A climatology of atmospheric pressure jumps over southeastern Australia

Laura Davies[a*] , Michael J. Reeder[b] and Todd P. Lane[a]

[a]*School of Earth Sciences, The University of Melbourne, Melbourne, Australia.*

[b]*School of Earth, Atmosphere and Environment and ARC Centre of Excellence for Climate System Science, Monash University, Melbourne, Australia.*

*Correspondence to: School of Earth, Atmosphere and Environment, Monash University, Melbourne, Australia. E-mail: michael.reeder@monash.edu

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Black Saturday provided the first evidence of an atmospheric bore affecting the behaviour of a bushfire. As the bore passed, the fire unexpectedly strengthened. This behaviour highlighted the lack of understanding of how common bores are in the southeastern part of Australia, a region of relatively high bushfire risk. The present study addresses that lack of understanding. Pressure jumps are identified in the one-minute records at four automatic weather stations in southeastern Australia by correlating the pressure time series with a large-amplitude step function. These jumps are then separated in two classes: bores and frontal pressure jumps. Bores are defined as pressure jumps without a change in relative humidity whereas frontal pressure jumps are defined by jumps with an accompanying decrease in temperature greater than 3 ^oC. About 15 pressure jumps per station per year are found. Most jumps are found in the spring and summer and fewest in winter. Bores are found most frequently in the early morning and late evening at most stations, whereas frontal pressure jumps are most frequently found in the late afternoon or early evening. Following their passage, frontal pressure jumps are associated with higher 30-min mean wind speeds than bores (9.0 m s^{-1} and 6.1 m s^{-1} respectively), both of which are higher than climatology (4.7 m s^{-1}). Copyright © 0000 Royal Meteorological Society

Key Words: bore; bushfire; front; pressure jump; wind variability

1. Introduction

On 7 February 2009, Black Saturday, many large wildfires (known locally as bushfires) occurred in southern Australia. Strong winds and rapid and large changes in wind direction intensified fire complexes and modified their behaviour, causing dangerous conditions and immense problems for emergency services.

A study of the meteorology on Black Saturday identified two bore-like features (Engel *et al.* 2013). The first bore was identified ahead of a cool change (the local name for a strong summertime cold front) in the early hours of the morning. Consistent with theory, the bore was identified by a sudden jump in pressure, a change in wind direction and an increase in wind speed and wind speed variability. A second bore, in the early evening, was identified as the leading edge of the cool change when it propagated further inland. Shortly after the passage of the bore, radar imagery showed an invigoration of a smoke plume associated with a fire complex in the area.

Atmospheric bores are propagating disturbances, characterised by a sudden and sustained increase in pressure. An undular bore is a bore for which the pressure jump is followed by a series of waves propagating downstream relative to the jump. Bores are generally accompanied also by an increase in wind speed and wind speed variability, and often by a change in wind direction (for example see Smith and Reeder (2014)). Unlike other mesoscale disturbances such sea breezes, cold fronts or thunderstorm gust fronts, idealised bores are not associated with changes in temperature and humidity. In practice, however, this need not be true; see for example Menhofer *et al.* (1997). The bores identified in Engel *et al.* (2013) showed small changes in temperature at the time of the bore. Thus, in practice, some bores have some of the characteristics of cold fronts.

Although Australia has a relatively long history of research on bores in the atmosphere, most of this research has been focused on northern and central Australia, and especially on those found in the Gulf of Carpentaria region. The cloud lines associated with bores in this region are known as *morning glories*. (For details see the reviews by Smith (1988), Reeder and Smith (1998), and Smith and Reeder (2014) and the references therein.) One study of particular relevance is that by Nudelman *et al.* (2010), who, using one year of surface observations, constructed a climatology of pressure jumps in the Gulf of Carpentaria region. Among other things, they found that the pressure jumps were most common in the early hours of the morning during the summer months.

Cloud structures similar to morning glories have been identified elsewhere around Australia, such as off the northwestern coastline of Australia (Birch and Reeder 2013) and over the Great Australian Bight (Schmidt and Goler 2010). Using satellite imagery, Birch and Reeder (2013) found that morning-glory-like cloud lines occur off northwestern Australia at least 2 to 3 times per month throughout the entire year. Likewise in a 4-year climatology, Schmidt and Goler (2010) found 14 morning-glory-like cloud lines over the Great Australian Bight, all of which occurred in summer. Moreover, numerical simulations of some of the cases reported by Schmidt and Goler (2010) and Birch and Reeder (2013) showed that the cloud lines were consistent with bores propagating on the marine inversion. In addition, Watson and Lane (2016) identified an undular bore propagating on a nocturnal inverson and showed using observations and numerical simulations that this bore helped initiate a mesoscale convective system upstream of the Australian Alps.

Cold fronts and bores are sometimes closely linked. When a cold front moves into a surface-based stable layer such as that sometimes found over the ocean (e.g. Schmidt and Goler (2010)) or at night over a radiatively cooled surface like central Australia (e.g. Smith *et al.* (1995), Deslandes *et al.* (1999), Thomsen *et al.* (2009) and Reeder *et al.* (2000)), the front commonly generates a bore. Depending on the relative speeds of the front and bore, the bore can separate from the front and propagate ahead as a distinct entity or it may remain bound to the front, modifying the frontal structure. For further discussion about the relationship between fronts and bores see Smith and Reeder (2014).

Black Saturday provided the first evidence of the effect of an atmospheric bore on the behaviour and spread of a bushfire. As is common, the bore was generated by a cold front moving into a surface-based stable layer. The Black Saturday bore underscored the practical importance of accurately forecasting small scale, localised wind changes, and pointed also to a lack of understanding of how common bores are in the south of the continent in regions of relatively high bushfire risk. This lack of understanding is particularly acute as localised wind changes, such as those produced by the passage of a bore, play a fundamental roles in determining the behaviour and spread of both controlled and uncontrolled fires. Moreover, bores are likely to propagate overland preferentially in the evening or overnight after the daytime turbulence has waned and a nocturnal inversion formed, which is of course, when fires, both controlled and uncontrolled are *expected* to become less active. Controlled fires are used extensively by farmers, foresters, park managers, and other land managers to reduce the fuel load and lower the risk of uncontrolled fires (bushfires). Presumably, controlled fires may behave unexpectedly with the passage of a bore. As controlled fires are ignited in the cooler parts of the year, outside of the bushfire season, a year-round climatology of bores would be useful. For these reasons the present study investigates the frequency of strong pressure jumps, which include bores, in southeastern Australia and determines the variability of the wind associated with the passage of these pressure jumps.

This paper is structured as follows. Section 2 introduces the observational data used and the method used to identify large-amplitude pressure jumps. These pressure jumps are divided into two classes, idealised bores and frontal pressure jumps, depending on whether or not temperature and moisture changes accompany the pressure jumps. In Section 3, a climatology of bores and frontal pressure jumps at selected locations over southeastern Australia is presented and a discussion of the associated wind variability given. The summary and conclusions can be found in Section 4.

