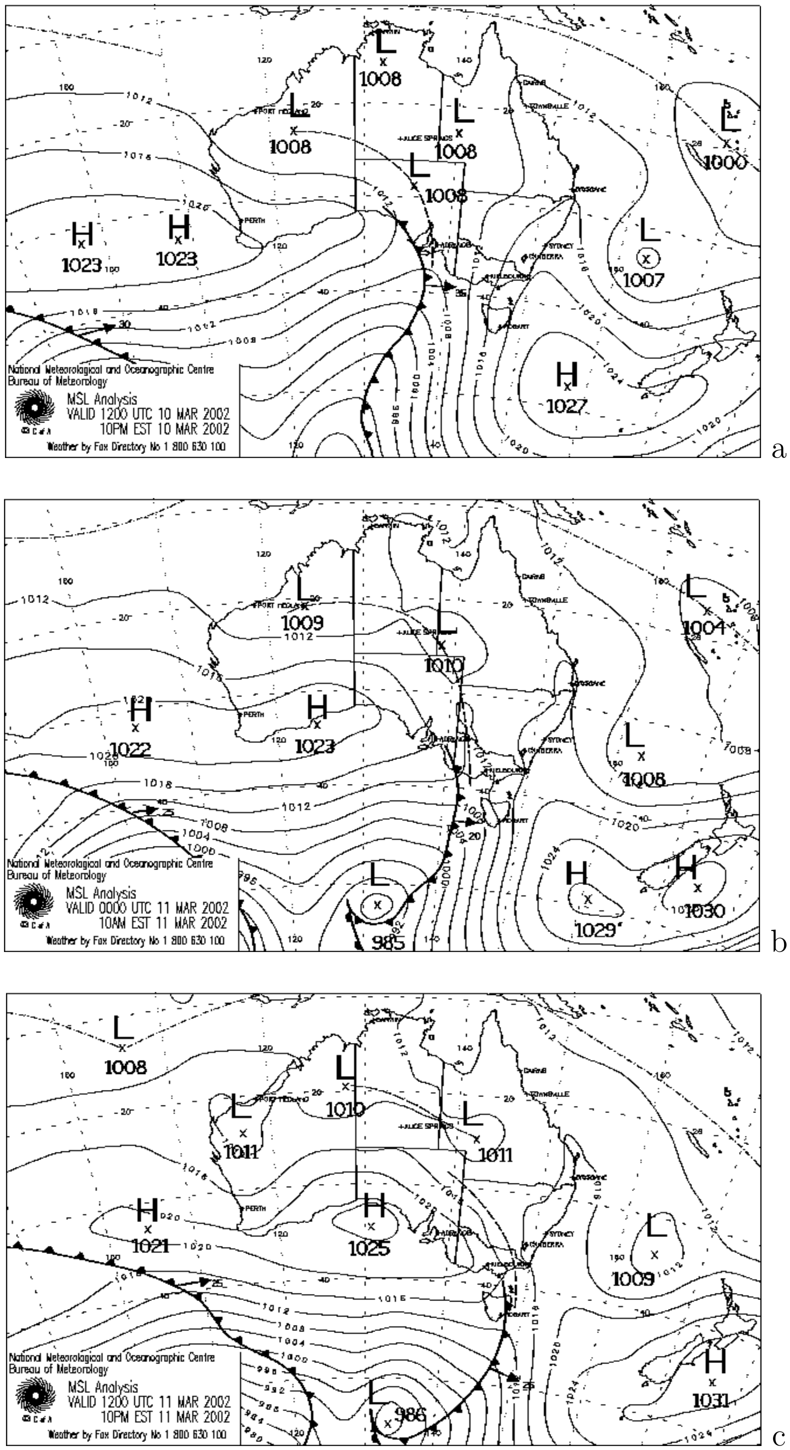


Figure 13: Case 1: mean sea level pressure analyses at 1200 UTC of 10 (a), 0000 UTC of 11 (b) and 1200 UTC of 11 (c) March 2002.

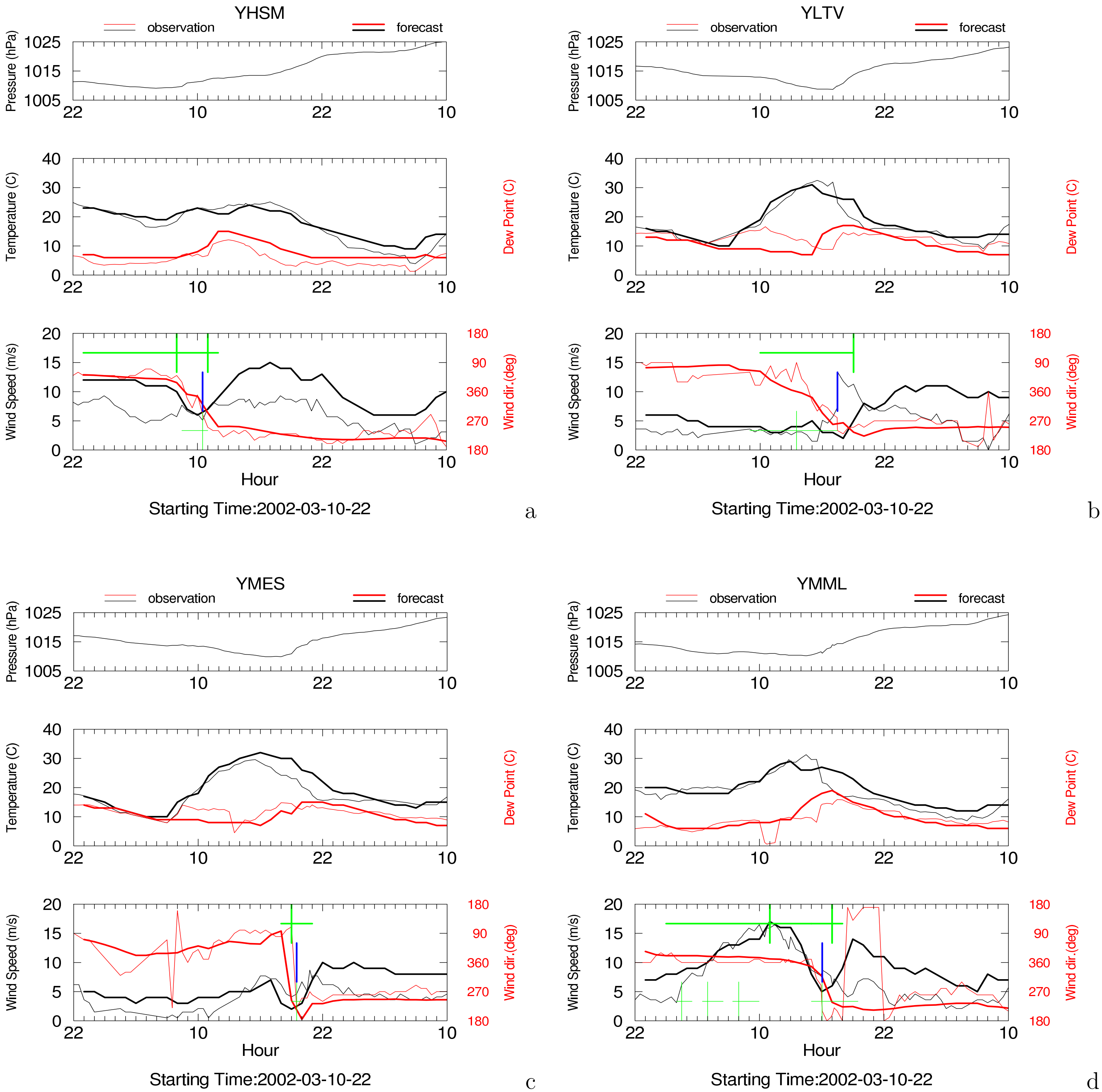
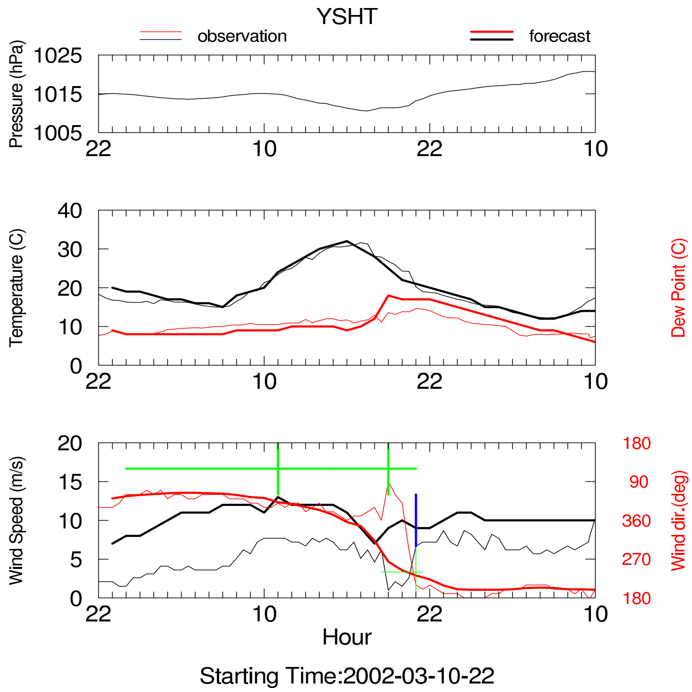
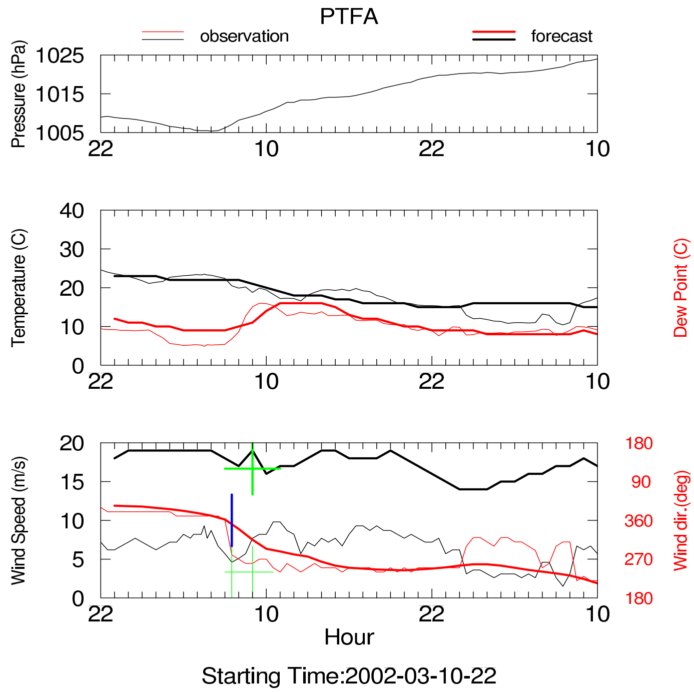


