The origin and characteristics of cold air outbreaks over Melbourne

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Cold air outbreaks, characterised by unseasonably low maximum temperatures, occurring over Melbourne between May 1972 and June 1991 have been identified and examined using an air parcel trajectory model and data from observations during the period of the outbreak events. Using a definition based on the long-term climatology of the region, thirteen outbreaks were identified during the study period.

The cold air pool source regions for each outbreak were examined via the use of the air parcel trajectory model using the assumption of travel along isobaric surfaces. Mean sea-level pressure patterns, the temporal behaviour of the maximum temperature surrounding an outbreak, three-hourly basic observational data and the determined isobaric trajectories were used to analyse the nature of each Melbourne outbreak.

It has emerged that air of recent Antarctic origin is not a feature common to the majority of outbreaks examined. It is also apparent that characteristic synoptic patterns are associated with cold outbreaks over the Melbourne region. These have been grouped into three categories, ‘classic’, warm front, and blocking anticyclone type. In the mean there is identifiable atmospheric organisation around the Antarctic continent associated with the events.

Introduction

Cold air outbreaks are known to affect much of southern Australia (Hannay 1959) and many other regions of the world such as North America (Mortimer el al. 1988; Konrad and Colucci 1989) and eastern China (Joung and Hitchman 1982; Lau and Lau 1984). They are characterised by unseasonably low daily maximum temperatures lasting one or two days. Melbourne (37°49'S, 144°58'E), the most southerly mainland Australia State capital, is prone to occurrences of cold air outbreaks which might be thought to be the result of the influx of air of recent high latitude, or even Antarctic, origin. Such outbreaks are often associated with extreme conditions in elements such as precipitation and high winds.

Outbreaks occurring in the northern hemisphere (NH) have received greater attention than those in the southern hemisphere (SH) with particular focus on forecasting such events (Dallavalle and Bosart 1975; Joung and Hitchman 1982; Mortimer et al. 1988; Konrad and Colucci 1989) and the study of cold air outbreak characteristics such as air-sea interaction, boundary-layer evolution and synoptic feature development (Agee and Howley 1977; Lau and Lau 1984; Sethuraman el at. 1986; Hartjenstein and Bleck 1991). Other studies of note have modelled particular events (Stage and Businger 1981; Yuen 1985; Sun and Hsu 1988) and analysed variables that determine the character of a cold air outbreak (Boers and Melfi 1987; Claud et al. 1992). It is important to note, however, that these NH studies relate to particular regions (and unique synoptic influences) and hence findings are expected to be specific to those regions. An example of this is east Asian coastal outbreak

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Many authors use qualitative criteria involving more than one atmospheric property to define cold outbreaks. Elliott (1989), for example, defines an outbreak as 'a surge of unseasonably cold air across the State [Tasmania] together with substantial precipitation falling as snow to low levels. As well, strong winds with low humidity are features.' Taylor and Stern (1982) define outbreak days relative to 'typical features' while Jong and Hitchman (1982) define an outbreak across East Asia as 'a mass of cold Siberian air advancing southwards across the East Asian coast, accompanied by strong northerly winds.' These definitions are obviously subjective and regionally specific.

It is important that an outbreak be regarded as cold relative to the mean pertaining to the location and time of year. The use of a single fixed temperature, at whatever level of the atmosphere, or a qualitative checklist to define an outbreak occurrence in practice means that no summer outbreaks, especially over Australia, will be so-identified. In investigating outbreaks in general, the restriction of events to a particular season would not permit, for example, possibly fruitful comparison of the synoptic structure of summer and winter outbreaks. Hence a full examination of outbreak properties requires a definition that is not restricted to season but which still recognizes the statistical significance of each outbreak occurrence so that the outbreak is indeed distinguished from the mean. Mortimer et al. (1988) use a condition based upon the drop in temperature 'to or below a critical value' but do not elaborate on this or clarify whether their 'critical temperature depends on season. Konrad and Colucci (1989) use a criterion that is felt to be physically and statistically realistic in selecting true cold air outbreak episodes that are significantly anomalous to the mean 850-hPa conditions. 