2. Data and method

2.1. Data

High frequency, quality controlled Bureau of Meteorology automatic weather station (AWS) data from stations in the west of southern Australia are analysed here. The data have a frequency of 1 min and the pressure has a precision of 0.1 hPa. The stations are chosen to capture pressure jumps that propagate onshore from the Great Australian Bight. The stations on Kangaroo Island, which is well located for the objectives of the present study, only have a few years of data and are therefore not included. Only stations with over 10 years of data are used for the climatology. Figure 1 shows the location of the stations used. North to south on the eastern side of the Great Australian Bight the stations are: Ceduna, Adelaide (Kent Town) and Mount Gambia. Further inland Yarrawonga station is also used. Note that the early evening bore which modified a bushfire complex on Black Saturday was identified by the Yarrawonga weather radar and AWS data.

2.2. Method

The study by Nudelman *et al.* (2010) simply identified bores in the Gulf region of northern Australia as pressure jumps greater than 0.3 hPa within 3 min, and that method worked well for their study. The mid-latitude data used here, however, are noisier and have greater temporal variation due to the passage of weather systems. Consequently, the method used by Nudelman *et al.* (2010) was less successful in reliably identifying bores in the AWS data for southeastern Australia. Instead, the method used here is based on the shape recognition method of Belušić and Mahrt (2012). A full description of the method is given in Belušić and Mahrt (2012) and only briefly outlined here.

Belušić and Mahrt (2012) identify key, recurring shapes in meteorological data by correlating the basic shape with

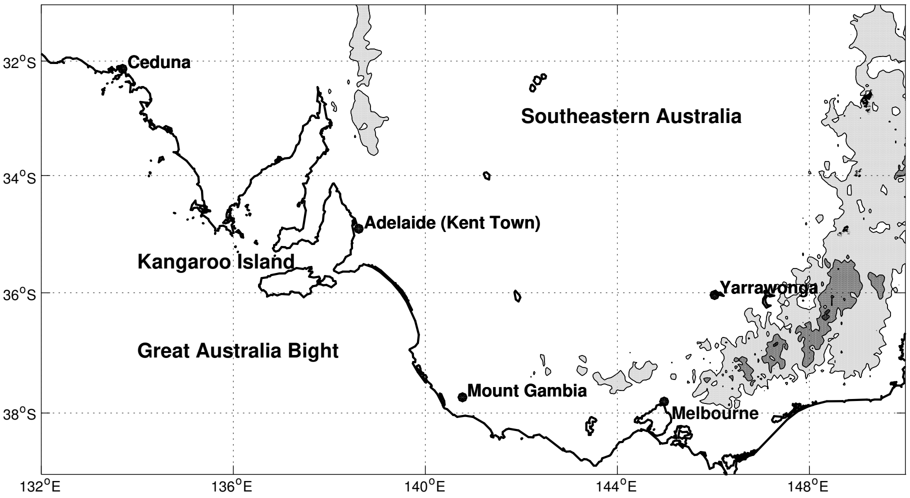

Figure 1. Location of observations in southeastern Australia. Topography contoured at 500 m, 1000 m and 1500 m.

the time series on a range of scales. Their method of identifying upward step features lends itself to extracting pressure jumps. Here the pressure time series is correlated with a step function 60 min long. The step is constant for 30 min before instantaneously increasing to a higher constant value for a further 30 min. Compared to just extracting instantaneous pressure jumps, the method separates sustained pressure rises, which may be the hallmarks of bores and cold fronts, from the isolated jumps that are found in noisy time series. First, the step function is correlated with the pressure time series at every point in time to create a time series of correlations. Second, the time at which the strongest correlation occurs is catalogued and retained and that 60 min period removed from the correlation time series to avoid an overlap of events. Third, the time with the next strongest correlation is chosen. This continues until all correlations greater than 0.92 are chosen and catalogued. Although this correlation threshold is slightly larger than that used by Belušić and Mahrt (2012), it was found that reducing the threshold resulted in structures that, on detailed investigation, were not bore-like. Similar to Belušić and Mahrt (2012) a steepness threshold is also applied. It is required that "the difference of medians of four data points before and after the shape centre is greater than" 45% "of the maximum absolute difference between any two points in the shape of the theoretical step function". (Note that Belušić and Mahrt (2012) used 40%.) We also insist that the pressure jump is of large amplitude; this requirement is enforced by only retaining pressure increases of at least 1 hPa in the 60 min period.

Two different classes of pressure jumps are identified here: idealised bores and cold fronts. These two classes are defined by the thermodynamics changes accompanying the pressure jump. Pressures jumps are defined as *bores* where the mean relative humidity before the jump is less than 5% different from the mean relative humidity after the jump. Similarly, a pressure jump is defined as a *frontal pressure jump* if the temperature falls by more than 3 ^oC when comparing the mean before the jump to the mean after the jump. Here the before and after conditions are calculated as follows. A 10 min gap centred on the jump is left to distinguish the before and after conditions. Then, the meteorological variables of interest are averaged for the preceding 30 min or the succeeding 30 min.

Whether or not frontal pressure jumps are actually sea breeze fronts was checked by manually inspecting the mean sea level charts (analysed by the Australian Bureau of Meteorology) for all the frontal pressure jumps identified. Only 9 out of the 134 frontal pressure jumps identified could plausibly called sea breeze fronts, and even these 9 might be better called heat troughs. More specially, of the 45 cold fronts identified at Adelaide, none were sea breezes; of the 39 at Ceduna, 4 may have been sea breezes; at Mt Gambia 23 fronts were identified, 2 of which may have been sea breezes; and of the 27 identified at Yarrawonga, 3 may have been sea breezes. Note, however, that not all the frontal pressure jumps were classical cold fronts. Many, especially in the warmer months, were prefrontal troughs (for a discussion of prefrontal troughs see Reeder and Smith (1998)).

3. Results

3.1. *Climatology of pressure jumps*

The method described above identifies approximately 15 pressure jumps per year per station, though there are only eight pressure jumps per year at Yarrawonga. Figure 2 shows the annual and diurnal cycles of the occurrence of these pressure jumps at four stations in southeastern Australia. Most pressure jumps are identified during the spring and summer months and fewest during the autumn. Pressure jumps are also most frequent overnight and are least common around midday at all stations. This result, which is consistent with the findings of Nudelman *et al.* (2010), presumably reflects the propensity for surface-based stable layers to be stronger at night. There are differences in the exact timing of the events between the stations. Although Adelaide and Ceduna show a stronger annual cycle, Mount Gambia and Yarrawonga, which lie inland of the coast, have a weaker annual cycle. There are also slight differences in the diurnal cycle between the stations. Ceduna shows a peak in pressure jumps in the morning whereas at Yarrawonga the number of jumps is largest in the evening.

3.1.1. *Sensitivity to the choice of method parameters*

Weakening the correlation threshold results in pressure jumps being identified that are less clearly step like. For example, jumps that had a more gradual increase in pressure or did not sustain that increase sufficiently are identified. The requirements for the maximum pressure difference across the jump to be greater or equal to 1 hPa and that the jump should be sharp, are both important in defining the pressure jumps. For example, visual inspection showed that pressure jumps that were clearly a bore or a front had pressure increases of at least 1 hPa in the 60 min time window. In fact, for many pressure jumps, the pressure rises much more suddenly (Section 3.2).