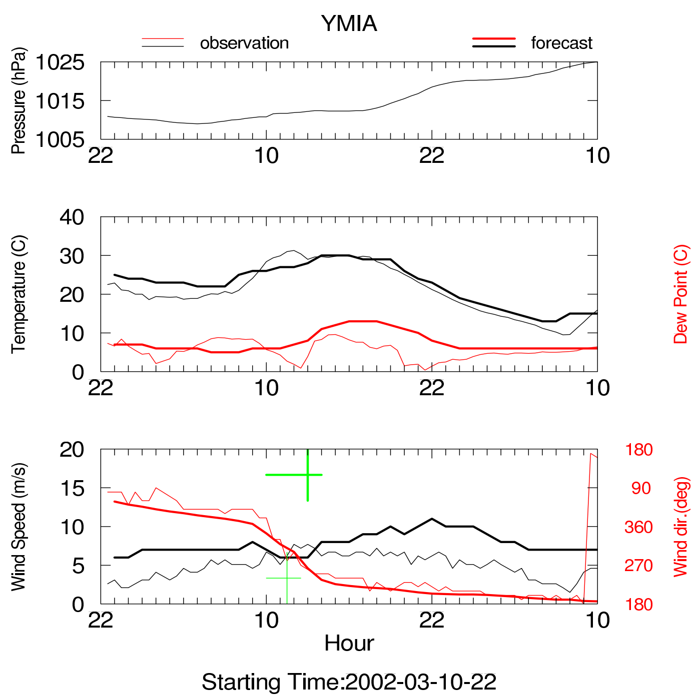
Figure 14: Case 1: time series of meteorological variables at selected surface stations. Vertical bars indicate the wind change identified from the observation (green thin bar), the forecast (green thick bar) and the VRFC (blue bar). The corresponding horizontal bars indicate the time spans of the wind change period for the observation and forecast respectively.



a

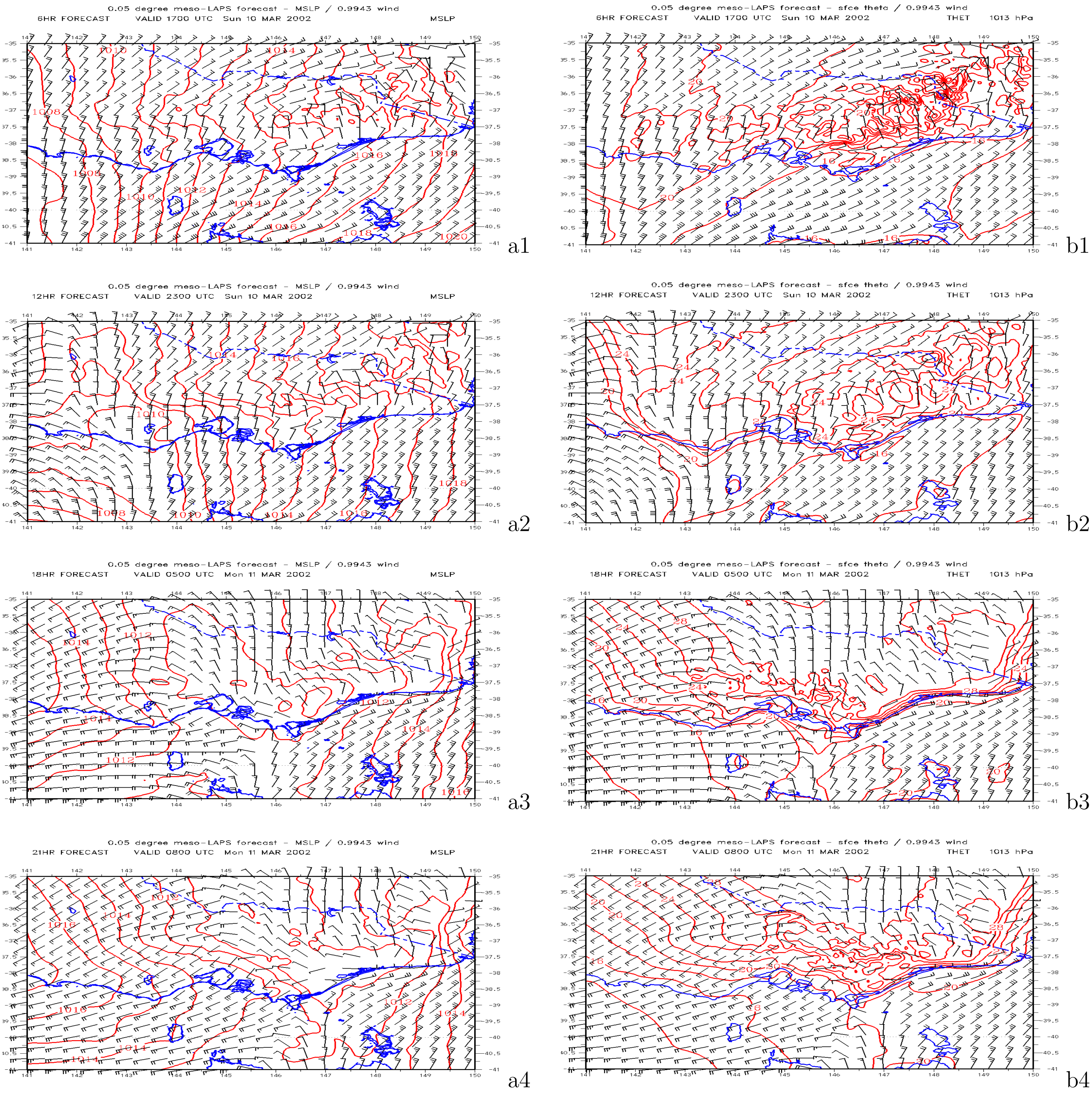


b



c

Figure 15: Case 1: time series of meteorological variables at selected surface stations. Vertical bars indicate the wind change identified from the observation (green thin bar), the model forecast (green thick bar) and the VRFC (blue bar). The corresponding horizontal bars indicate the time spans of the wind change period for the observation and forecast respectively (continued).