The definition of a cold air outbreak in this research

In this study, a cold air outbreak is considered to have occurred when

\[ T_{\text{max}} < T_{\text{crit}} \]

where

\[ T_{\text{crit}} = T_{\text{mean}} - \kappa \sigma \]

In the above, \( T_{\text{max}} \) is the maximum (screen) temperature for the day in question, \( T_{\text{mean}} \) is the Melbourne average maximum temperature for the calendar month (these means have been calculated from the daily data collected by the Bureau of Meteorology which cover the period May 1855 to June 1991), \( \sigma \) is the daily standard deviation of the population, also calculated from the entire record for each month, and \( \kappa \) is taken to be 2.0. If the temperature time series was stationary and its distribution normal, this choice for \( \kappa \)

Definition of a cold air outbreak

There is no standard definition of a 'cold outbreak' and many are used in the literature. Some are fairly simplistic, such as that of any day with a surface temperature (Wayland and Raman 1989) or 850 hPa temperature (Hannay 1959) below 0°C, or days upon which short-term changes in surface temperature, surface pressure and surface wind speed and direction are observed (Lau and Lau 1984). These definitions take no account of the long-term average conditions of the study region, especially in terms of temperature. This is considered to be important for Melbourne outbreaks as they are unusual and infrequent occurrences which must be reflected in their definition. The classification of periods as outbreaks that, although cold, are not unusual with respect to often experienced weather events is common in literature of cold air outbreak definitions.
would 'result' in cold outbreaks occurring on 2.28 per cent of days. Hence this choice would be expected to indicate events which are genuinely extreme, yet will occur sufficiently frequently so as to provide a set of case studies of sufficient size to allow reliable analyses of the general properties. Table 1 shows the average, standard deviation and the derived critical temperature for each month.

<table>
<thead>
<tr>
<th>Monthly</th>
<th>$T_{max}$ (°C)</th>
<th>$\sigma$ (°C)</th>
<th>$T_{crit}$ (°C)</th>
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<tbody>
<tr>
<td>January</td>
<td>25.8</td>
<td>6.2</td>
<td>13.4</td>
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<tr>
<td>February</td>
<td>25.7</td>
<td>5.8</td>
<td>14.1</td>
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<td>March</td>
<td>23.8</td>
<td>5.3</td>
<td>13.2</td>
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<tr>
<td>April</td>
<td>20.0</td>
<td>4.5</td>
<td>11.0</td>
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<tr>
<td>May</td>
<td>16.6</td>
<td>3.0</td>
<td>10.6</td>
</tr>
<tr>
<td>June</td>
<td>13.9</td>
<td>2.2</td>
<td>9.5</td>
</tr>
<tr>
<td>July</td>
<td>13.3</td>
<td>2.1</td>
<td>9.1</td>
</tr>
<tr>
<td>August</td>
<td>14.8</td>
<td>2.6</td>
<td>9.6</td>
</tr>
<tr>
<td>September</td>
<td>17.1</td>
<td>3.5</td>
<td>10.1</td>
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<tr>
<td>October</td>
<td>19.5</td>
<td>4.5</td>
<td>10.5</td>
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<tr>
<td>November</td>
<td>21.8</td>
<td>5.3</td>
<td>11.2</td>
</tr>
<tr>
<td>December</td>
<td>24.1</td>
<td>5.9</td>
<td>12.3</td>
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It is interesting to note that most outbreaks occurred in the periods July 1972 to July 1973 (four events) and July 1982 to July 1984 (five events) and three occurred in 1973 and in 1983. It may at first appear surprising that July experienced the greatest number of outbreaks (eight) while three occurred in June and one in both May and September since from the assumption of normality for each monthly temperature distribution, cold outbreaks would be expected to occur 2.28 per cent of the time (i.e. 158 events over the 19 years or about 13 in each calendar month). This deviation from what might have been expected can be explained via the examination of the frequency analyses of the daily maximum temperatures for each month and local warming trends. The frequency analyses show that while some months display a normal-type distribution (such as June and July shown in Fig. 1), most months have a positively skewed-type pattern (for example January and March as also shown in Fig. 1). This skewness, greatest during the summer months, and the associated relatively high standard deviations, makes it very 'difficult' to obtain temperatures two standard deviations below the mean as this is either below the lowest temperature ever experienced for that month (such as apparent for January, February and March) or above only the rarest of events over the 136 years of record. Hence the nature of our definition is such that few or no 'cold outbreaks' occur over Melbourne in summer.