3.2. *Examples of bores and fronts*

A variety of meteorological phenomena are identified as the method looks simply for strong, sustained pressure jumps. Some of these events are clearly atmospheric bores (Figure 3) whereas others are more likely to be cold fronts, thunderstorm outflows or gravity currents (Figure 4). The thresholds described in Section 2.2 are used to separate these events in order to calculate their mean characteristics. A climatology of these events is given in Section 3.3. Here we discuss the typical characteristics of bores and frontal pressure jumps.

Figure 3 shows the time series of some meteorological quantities associated with a bore identified around 0600 LST 8 December 2011. This particular bore shares many characteristics with other bores identified in the dataset. After several hours of reasonably constant pressure, the pressure increases nearly 2 hPa in 3 min and thereafter remains high. The jump itself is followed by pressure fluctuations, giving the bore its undular character. Consistent with bore theory, there is little change in temperature, dew point temperature or wet-bulb temperature and, correspondingly, the relative humidity only slightly decreases by less than 5%. In general, the bores identified here show a small change in temperature related variables at the time of the bore. Considering the whole data set of bores, the mean change in temperature is -0.1 ^oC and the change in dew point temperature is 0.1 ^oC. Therefore, most of these bores differ from the early morning bore found in Engel *et al.* (2013), where that

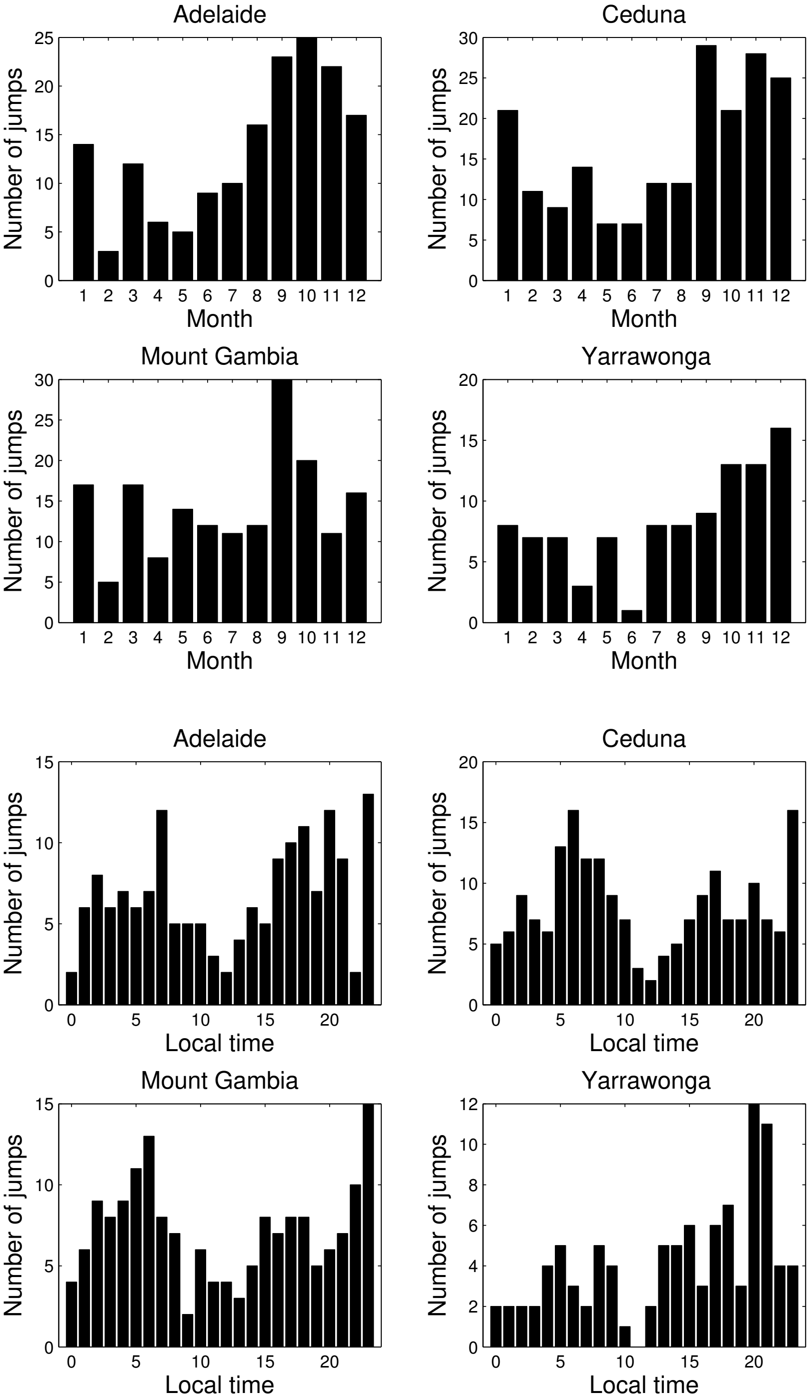

Figure 2. (a) Annual and (b) diurnal cycle of pressure jumps per month/hour at four stations in southeastern Australia.

bore was marked by a slight temporary *increase* in surface temperature. Temperature rises are due presumably to the downward mixing of potentially warmer air from above the surface inversion (Smith *et al.* 1995). Temperature falls can occur when cold air is advected with the bore; this is of course a departure from the behaviour of an idealised bore. Such a situation is possible when the speed of the wave that propagates on the surface inversion is less than the speed of the gravity current or front that generates the wave; for example see Haase and Smith (1989).

The wind speed and direction associated with this bore (Figure 3) is similar to the other bores identified at Ceduna. In this example bore, the wind speed more than doubles at the time of the pressure jump and the wind variability