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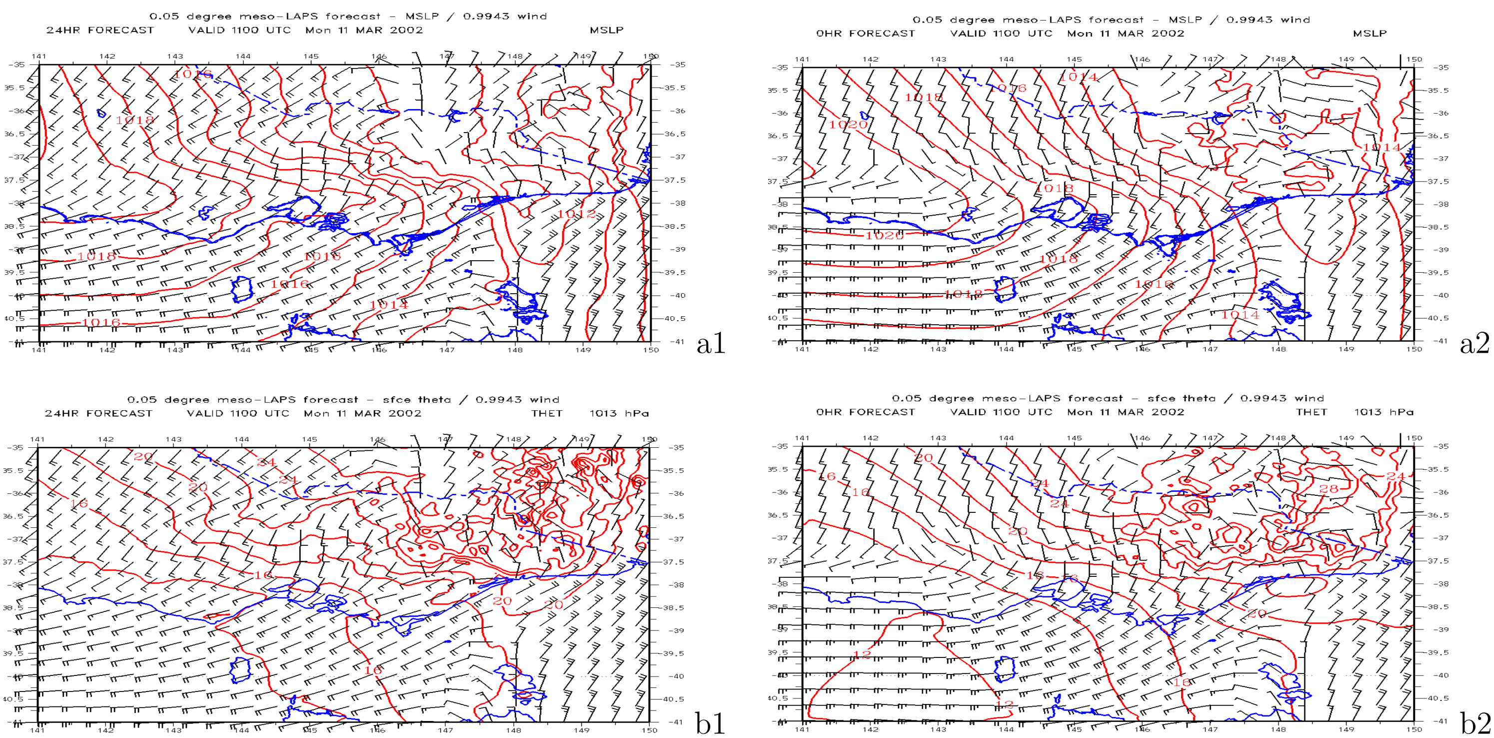

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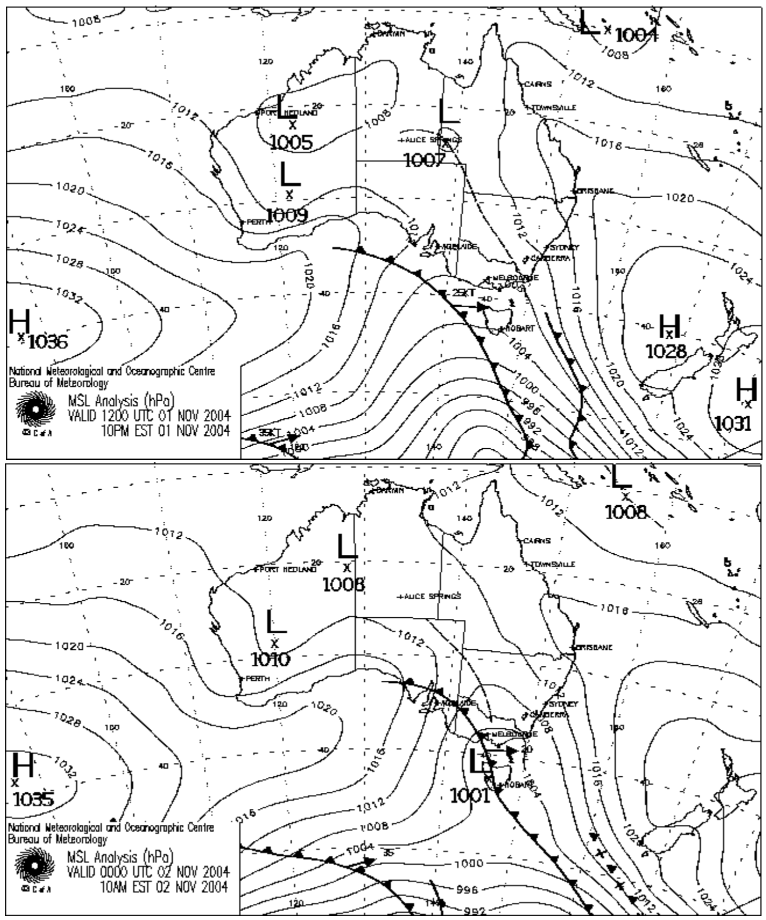


a

b

Figure 18: Case 2: mean sea level pressure analyses at 1200 UTC, 1 NOV (a) and 0000 UTC, 2 Nov, 2004 (b).