The distributions were closest to normal in the winter months, particularly June and July, but the number of events which have been identified is still less than the 13 expected. The reason for this is due to the presence of warmer than average temperatures during the study period. As can be seen
Fig. 1  Frequency analyses of daily maximum temperatures for all January, March, June and July days at Melbourne since records commenced in 1855. N is the number of cold outbreaks occurring in the month between 1972 and 1991.

From Table 3, the average winter month temperatures during the interval considered in this research were above the long-term climatological averages. These differences are significant considering the outbreak condition \( T_{\text{crit}} \) is derived from the long-term average but we are only searching the temperature data of the last 20 years. Hence it is considerably ‘harder’ to satisfy the outbreak criterion during this warmer interval and this results in the low number of events identified. When considering only the data from the years 1972 to 1991, the outbreak critical temperature differs significantly from the long-term criterion with the result that six ‘outbreaks’ are selected for May, a very large 11 for June and nine for July. Therefore, the warmer nature of the study period is particularly significant for these months.
Table 3. The long (1855–1991) and short (1972–1991) term characteristics of $T_{\text{max}}$.

<table>
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<tr>
<th></th>
<th>June</th>
<th>July</th>
<th>August</th>
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<tr>
<td>Difference</td>
<td>0.37</td>
<td>0.44</td>
<td>0.29</td>
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Cold outbreak air parcel trajectories

In this paper we perform trajectory analyses for all the cold outbreaks to determine the origin of the air. The accuracy of derived trajectories is often determined by the spatial and temporal resolution of data observations (Doty and Perkey 1993) and errors associated with data measurement (Danielsen 1975). Methods employed to analyse observed information and transfer that information into a gridded dataset (Danielsen 1975), assumptions necessary in the determination of the trajectories, such as the form, whether isobaric, isentropic, 'isosigma' etc., in which the data will be used (Danielsen 1961, Kuo et al. 1989), and interpolation techniques (Law 1993) also affect trajectory accuracy. The trajectory model used in this research is that developed by Law (1993) and uses wind fields centred on 2300 UTC that are cubically interpolated in space and linearly in time, in conjunction with a fourth-order Runge-Kutta method. The procedure is described in detail in the appendix. More frequent data would have made the air parcel tracking easier and possibly eliminated a few problems which resulted from the sampling interval.

Horizontal trajectory methods

Even though the assumption that 'horizontal' trajectories follow isentropic rather than isobaric surfaces may be thought more reasonable in theory, this is not necessarily true in all applications. The fact that the input trajectory data are often on isobaric surfaces enhances the usefulness of the assumption of atmospheric travel along constant pressure surfaces. In this study the isobaric 1000 and 850 hPa pressure levels were chosen as trajectory surfaces since 1000 hPa is the lowest pressure level at which analyses are presented and is considered to be most representative of a near-surface level, whilst 850 hPa is approximately at the boundary between the surface wind regime and that of the upper winds relatively free from local surface effects (Dayan 1986). Before deciding to use isobaric surfaces for our trajectory analyses we wished to establish that our results would not differ significantly from those we would obtain on isentropic surfaces. After consideration of a number of cases it was apparent that the isentropic trajectories were essentially the same as the isobaric counterparts and had therefore failed to reveal any large errors associated with the isobaric assumption. Others (e.g. Kuo et al. 1985; Kahl et al. 1989) have found that 'the trajectories [isobaric and isentropic] are nearly equivalent at least for the purpose of identifying an upwind source region.' In general, the greatest overall differences between the isobaric and isentropic trajectories were apparent for air parcels originating from latitudes greater than 35°S. These differences were largest in terms of the longitude of the origin location and highlight the behaviour of isentropic surfaces in high latitudes of the globe. However, in our study the geographical location of the origin of the air parcels is of more importance than the height. The comparable cold outbreak air parcel origin results, the ease of use of the isobaric technique, its minimisation of computational cost and qualitatively similar results led to it being selected in this research.