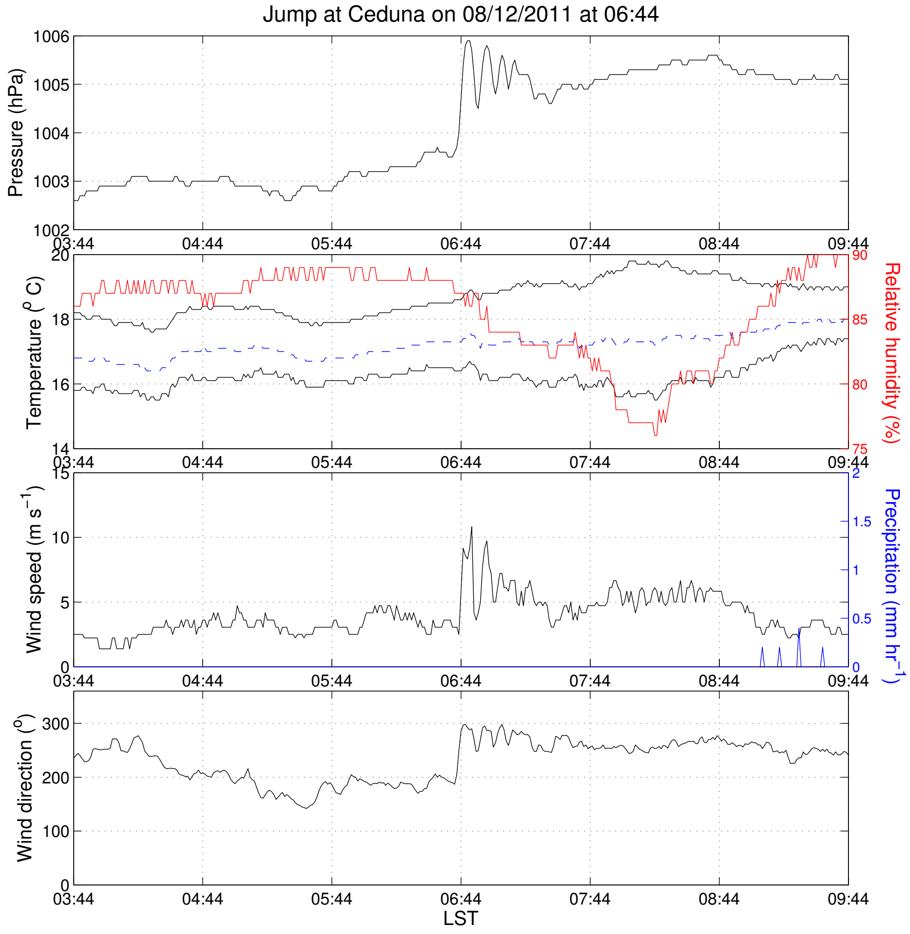

Figure 3. Time series of pressure, temperature, wet-bulb temperature, dew-point temperature, relative humidity, precipitation, wind speed and wind direction for an undular bore at Ceduna. In the second panel temperature and dew-point are the upper and lower solid black lines, respectively, and wet-bulb temperature is the dashed line.

increases also. Wind speed variability is defined as the standard deviation of wind speed over the 30 min period after the passage of the bore. The mean change in wind speed when averaged across all the bores is 0.1 m s^{-1}, while the mean wind speed variability after the bore is 1.1 m s^{-1}. This is the same time period as the mean wind speed is calculated and is described in Section 2.2. Although a wind speed increase accompanies the bore, perhaps the more significant effect in connection with fires is the increase in the variability of the wind. After the jump, the wind speed remains higher than before the passage of the bore in the example. At the time of the jump, the wind direction veers from south to west.

Figure 4 shows a pressure jump with many of the characteristics of a sharp cold front or gravity current, (e.g. a thunderstorm outflow). We refer to this class of pressure jump as a frontal pressure jump. Like the bore shown in Figure 3, the pressure rises sharply (more than 1 hPa in 3 min) and remains elevated, which are the characteristics built into the identification method. Unlike the bore, however, the temperature also falls sharply, by more than 5^oC. There is a corresponding drop in dew point temperature and wet-bulb temperature and a strong increase in relative humidity. This frontal pressure jump differs from many of the other frontal pressure jump identified, which have increases in dew point temperature. The mean change in temperature and dewpoint temperature with the passage of all identified frontal pressure jumps is -5.8 ^oC and and 5.1 ^oC respectively. On average, frontal pressure jumps have relative humidity rises of 26.9%. Unlike a bore, a frontal pressure jump may be accompanied by surface

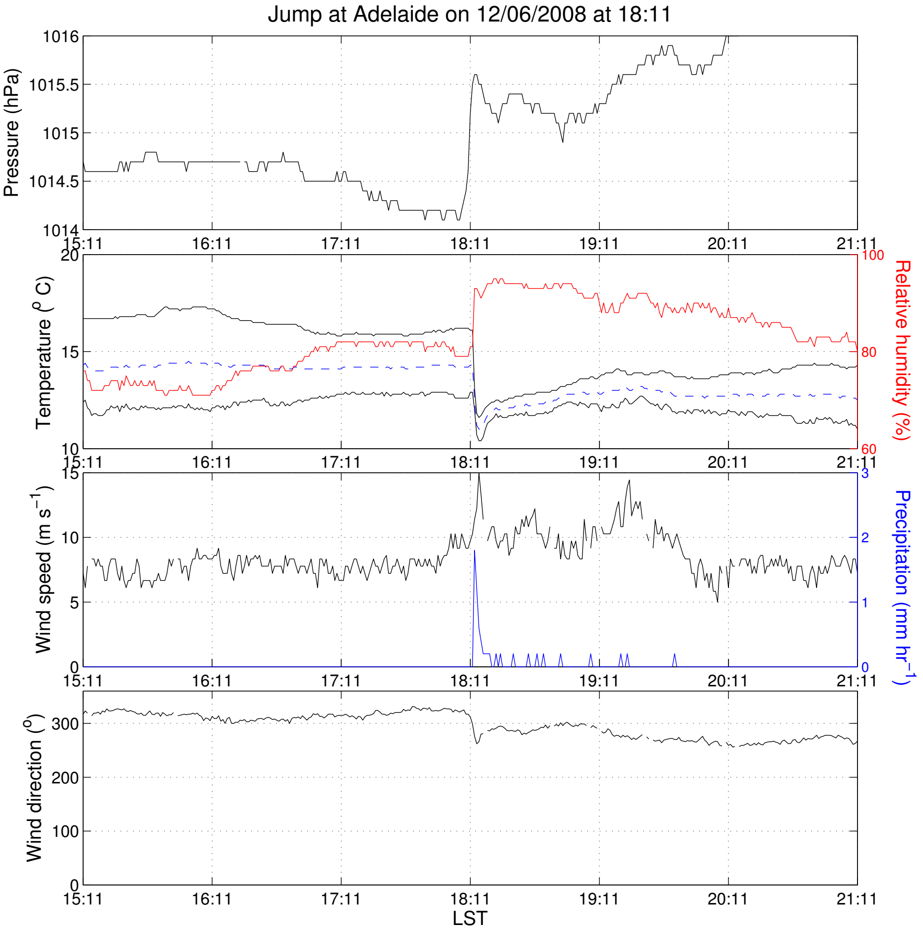

Figure 4. Time series of pressure, temperature, wet-bulb temperature, dew-point temperature, relative humidity, precipitation, wind speed and wind direction for a frontal pressure jump at Adelaide. In the second panel temperature and dew-point are the upper and lower solid black lines, respectively, and wet-bulb temperature is the dashed line.

precipitation as this example shows. Few of the other identified frontal pressure jumps, however, precipitate.

The wind speed and its variability increases, the mean change in wind speed is 0.4 m s^{-1} and the mean variability after the frontal pressure jump is 1.7 m s^{-1}. Although in this particular event the wind direction does not markedly shift from north-westerly, most other frontal pressure jumps identified have larger shifts in wind direction (see Section 3.5).

The increase in wind speed, wind variability and changes in the wind direction associated with both events illustrated in Figure 3 and Figure 4 could affect the behaviour of fires, both uncontrolled and controlled. These results show that although frontal pressure jumps are associated with larger increases in wind speed, the wind speed variability is almost as large after the passage of a bore. As controlled fires are lit out of the fire season, in what are considered to be low-risk conditions, the effect of the wind variations associated with bores may be a potentially unexpected problem.

3.3. *Climatology of bores and frontal pressure jumps*

Given that both bores and frontal pressure jumps are identified in this dataset it is useful to understand when the two features occur in the climatology.