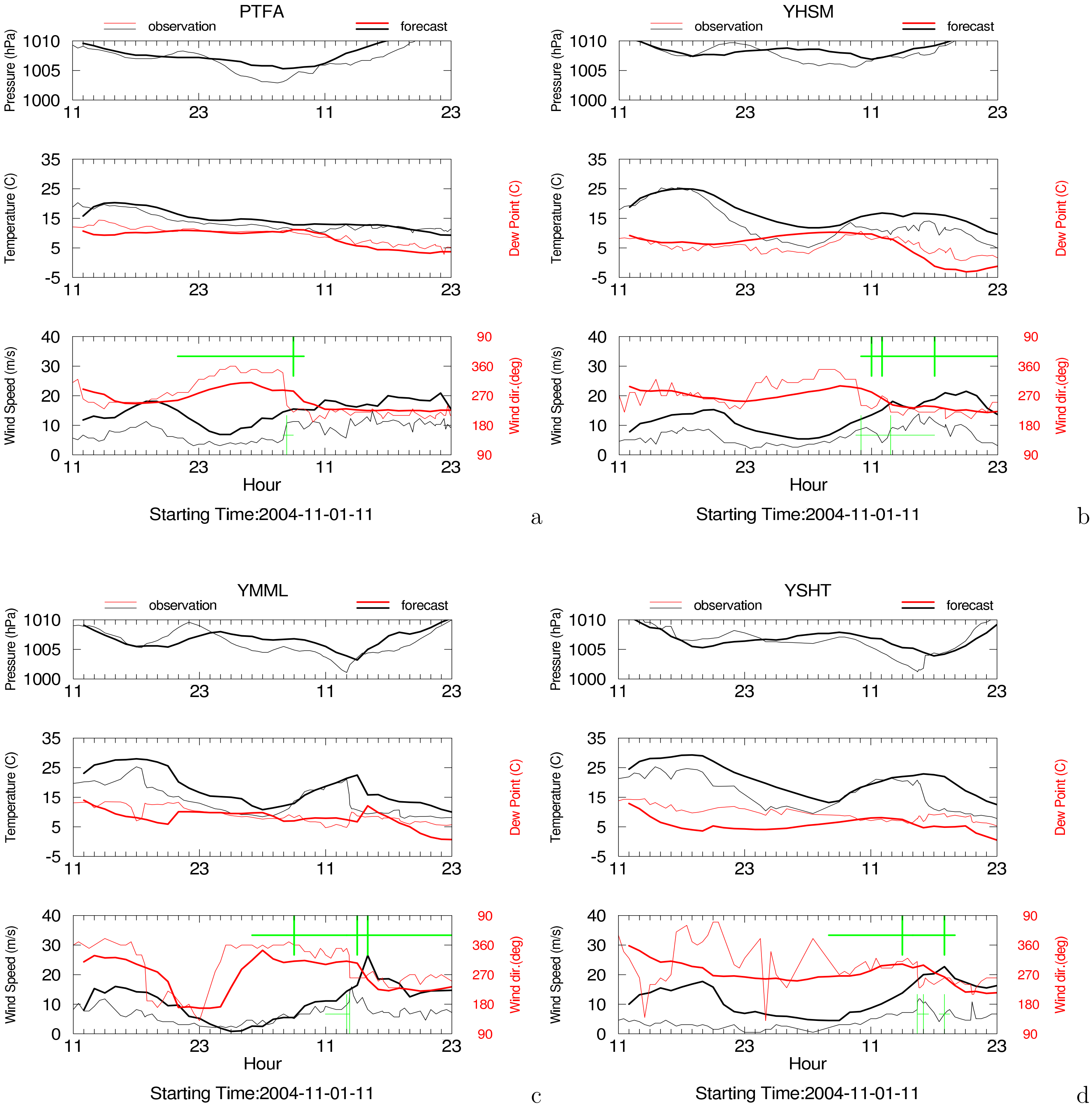


Figure 19: Case 2: time series of meteorological variables at selected surface stations. Vertical bars indicate the wind change identified from the observation (green thin bar), the model forecast (green thick bar) and the VRFC (blue bar). The corresponding horizontal bars indicate the time spans of the wind change period for the observation and forecast respectively.

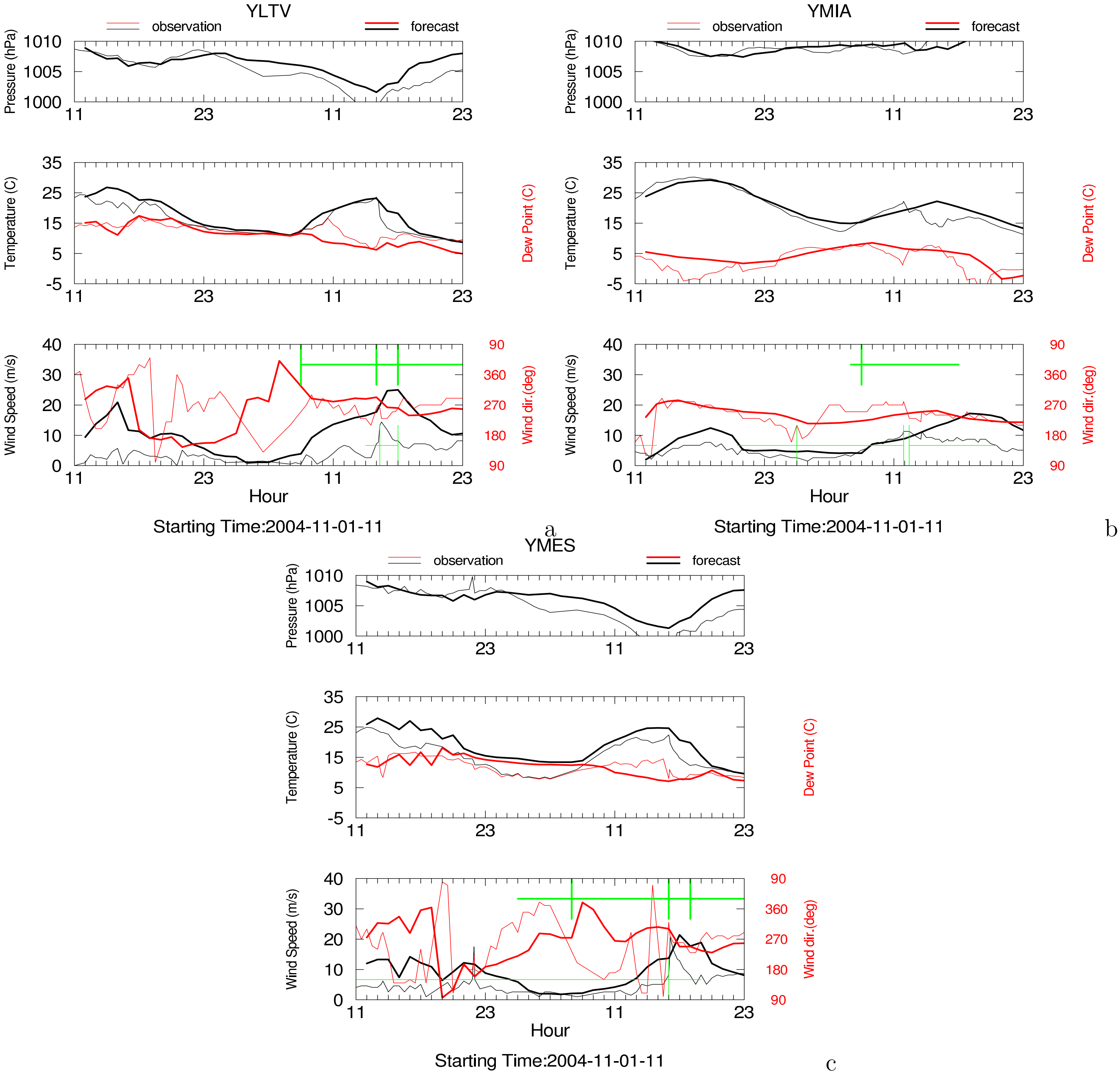


Figure 20: Case 2: time series of meteorological variables at selected surface stations. Vertical bars indicate the wind change identified from the observation (green thin bar), the model forecast (green thick bar) and the VRFC (blue bar). The corresponding horizontal bars indicate the time spans of the wind change period for the observation and forecast respectively (continued).