Isobaric trajectory results

The six-day isobaric trajectories to Melbourne for all thirteen events at both the 1000 and 850 hPa pressure levels are shown in Fig. 2. The July 1982 (190782) and 1983 (200783) trajectories are for the day after the outbreak event since the southwesterly airstream, known to have initiated the outbreak, became established over Melbourne after the 2300 UTC data analysis time used by the trajectory model. These winds persisted into the day after the outbreaks before changing direction soon after the trajectory time. As is clearly revealed for both levels, cold air outbreaks are not always the result of surges of, or indeed recent, Antarctic air. Only two events, those of 19 July 1982 and 25 July 1986 (250786), also investigated by Elliot (1989) and Pook (1992), are found to originate from Antarctica. The air in these outbreaks, for both levels, was found to have been over the Antarctic continent as little as four days before the outbreak occurred, but we can see that they are not typical.

As the trajectories on the two levels near Melbourne, they seem to divide themselves into three types: parcels from either an easterly sector, a south to southwesterly sector or a west to northwesterly sector. Analysis, to be discussed later, shows these trajectories to be related to three differing synoptic scenarios which are each represented by a contrasting line type in Fig. 2. The trajectories on the 1000 hPa surface appear to be less organised and more erratic than those at 850 hPa. The scatter of trajectories does not reveal any obvious difference in the southerly extents between the two levels with some events, such as July 1972, originating from higher latitudes at 850 hPa whilst others, such as July 1984, show the opposite to be the case. Hence a general
statement as to the preferred height of the cold air as it moves towards and arrives at Melbourne is not possible but may be linked to the apparently different synoptic scenarios.

Fig. 2 Melbourne cold air outbreak six-day isobaric parcel trajectories on the 1000 hPa (a) and 850 hPa (b) levels. Solid lines represent ‘classic’-type outbreaks, short dashed lines are ‘warm front’ outbreaks and long dashed lines are ‘blocking anticyclone’ outbreaks.

The characterisation of Melbourne cold air outbreaks

As stated above, the trajectory analysis suggests that Melbourne outbreaks exist as three distinct outbreak types. This was confirmed by examining the MLSP analyses accompanying the outbreaks and we henceforth refer to them as ‘classic’ cold air outbreaks, warm front outbreaks and blocking anticyclone outbreaks. We discuss these below.

‘Classic’ cold air outbreaks

The outbreaks which occurred on 7 June 1972, 31 May 1977, 18 July 1982, 19 July 1983, 3 July 1984 and 25 July 1986 (denoted by * in Table 2) were associated with quite strong and very cold south to southwesterly airstreams. In what we call ‘classic’ outbreaks, these events were initiated over Melbourne after the passage of cold fronts across Victoria. The synoptic evolution of the July 1984 event shown in Fig. 3 provides a typical example. The MSLP analyses show the recent passage of a cold front with a southwesterly airstream in its wake. An anticyclone located in the vicinity of the Great Australian Bight, which is rather elongated due to the influence of two cyclonic systems located on either side of the the high, is associated with a strong ridge of high pressure.

The composited evolution of the six ‘classic’ types is shown in Fig. 4. Two days before the outbreak day it shows a distinct wave-type disturbance in the flow with a relatively weak ridge, located to the southwest of Western Australia. The Indian Ocean anticyclone associated with the ridge moves to the east and amalgamates with a large high centred over northern New South Wales. As the ridge and anticyclone system moves eastwards, a large low pressure system develops to the south of Tasmania and establishes a southwesterly airstream across southeastern Australia.

The very low temperatures experienced in this situation do not last very long due to the rapid passage of the cold pool behind the mobile cold front. The cold air is usually dry but quite unstable. As a result, these events are all associated with significant cloud amounts throughout most of the daylight hours. The observed clouds were mostly of the cumuliform type, with cumulonimbus observed during the May 1977 and July 1986 events, and rain and snow down to low levels were observed during each of the events. Snow fell in Melbourne during the 1984 and 1986 outbreaks. There was little overnight cloud (except for the 1986 event), contributing to long wave cooling of the near-surface air and resulting in low overnight temperatures (Table 2).