A summary of the total number of bores and frontal pressure jumps identified over the 10 year period is given in Table 1. Of the pressure jumps identified, around 60% fall into one of these two categories with more bores identified than frontal pressure jumps. In the whole dataset, only two of the diagnosed bores also occur in the subset of frontal pressure jumps and so the thresholds chosen discriminate clearly between these two types of event. The remaining pressure jumps, which are neither categorised as a bore nor a frontal pressure jump, have relative humidity changes of more than 5% but temperature decreases of less than 3 ^oC. These jumps will be called weak frontal pressure jumps, but are not discussed in detail.

Figure 5 shows the annual and diurnal cycle of bores and frontal pressure jumps at all stations. Both the bores and frontal pressure jumps have similar annual cycles at all stations with most occurring in spring and summer and fewest in winter. There is a marked difference, however, in the diurnal cycle between bores and frontal pressure jumps. At most stations, bores occur in the early morning and late evening while frontal pressure jumps occur in the late afternoon and early evening. The exception is at Yarrawonga where bores occur slightly more frequently in the early evening. Bores occurring in the morning most likely propagate inland on the stable layers that develop overnight. On the other hand, summertime fronts have previously been found to move onshore most frequently in the late afternoon. Reeder (1986) and Muir and Reeder (2010) discuss how fronts propagate into a daytime mixed layer and decelerate, but serve to strengthen the coastal temperature gradient. They propagate inland later in the day when the mixing weakens, often producing large falls in the temperature.

Although both bores and frontal pressure jumps occur in the bushfire prone spring and summer months, bores generally occur in the morning and frontal pressure jumps in the late afternoon or early evening. Frontal pressure jumps are therefore more likely to be relevant for fires; however, bores can occur in the late evening and an unfortunately timed bore may affect the fire behaviour in ways unforeseen. Indeed, as discussed previously, a late evening bore near Yarrawonga invigorated a fire on Black Saturday. Figure 5 shows that bores at that time of day are not uncommon. The number of weak frontal pressure jumps has a small diurnal cycle with slightly fewer events in the middle of the day and slightly more later in the day (not shown).

3.3.1. *Sensitivity to thresholds*

When choosing the thresholds to separate bores and frontal pressure jumps, the primary considerations are to have as many of each event as possible, but without a large number of events which are simultaneously diagnosed as both bores and frontal pressure jumps (Table 1). Relaxing the thresholds to define a bore with a 6% change in relative humidity and a frontal pressure jump by a temperature fall greater than 2 ^oC increases the number of events by at least 10% depending on the station. (The increase in the total number of bores and frontal pressure jumps with these thresholds are 35%, 11%, 31% and 18% for Adelaide, Ceduna, Mount Gambia and Yarrawonga respectively.) As might be expected, this increase in events arises due to considerably more frontal pressure jumps being identified rather than many more bores. However, the total number of events diagnosed as both a bore, but also a frontal pressure jump, increases to 12. Visual inspection showed some events that are clearly neither bores nor frontal pressure jumps are identified. For example, events were identified where pressure and temperature related variables were highly variable around the time of the diagnosed pressure jump and there was no clear transition at the time of the jump. When the threshold is tightened to 4% and 4 ^oC for bores and frontal pressure jumps respectively, no events are diagnosed as both. However, some events that are clear examples of bores or frontal pressure jumps are missed with a tighter threshold. For example, a bore may be missed with this more stringent threshold as the relative humidity changes too much over the hour period at the time of the jump. A clear frontal pressure jump may be missed as the temperature falls, but less than the required 4 ^oC when averaged over the required period.

3.4. *Wind speed and wind speed variability associated with bores and frontal pressure jumps*

Rapid and large changes in wind speed have implications for managing both controlled and uncontrolled fires.

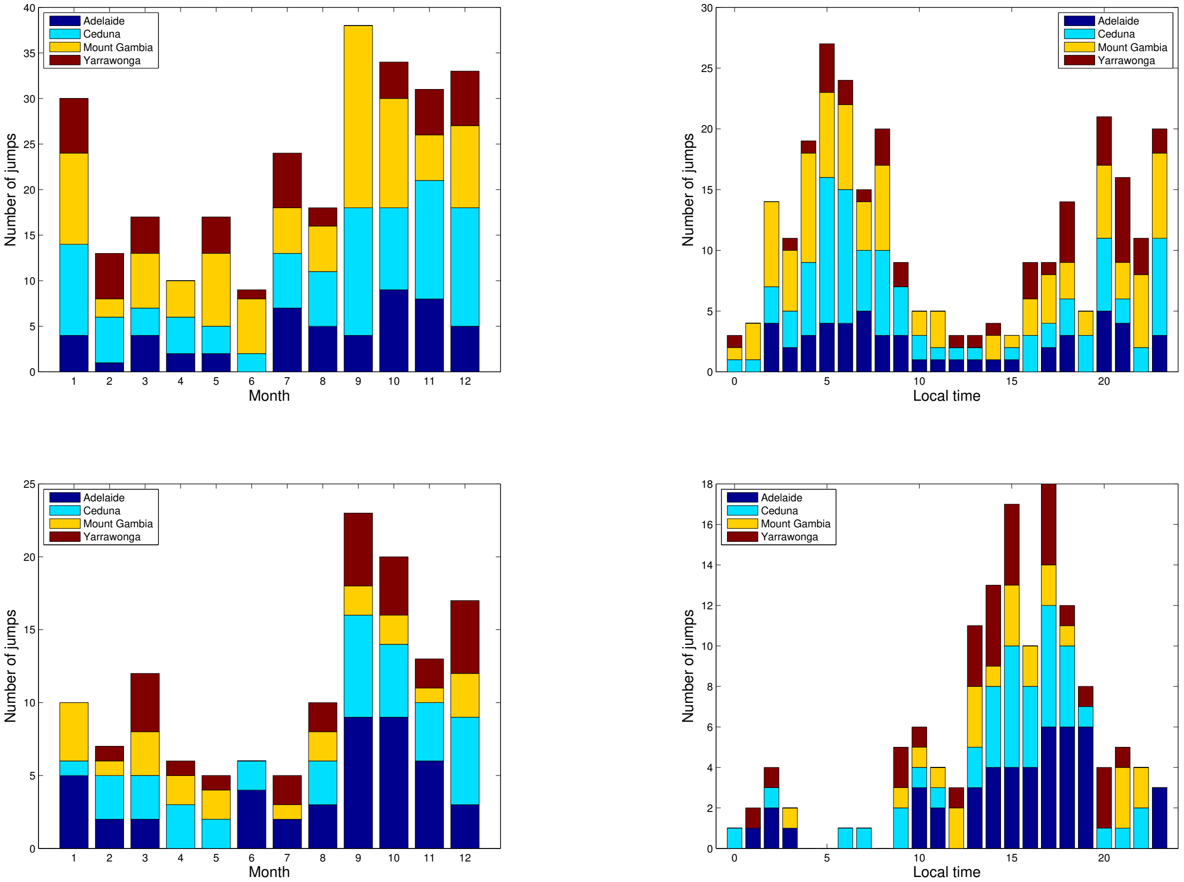

Figure 5. Annual (left) and diurnal (right) cycle of the total number of bores (top) and frontal pressure jumps (bottom) at all stations. These plots are stacked distributions.

Table 1. Table of the total number pressure jumps identified and the number bores and frontal pressure jumps further identified at each station. Also shown is the number of events diagnosed simultaneously as both a bore and a frontal pressure jump. This overlap is minimised by the selection of the thresholds used to identify a bore or a frontal pressure jump (see Section 3.3.1 for discussion).