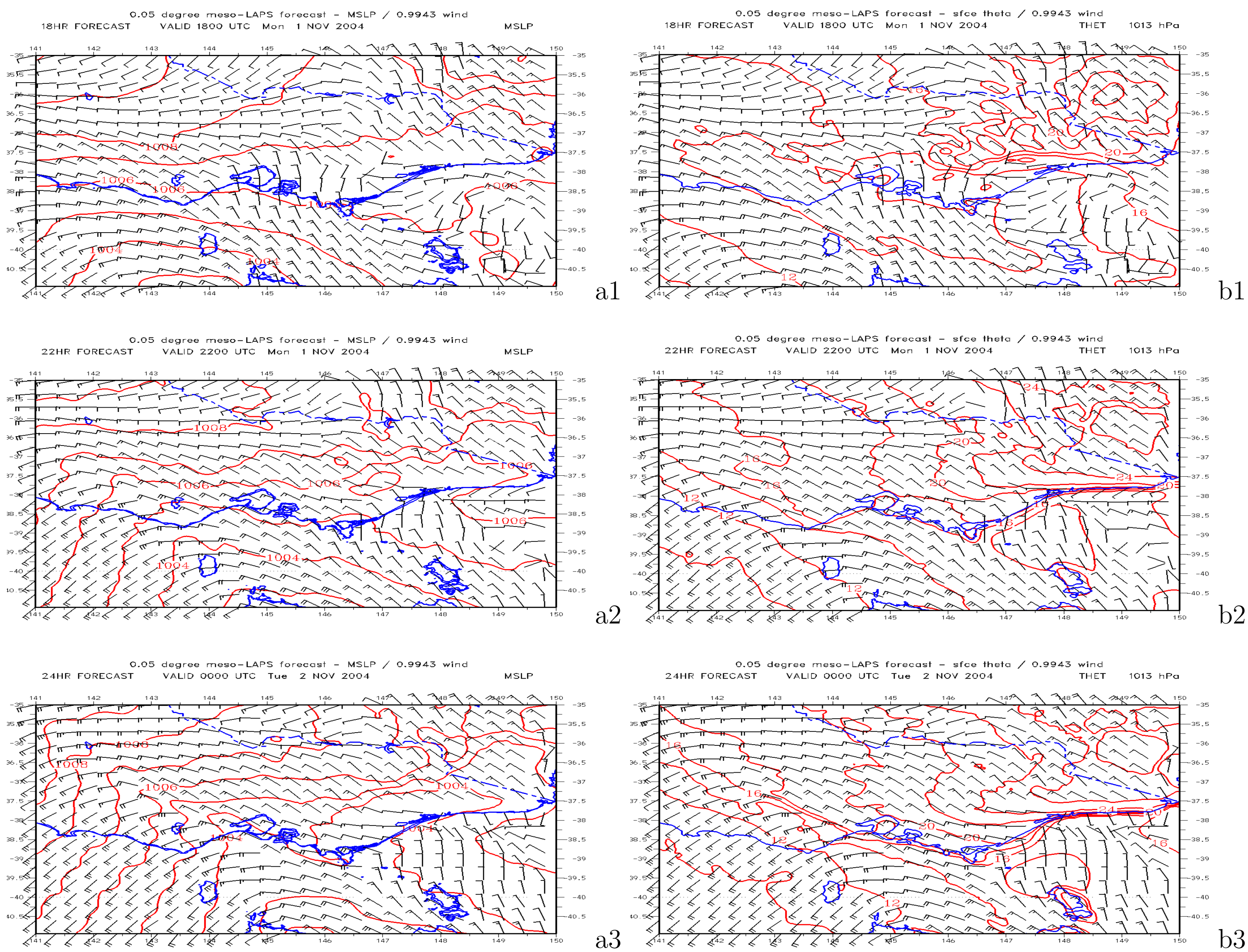
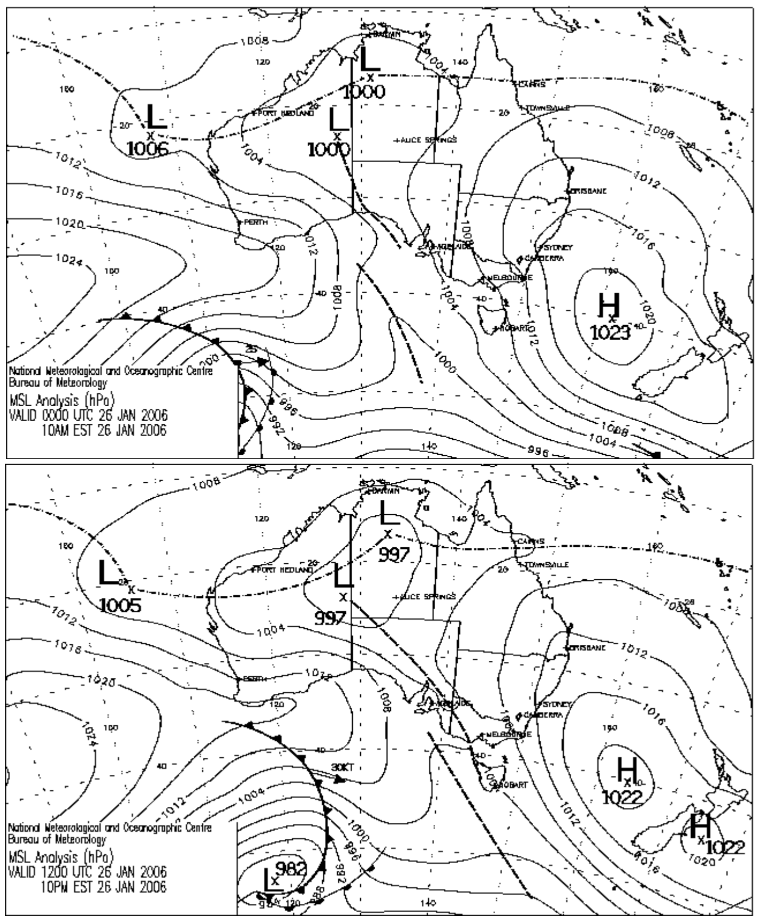


Figure 21: Case 2: The second front passage. a is referred the reduced sea level pressure and b is referred to the near surface potential temperature. The sequences are shown at 1800 UTC (5 AM ADST) 1 Nov 2004 when the trough is off the coast (1), 2200 UTC (9 AM ADST) when the trough first moves to coast (2) and 2400 UTC (11 AM ADST) when the trough is further inland (3).



a

b

Figure 22: Case 3: mean sea level pressure analyses at 0000 UTC (a) and 1200 UTC (b) 26 Jan, 2006.