Typical characteristics of the Melbourne maximum temperature with time relationships for the classic outbreak type are shown in Fig. 5 for July 1986. Those obtained for the July 1983, 1984 and 1986 cases all displayed a sudden drop to the outbreak temperature before quickly recovering, consistent with the speed of the cold fronts associated with this outbreak type. The 1977 and 1982 outbreaks display a more gradual drop in temperature to the outbreak minima while the results for 1972 display no definite relationship. The 1982 (Fig. 6) plot suggests the existence of a precursor outbreak (as discussed in Mortimer et al. 1988) whereby the temperature falls to a minimum, rises
Fig. 3  MSLP analyses (0000 UTC) from 1 to 3 July for the July 1984 cold air outbreak over Melbourne.

Fig. 4  Average classic outbreak MSLP analyses (2300 UTC) for two days before the outbreak event (top) to the outbreak day (bottom).
Fig. 5 Melbourne maximum temperature with time relationship for the 25 July 1986 classic cold air outbreak.

The trajectories for each of the six classic cases shown in Fig. 2 as solid lines are all observed to be different. However, the isobaric trajectories on both pressure levels for the 1972, 1977, 1983 and 1984 outbreaks are each seen to indicate a definite northeastward motion. The path of the trajectories apparent in most of these cases (on both isobaric surfaces) is consistent with travel along the wave disturbance evident in the MSLP patterns shown in Fig. 4. The differing nature of the 850 hPa trajectories for the 1972 and 1977 outbreaks is most likely the result of the more zonal flow and reduced influence of the wave disturbance at the 850 hPa height for these events. The 1986 outbreak is the only significantly northward trajectory produced for air parcels reaching Melbourne at 2300 UTC on an outbreak day. The 19 July trajectory is of a very similar nature to the 1986 case. However, since the 19 July trajectory is for the day after the outbreak occurred, it is difficult to establish the precise nature of the outbreak air trajectory but the results still suggest that the 1982 outbreak event was indeed associated with air of recent high latitude origin. It is apparent that the 1982 and 1986 cold outbreak air masses did truly surge across Melbourne having taken only three days to travel from Antarctica.

Average trajectories on both the 1000 and 850 hPa pressure levels (not shown) were found to originate from quite high latitudes (55.5°S for the 1000 hPa trajectory and 59.1°S for the 850 hPa trajectory) while displaying distinct northeastward tracks consistent with Fig. 4. There is also a 20° longitude difference between the trajectories on the two pressure levels which shows that, on average, the 850 hPa trajectories are longer than those at 1000 hPa.

Fig. 6 Melbourne maximum temperature with time relationship for the 18 July 1982 classic cold air outbreak.

'strong front' outbreaks
The next most common cold outbreak category is the 'warm front' (WF) outbreak type which was seen in four outbreaks which occurred on 9 June 1973, 29 June 1983, 13 September 1983 and 1 July 1990 (denoted by § in Table 2). These outbreaks are established when cold maritime polar air is pumped over Victoria in the wake of a passing northeastward-directed cold front. The cold air pool then slowly moves in a northeastward direction over the State under the influence of light south to southwesterly winds before returning over Melbourne ahead of a warm front, moving to the southeast in advance of a low pressure system. The MSLP analyses leading up to the 13 September 1983 event provide a good example of this and are shown in Fig. 7. The synoptic evolution of the composites of the four cases of this outbreak type is shown in Fig. 8 for up to two days before the outbreak event. There is a cold southwesterly airstream across the State two days before the outbreak with cyclogenesis apparent.
Fig. 7 MSLP analyses (0000 UTC) from 11 to 13 September for the September 1983 cold air outbreak over Melbourne.

Fig. 8 Average warm front outbreak MSLP analyses (2300 UTC) for two days before the outbreak event (top) to the outbreak day (bottom). The warm front/cold front pair are shown for the day of the outbreak.
off the southwest tip of Western Australia. The low pressure system develops and, with very little intensification, moves eastwards towards Victoria while light winds prevent the cold air pool from leaving the State (and actually inject more cold air over Melbourne). On the day of the outbreak, the centre (or possibly centres since the contours suggest the system might be a complex low) of the low pressure system is located south of the Bight with northerly winds returning the cold air mass across Melbourne.