	Adelaide	Ceduna	Mount Gambia	Yarrawonga
All pressure jumps	162	196	173	100
Bores	51	88	92	43
Frontal pressure jumps	45	39	23	27
Both	0	0	1	1

Therefore, an understanding of how wind speed is modified by the passage of a bore and how compares to that associated with the passage of a frontal pressure jump is important. Furthermore, this should be compared to the background wind speed climatology. Figure 6a shows the frequency distribution of mean wind speed in the 30 min after a bore or a frontal pressure jump, and Figure 6b shows the wind speed variability (defined as the standard deviation of the wind speed over the same period). (This time interval has been discussed in detail in Section 2.2.) The frequency distributions include all bores and frontal pressure jumps identified at all stations. It was found that there was little difference between the frequency distributions for bores and frontal pressure jumps at the different stations, and so the distributions for all stations were combined for simplicity and to improve the reliability of the statistics. For comparison, the frequency distributions of the climatological 30-min mean wind speed and wind speed variability at all stations are also plotted. All frequency distributions are normalised by the total number of data points in each distribution. There is a small difference in the climatological 30-min mean wind speed between Yarrawonga (3.9 m s^{-1}) and all other stations (5.0 m s^{-1}). The mean value for all stations is 4.7 m s^{-1}. There is no difference between the distributions of climatological wind speed variability at the different stations, the mean of which is 0.6 m s^{-1}.

Both frontal pressure jumps and bores are associated with some of the highest 30-min mean wind speeds at these stations. On average, higher wind speeds occur after frontal pressure jumps than after bores with the 30-min means being, 9.0 m s^{-1} and 6.1 m s^{-1} respectively. Also, when comparing the 30-min wind speed variability observed at these stations (Figure 6b), bores and frontal pressure jumps have greater variability than the climatology. Although the wind speed after the passage of a frontal pressure jump is slightly more variable than after the passage of a bore, 1.7 m s^{-1} and 1.1 m s^{-1} respectively, the variations in wind speed caused by both types of pressure jump have implications for fires. The distribution of wind speed and wind speed variability of weak frontal pressure jumps lies between the distributions for bores and frontal pressure jumps (not shown).

3.5. *Wind direction and wind direction variability associated with the bores and frontal pressure jumps*

A numerical method must be used to calculate mean wind direction and wind direction variability due to the discontinuous nature of wind direction measurements. The method used here is described by Yamartino (1984). Turner (1986) quantified the error associated with this method and several similar methods. It was found that the error in calculating the mean wind direction from the arctangent of the mean sines and cosines of the wind direction was less than 1% for distributions where the standard deviation is less than 75^o. Turner (1986) also found that errors in wind direction variability using the Yamartino (1984) method were less than 0.2^o.

Figure 7 shows distributions of the mean wind direction for a 30 min interval before and a 30 min interval after the passage of bores and frontal pressure jumps at all stations. All distributions are normalised by the total number of data points in each distribution. The distribution for frontal pressure jumps shows the expected distribution for southern Australia; northerly winds before the front give way to more westerly winds afterwards. Between the stations, there is little difference in this characteristic, although after a frontal pressure jump wind at Ceduna and Yarrawonga are more south-westerly than westerly. The distribution is completely different for jumps classified as atmospheric bores. At all stations bores can occur when the wind comes from any direction. After the passage of a bore, the wind direction is more likely to be westerly at Ceduna and Mount Gambia whereas at Adelaide and Yarrawonga the wind may still come from any direction. Weak frontal pressure jumps tend to occur when the wind is northerly or north-westerly and after the passage, the wind is more likely westerly (not shown). There is more spread in the distributions than for frontal pressure jumps, however, the distributions have much less spread than the wind direction distributions for bores (not shown). Therefore the wind direction distributions of weak fronts lie between those of bores and frontal pressure jumps.

Figure 8 shows the normalised frequency distribution of variability in the wind direction at all stations after the passage of a bore and a frontal pressure jump compared to the background nocturnal wind direction variability. All distributions are normalised by the total number of data points in each distribution. The background wind variability is calculated from all 30 min nocturnal periods. The variability in wind direction has a very similar distribution at all stations. These changes in wind direction could have very significant effects on fire behaviour. Figure 8 shows there is a slight tendency for wind direction variability to be larger after the passage of a bore than a frontal pressure jump. After the passage of either event, the wind direction is slightly more variable than the background nighttime variability. Therefore after the passage of either event changes in wind direction could have more of an effect on fire behaviour than mean background variability.

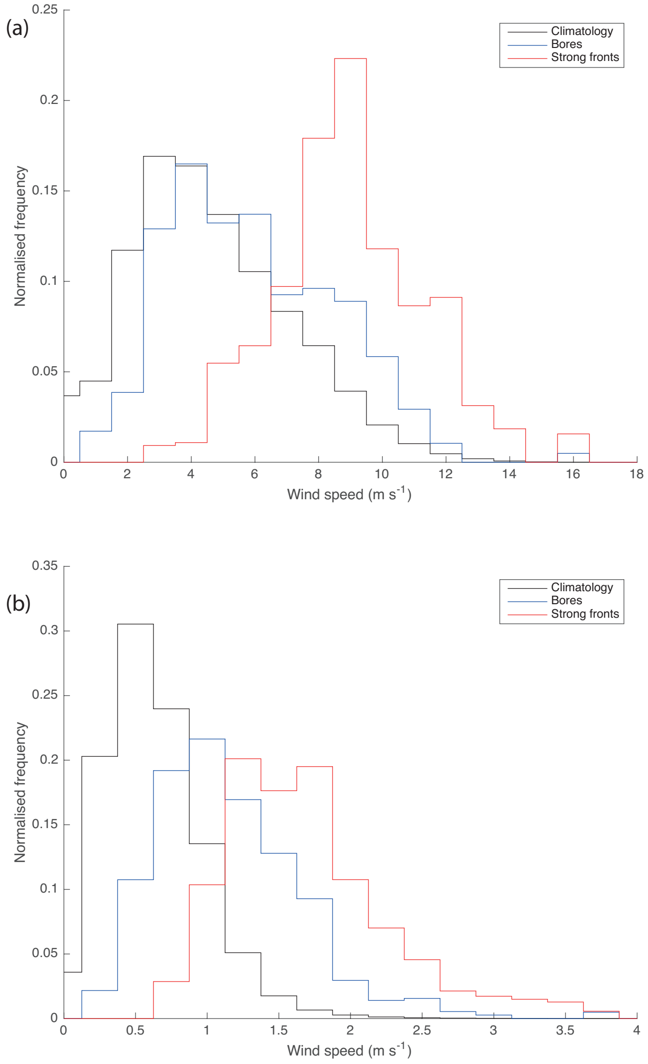

Figure 6. Normalised frequency distributions of (a) mean wind speed and (b) wind speed variability for all stations associated with bores and frontal pressure jumps compared to climatology. Mean wind speed is the 30-min mean after the passage of the bore/frontal pressure jump while the wind speed variability is calculated as the standard deviation over the same period. This time period is discussed in Section 2.2. The climatology is calculated from the 30-min running mean or standard deviation for the whole dataset. The bin size is 1 m s^{-1} for panel (a) and 0.25 m s^{-1} for panel (b).