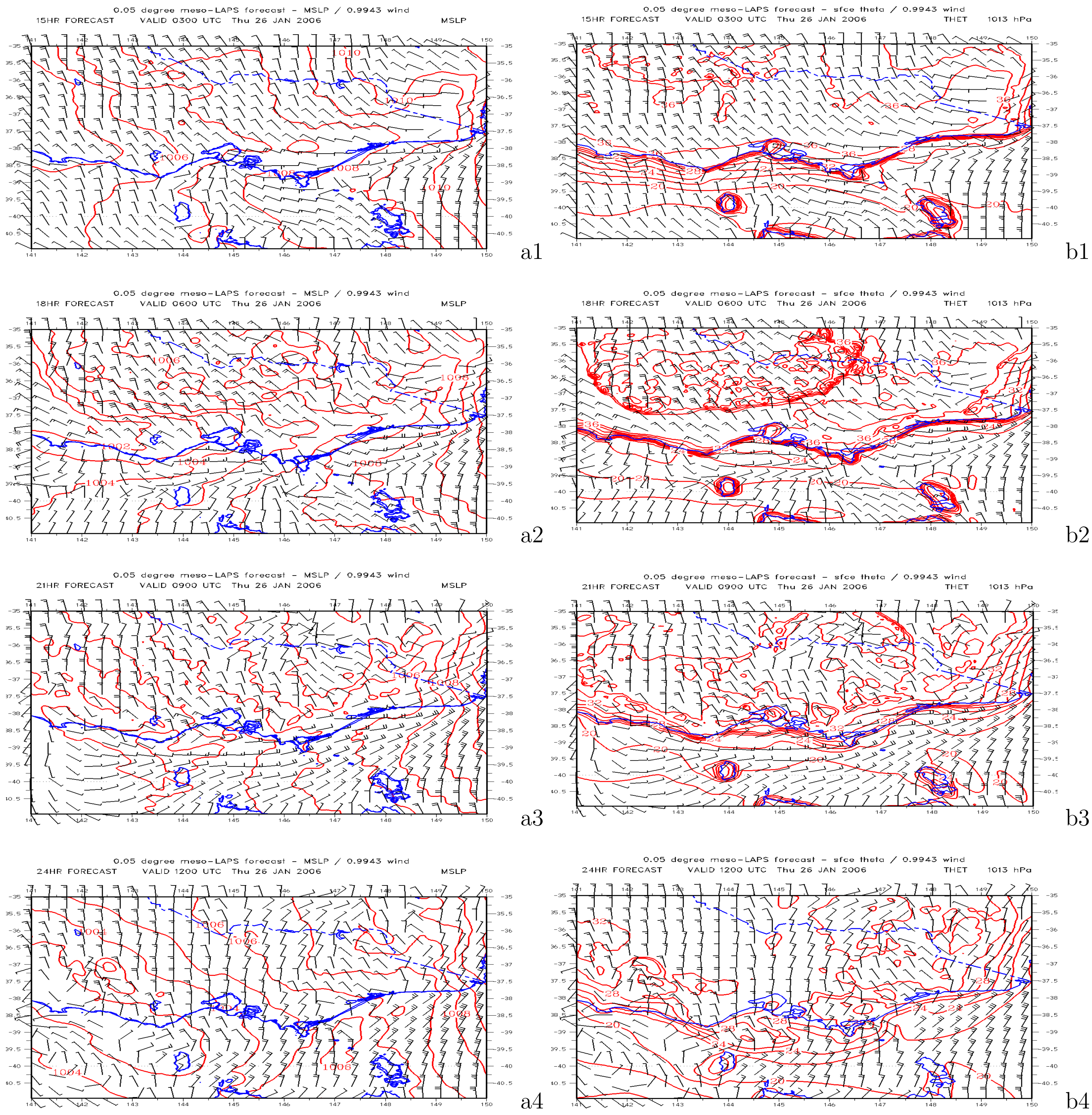


Figure 23: Case 3: a is referred the reduced sea level pressure and b is referred to the near surface potential temperature. The sequences are shown at 1800 UTC (5 AM ADST) 1 Nov 2004 when the trough is off the coast (1), 2200 UTC (9 AM ADST) when the trough first moves to coast (2) and 2400 UTC (11 AM ADST) when the trough is further inland (3).

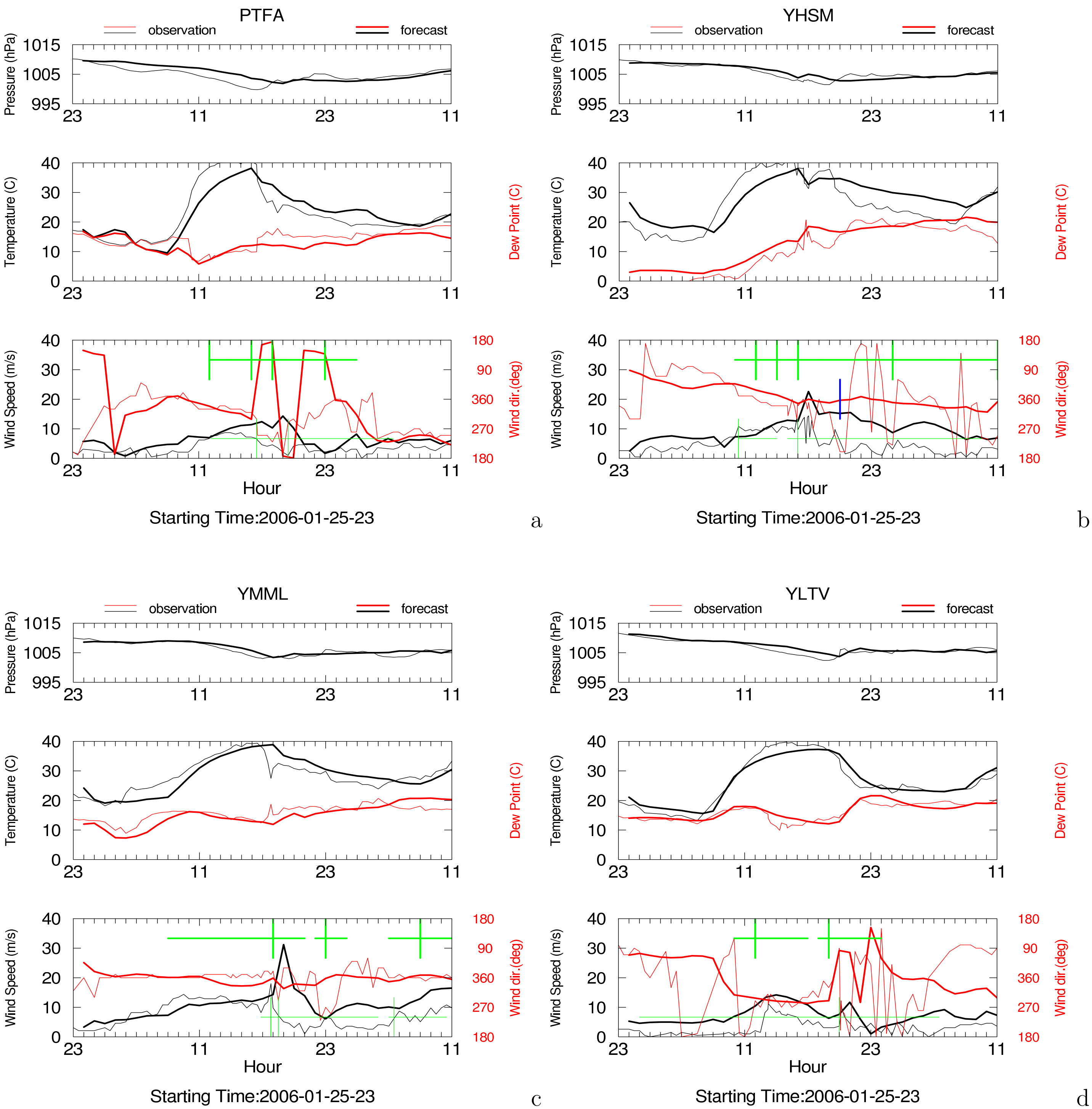
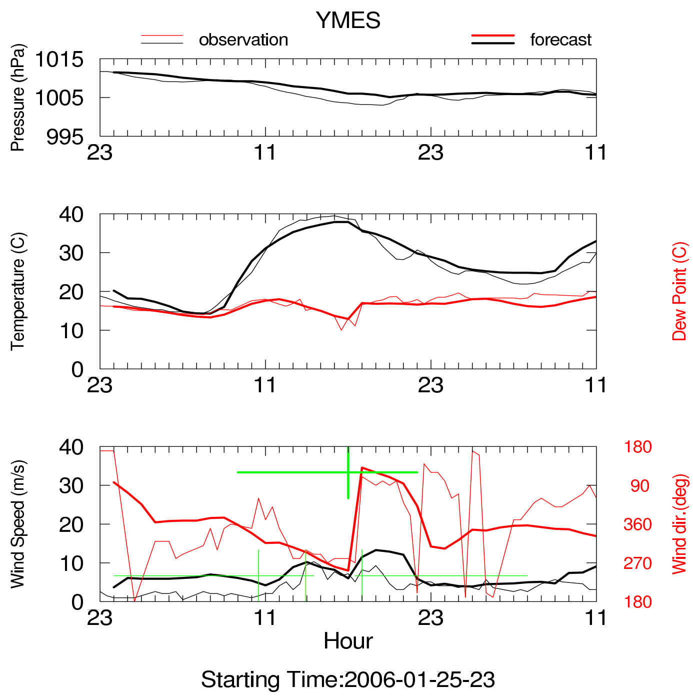
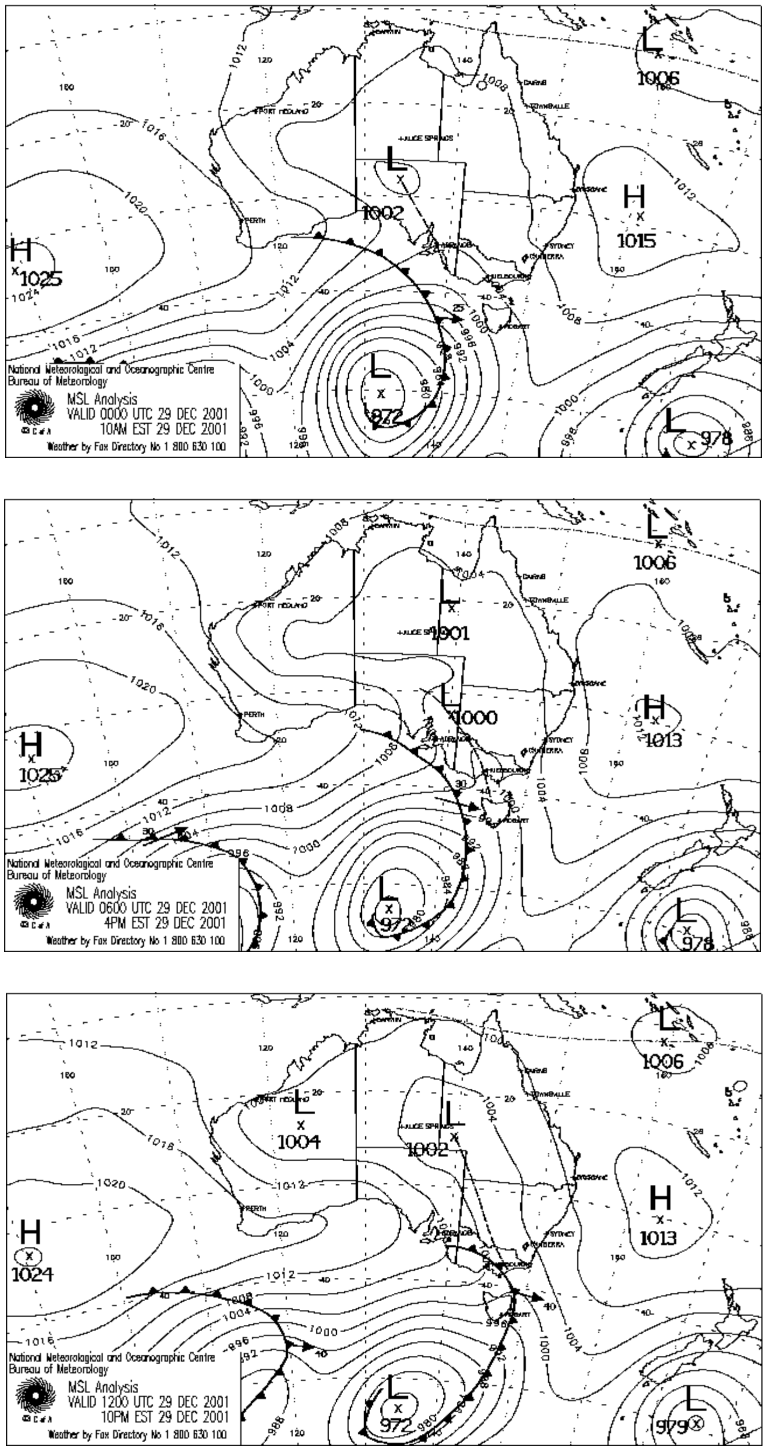