All the WF outbreaks (with the exception of the 1990 event) are associated with low overnight cloud amounts and cool minimum temperatures before the cloud increases ahead of the warm front, with overcast conditions persisting throughout the day. The extensive daytime cloud deck greatly reduces the amount of solar radiation received at the surface while the precipitation recorded during each of the four WF outbreaks may be responsible for dragging cold air down to the surface and then chilling the near-surface air further via evaporative cooling effects. This type of outbreak is somewhat similar to the classic outbreak. What distinguishes it, however, is that the cold air mass is a returning cold pool that is relatively moist, yet shallow, with mild temperatures aloft.

The temporal behaviour of the maximum temperature for both of the 1983 (Fig. 9) and the 1990 (not shown) outbreaks shows little structure and is indicative of the very changeable synoptic conditions surrounding the outbreak day. Northerly to westerly to southwesterly-type wind changes were apparent in the MSLP analyses with each flow type only lasting on the order of one day. Of relevance is the quite low temperature associated with the minima before the outbreak temperature. This corresponds to the initial influx of the cold pool of air across Melbourne before it returns on the day of the outbreak and is essentially a precursor outbreak.

The temperature versus time relationship associated with the June 1973 outbreak shown in Fig. 10 is different from the other three outbreaks in this category in that it reveals a gradual drop to the outbreak minima without an obvious initial cold air mass influx. This behaviour is the result of an anticyclone which became established over Victoria after the initial influx of cold air behind a cold front which crossed Melbourne five days before the outbreak occurred. The anticyclone directed cold air of increasingly southerly origin over Melbourne in the two days following the passage of the cold front before the winds weakened under the influence of the high as it slowly moved southeastwards. The conditions then changed sufficiently to minimise the heating of the near-surface air over Melbourne causing a WF-type cold outbreak day.

The July 1990 outbreak is very different from the three other WF outbreaks. The fact that an outbreak occurred at all on this day is odd when considering that Melbourne was in fact in the 'warm' sector of the warm front–cold front pair, indicated by Fig. 11, for most of the day. One possible explanation for the outbreak occurrence is that a very cold air pool was drawn over the
continent in the region of the Bight as a result of an intense high pressure system centred just off the tip of southwest Western Australia on 26 June 1990. This cold pool may, while under the influence of a light west to southwesterly wind, have moved slowly across the continent before changing direction towards the southeast due to the progression of the centre of the high across central Australia. The cold air mass could then have been brought over Melbourne by the rapidly forming and intensifying low associated with the warm front. However, the reasons behind this particular outbreak are not confirmed despite the fact that it is associated with all the broadscale synoptic conditions common to this type of outbreak.

The trajectories, shown as short dashed lines in Fig. 2, exhibit the complex nature of this outbreak type. Only three of the eight (i.e. four cases at two levels) WF trajectories are as expected from the knowledge of the synoptic influences responsible for the occurrence of WF-type outbreaks. These are the 1000 and 850 hPa trajectories for 9 June 1973 and the 1000 hPa trajectory for 13 September 1983. The 1990 trajectories are fairly consistent with the proposed theory behind this event. The 1000 hPa trajectory for June 1983 and the 850 hPa trajectory for the September 1983 are associated with the movement of the important low pressure systems while the 850 hPa trajectory for the June 1983 outbreak is almost directly from the west.

Interestingly, the average WF trajectories at both atmospheric levels originate (six days earlier) from latitudes equatorward of Melbourne (38.4°S at 1000 hPa and 38.2°S at 850 hPa). The trajectories are very similar at the two levels, even crossing the mainland at the same location and shifting southeastward during the last day of travel.

‘Blocking anticyclone’ outbreaks
The third and least common of the outbreak categories is the blocking anticyclone (BA) outbreak. This outbreak type was associated with the three events occurring on 7 July 1973, 8 July 1973 and 19 June 1975 (denoted by ‡ in Table 2). A BA outbreak is established by the influx of southwesterly air over Melbourne behind a cold front. The cold air then forms into a large, almost stationary air mass under the light winds of a dominating blocked high pressure system as indicated by Fig. 12 for the 7 and 8 July 1973 outbreaks. The high pressure system located over the southeast of Australia is quite intense and very slow-moving as shown in Fig. 12 and the composite BA outbreak MSLP analyses (Fig. 13).