However, a Kolmogorov–Smirnov test shows that none of these differences in distribution are statistically significant. Although not shown, the frequency distribution of the wind direction variability for weak frontal pressure jumps is very similar to the distributions shown in Figure 8. These changes in the wind direction could have very significant effects on the spread of the fire along its flank (see for example Cheney and Sullivan (2008)). In fact, given that bores occur most frequently at night when the general wind direction is less variable, the increased variability in wind direction caused by the passage of a bore could be as problematic for managing controlled and uncontrolled fires as the passage of a front.

3.6. *Other mesoscale events*

Bores and frontal pressure jumps are not the only mesoscale events of significance to fires that have been identified in this data set. For example, a cnoidal-like wave was identified on 25 March 2002 at Adelaide (Figure 9). A cnoidal wave is a periodic solution of the Korteweg-de Vries equation which can be expressed in terms of Jacobi elliptic functions (Benjamin and Lighthill 1954). Like the waves depicted in Fig. 9, they can be waves of depression and can be characterised by sharp troughs and flat ridges. Waves with these characteristics are sometimes called simply mesoscale gravity waves and have been implicated in severe

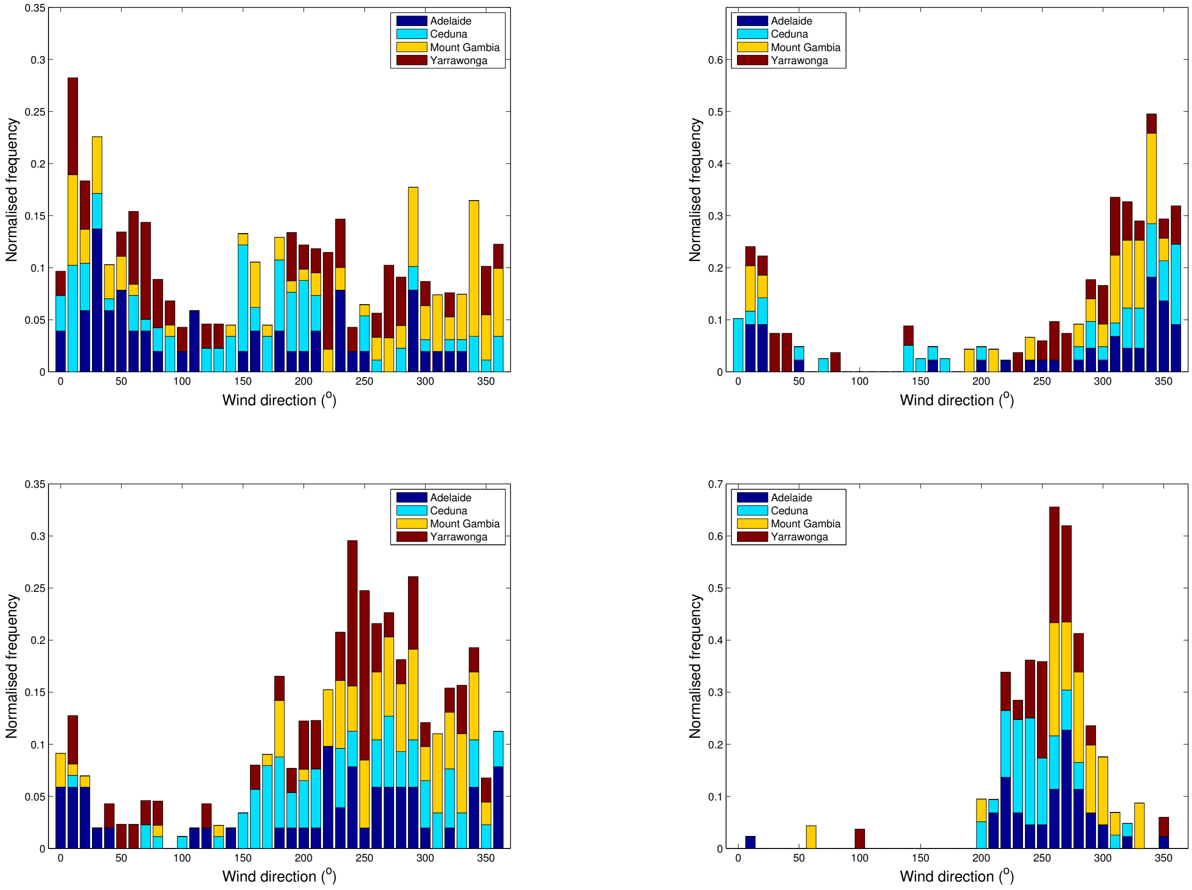

Figure 7. Stacked, normalised distributions of 30-min mean wind direction after the passage of bores (left) and frontal pressure jumps (right) before (top) and after (bottom) the event at all stations. This 30-min time period is discussed in Section 2.2.

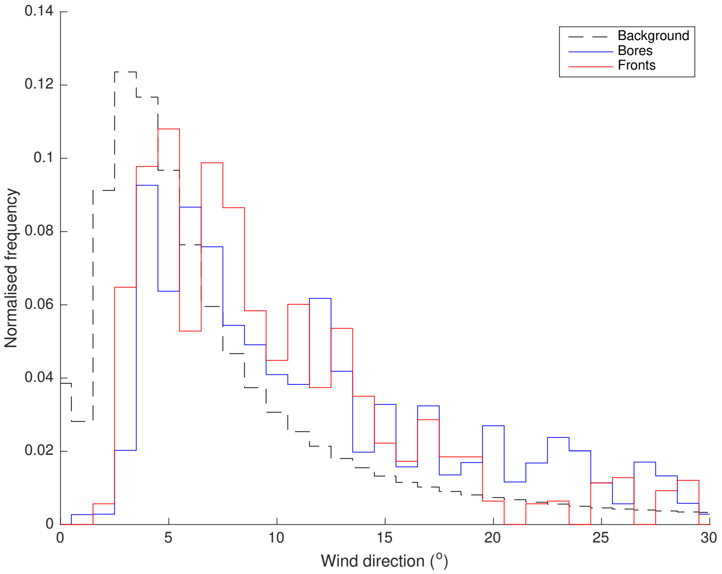

Figure 8. Normalised frequency distributions of wind direction variability for all stations after a bore or a frontal pressure jump compared to the background wind variability when there is no identified pressure jump event. Wind direction variability is calculated by the standard deviation over the 30 min after the passage of the bore/front. This 30-min time period is discussed in Section 2.2. The background distribution is calculated as the standard deviation of all 30 min nighttime periods at each station. Here nighttime is between 10 pm and 5 am LST. The bin size is 1^o.

weather in the US (for a recent example see Rupert Jr and Bosart (2014).) Waves with similar structures have been observed over the Gulf of Carpentaria in northern Australia in connection with the morning glory (Smith *et al.* (2006); see their Fig. 15)

The cnoidal-like wave was not identified using the method outlined earlier (Section 2.2) as that method only identifies step changes in the pressure; instead it was identified by simply seeking disturbances for which the pressure changed by more than 0.4 hPa in 3 min. The event is characterised by two sharp pressure troughs separated by relatively broad periods of higher pressure. The two sharp pressure troughs are superimposed on a gradual pressure decrease.