Figure 24: Case 3: time series of meteorological variables at selected surface stations. Vertical bars indicate the wind change identified from the observation (green thin bar), the model forecast (green thick bar) and the VRFC (blue bar). The corresponding horizontal bars indicate the time spans of the wind change period for the observation and forecast respectively.



a

Figure 25: Case 3: time series of meteorological variables at selected surface stations. Vertical bars indicate the wind change identified from the observation (green thin bar), the model forecast (green thick bar) and the VRFC (blue bar). The corresponding horizontal bars indicate the time spans of the wind change period for the observation and forecast respectively (continued).



a

b

c

Figure 26: Case 4: mean sea level pressure analyses at 0000 UTC (a), 0600 UTC (b) and 1200 UTC (c) on 29 Dec, 2001.

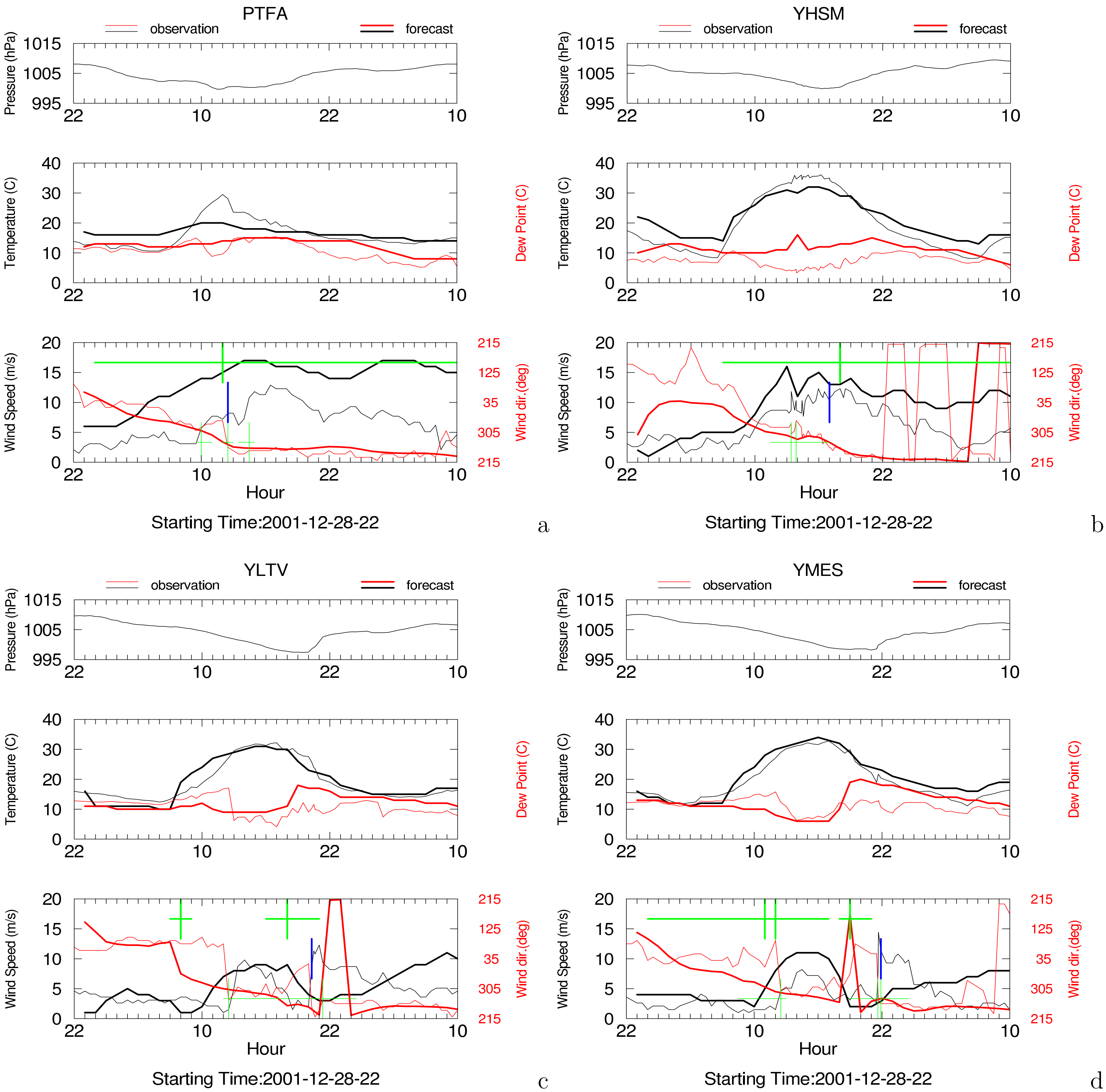


Figure 27: Case 4: time series of meteorological variables. Vertical bars indicate the wind change identified from the observation (green thin bar), the model forecast (green thick bar) and the VRFC (blue bar). The corresponding horizontal bars indicate the time spans of the wind change period for the observation and forecast respectively.