At 10 am EST on 25 March 2002 two cold fronts are analysed by the Australian Bureau of Meteorology over southern Australia. The first lies almost over Melbourne while the second lies to the west of Adelaide over the Great Australian Bight. The first wave passes Adelaide at about 11:15 am LST, which is 11:45 am EST. Hence, the waves lie between the two cold fronts. It is possible that the waves are generated by the second cold front, but propagate on the relatively stable layer behind the first cold front. The thermodynamic variables and the wind speed are relatively unaltered by the passage of the wave. However, the wind direction veers sharply from westerlies to northerlies at the time of the first trough in pressure before quickly returning to westerlies as the pressure quickly rises. Similar to a bore or a front, this change in wind direction could have an important and unexpected effect on the propagation of a fire.

4. Summary and discussion

On Black Saturday, 7 February 2009, strong winds and rapid and large changes in wind directions modified the behaviour of large bushfire complexes that caused massive devastation and loss of life. Two atmospheric bores were identified in high-frequency automatic weather station data and radar observations showed one bore invigorate a fire complex. Both bores could be identified by a characteristic pressure jump and were associated with an increase in wind speed and a change in wind direction. The present study has developed a climatology of atmospheric bores over southeastern Australia to determine how frequently they occur. As changes in wind speed and direction have implications for the prediction and management of controlled and uncontrolled fires in the open, these variables and their associated variability is also investigated.

One-minute automatic weather station data were objectively analysed to identify significant jumps in pressure that might be atmospheric bores. Pressure jumps that were strongly correlated with a large-amplitude step function were retained. These large-amplitude pressure jumps were separated into two classes: bores and frontal pressure jumps. Bores were defined as pressure jumps without a change in relative humidity whereas frontal pressure jumps were defined by a decrease in temperature greater than 3 ^{o}C. The method identified about 15 pressure jumps per station per year and about 60% of these pressure jumps were either classified as bores or frontal pressure jumps. At all stations, more bores were identified than frontal pressure jumps.

The annual cycle was found to be similar for bores and frontal pressure jumps with more jumps in the spring and summer and fewest in winter. The diurnal cycle of bores was very different from that of frontal pressure jumps. Bores occurred most frequently in the early morning and late evening at most stations with the exception of Yarrawonga where most bores occurred late in the day. Frontal pressure jumps, on the other hand, occurred in the late afternoon or early evening. Overall the mean wind speed after the passage of a bore or a frontal pressure jump was larger than the climatological 30-min mean wind speed; frontal pressure jumps were associated with larger wind speeds than bores. The variability in the wind speed over the same 30 min period was larger for both bores and frontal pressure jumps than the climatological wind speed variability. The wind directions and their changes for bores were very different from that for frontal pressure jumps. The wind associated with a frontal pressure jump changed from northerly to more westerly, whereas bores could occur when the wind was in almost any direction and had only a slight tendency to westerly direction after the event.

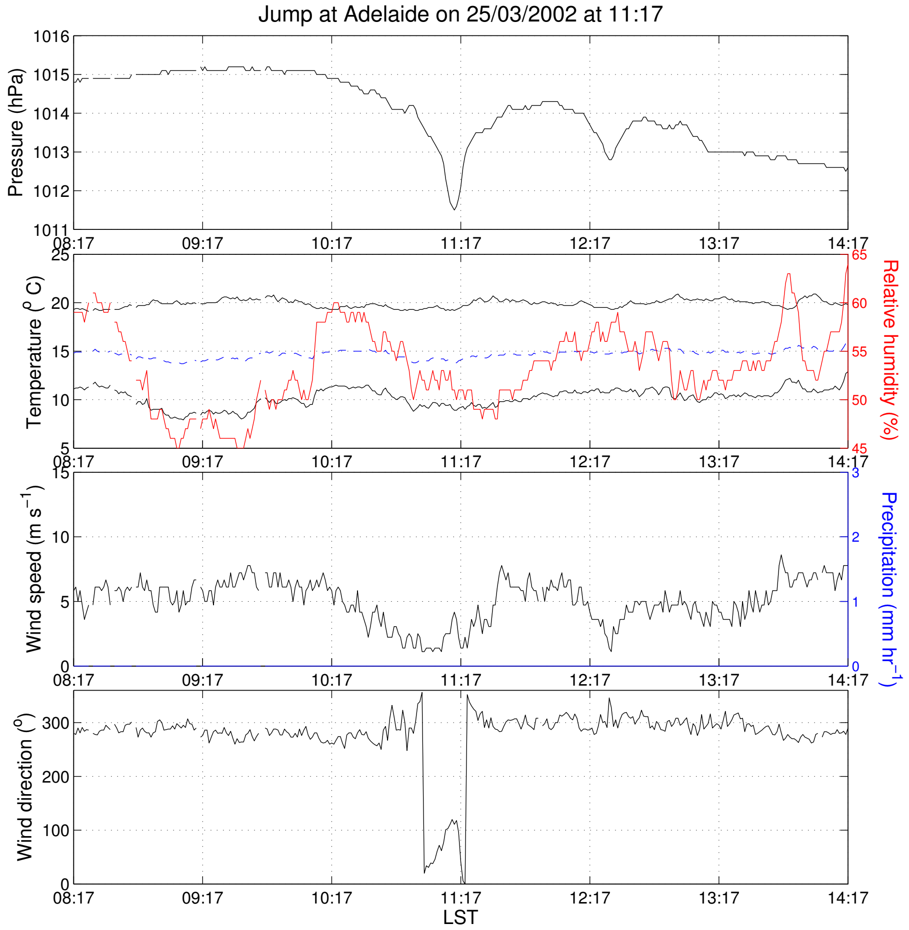

Figure 9. Time series of pressure, temperature, wet-bulb temperature, dew-point temperature, relative humidity, precipitation, wind speed and wind direction associated with a cnoidal wave at Adelaide. In the second panel temperature and dew-point are the upper and lower solid black lines, respectively, and wet-bulb temperature is the dashed line.

The influence of wind changes on fire behaviour is well known (Reeder *et al.* 2015). Careful consideration must be given to the prediction of a cool change in the weather forecasts when managing both uncontrolled and controlled fires. The results here suggest that bores have similar wind speed and wind direction variability to frontal pressure jumps and are likely therefore to have a similar influence on bushfire behaviour. Bores also occur overnight when turbulence is low and a highly variable winds may not be expected.

This study has shown that bores occur frequently in southeastern Australia and they occur more often than frontal pressure jumps, as defined here. Particularly inland, bores can occur in the late evening when fires may be expected to become less active. Bores are associated with similar wind variability to frontal pressure jumps, but may occur for a greater range of wind directions. The changes in wind due to the passage of a bore may promote fire spread and therefore should be a consideration when managing fires, both controlled and uncontrolled. While cold fronts are generally very well predicted, bores are currently not forecast. Moreover, the degree to which fronts with large pressure changes (frontal pressure jumps) are well forecast is also unknown. Given these results, it would be useful to determine the extent to which bores and frontal pressure jumps are forecastable, although this extension to the work remains for another study.

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