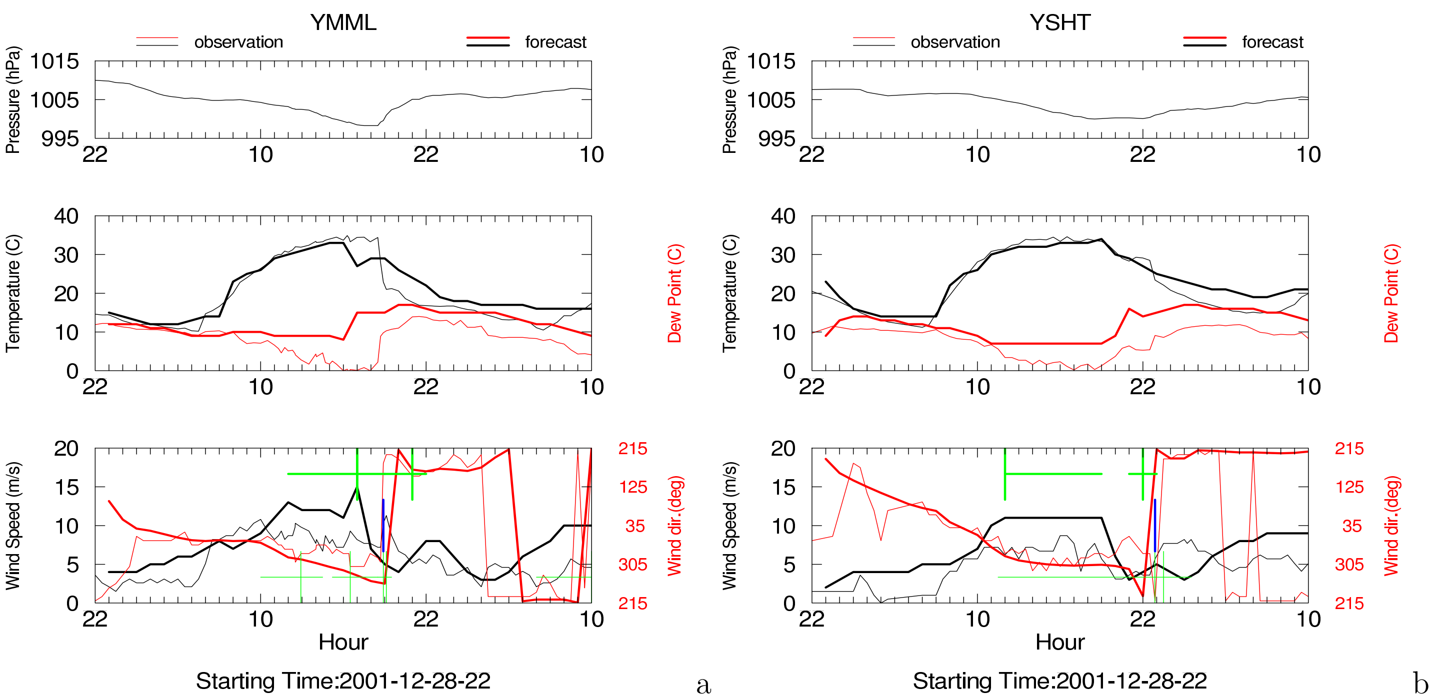


Figure 28: Case 4: time series of meteorological variables. Vertical bars indicate the wind change identified from the observation (green thin bar), the model forecast (green thick bar) and the VRFC (blue bar). The corresponding horizontal bars indicate the time spans of the wind change period for the observation and forecast respectively (continued).

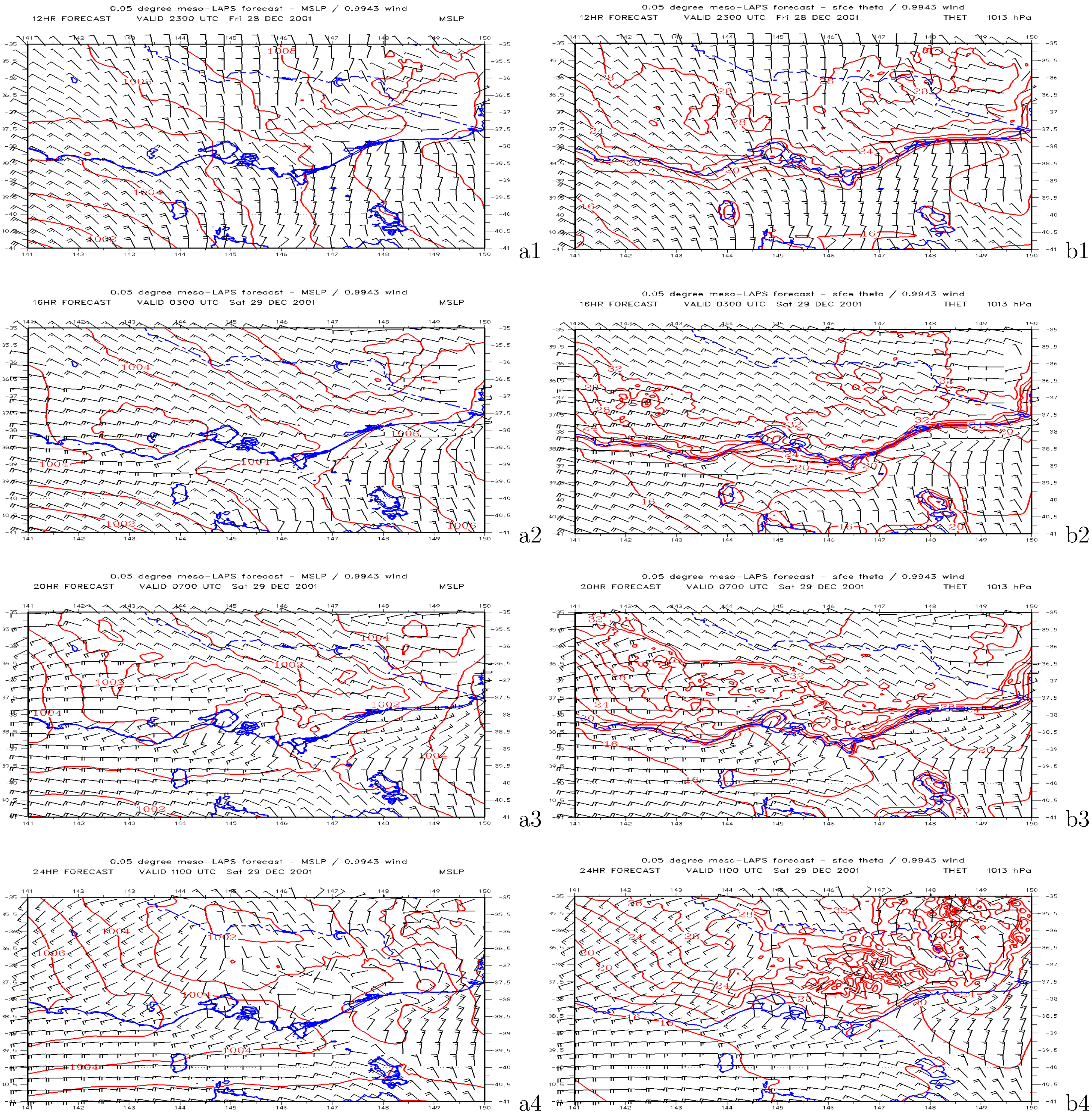


Figure 29: Case 4: The forecasts of reduced sea surface pressure (a) and near surface potential temperature (b) at 12 (1), 16 (2), 20 (3) and 24 (4) forecasting hours, respectively

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