Once the cool air pool is established over the State, light easterlies originating from the Tasman Sea increase the humidity of the air mass with the result that the cloud amount increases. Under the influence of the anticyclone, cloud forms near the surface resulting in foggy conditions. This results in very low solar insolation amounts and, combined with the cool air mass, the maximum temperature remains very low. The atmosphere is quite stable, with a shallow layer of cold air near the surface and mild temperatures aloft above an upper subsidence inversion. Precipitation is generally not associated with this outbreak type (only the 8 July 1973 outbreak received a trace). The 7 July 1973 outbreak was particularly cold (maximum temperature only 7.2°C) due, partially, to infrared cooling under clear skies on the previous night before the establishment of foggy conditions. Hence the temperature was not able to increase significantly from the very low overnight minimum of 0.4°C.

The maximum temperature versus time relationships are similar for all three outbreaks of this type. The June 1973 trace, shown in Fig. 14 provides an example showing a progressive cooling in the days leading up to the outbreak event. This is also apparent for the May 1977 and June 1973 events previously discussed. This relationship is the result of the cold air pool overlying Melbourne chilling due to the combined effects of such factors as nocturnal cooling, small amounts of solar radiation received at the surface during the day and the absence of any significant heat advection into the Melbourne region. The maximum temperature reaches a minimum on the outbreak day (or days for the July 1973 events) before the wind increases and changes direction with the progression of the anticyclone and the temperatures return to more typical levels. Hence the term ‘outbreak’ applied to these particular Melbourne events need not imply sudden cold temperatures and emphasises the complex nature of southern Australian extreme cold temperature events.

The air parcel trajectories for the three BA outbreaks are shown as long dashed lines in Fig. 2 and
Fig. 12 MSLP analyses (0000 UTC) from 6 to 8 July for the July 1973 cold air outbreaks over Melbourne.

Fig. 13 Average blocking anticyclone outbreak MSLP analyses (2300 UTC) for two days before the outbreak event (top) to the outbreak day (bottom).
are similar at the two levels. They display the paths of travel of the easterly air which serves to increase the humidity of the cool air pool. Hence the trajectories may indeed be showing the most important aspect of these outbreaks since the initial cool southwesterly airstreams, and their associated weather elements, have been shown to be insufficient to cause a cold air outbreak on their own.

The BA trajectory composite indicates that, on average, the outbreak air originates at 40.8°S (1000 hPa) and 44.0°S (850 hPa), and hence is middle latitude rather than high latitude air. The distance travelled, combined with the fact that the air proceeds well to the east and over the Tasman Sea, suggests that the air in the BA outbreaks has the opportunity to undergo reasonable modification over the ocean.

**Characteristic outbreak similarities**

Despite the individual nature of many of the characteristics of the thirteen Melbourne cold air outbreaks, there are some features they have in common. In each case, the outbreak air mass moved over Melbourne in the wake of a south to southwesterly cold front. Each outbreak day was also found to be associated with significant cloud amounts throughout the daylight hours which served to extensively reduce the level of solar insolation, restricting surface-induced heating of the lower layers of the atmosphere and inhibiting any major temperature rise from the already low overnight temperatures. However, the small number of features that the outbreaks have in common cautions against describing southern Australian cold air outbreaks, and Melbourne outbreaks in particular, in terms of generalities.

A very important result of this research is a realisation of the difficulty in establishing precursors in the days leading up to a cold air outbreak. This is evident from the temperature traces of several outbreaks (1972, June 1973 and 1982) which suggest that the existence of the broadscale synoptic patterns for any of the three outbreak types does not always lead to the formation of a cold air outbreak over Melbourne. This fact is deserving of examination to a greater extent to determine the uniqueness of the determined general outbreak mechanisms in producing cold air outbreak events.

**Is high latitude air reaching Melbourne always cold?**

The isobaric trajectories were used to determine if there was a connection, in general, between the temperature of the air at Melbourne and the latitude at which it originated. The latitudes of air parcels from one to six days before reaching Melbourne, for each day of the winter months (June, July and August), were plotted against the maximum temperature for the winters of 1972, 1980 and 1986 (chosen arbitrarily but representing a reasonable spread of years over the analysis period).

The results for winter 1986 at 1000 hPa are displayed in Fig. 15 and are typical of each of the three years and two levels. The plot shows a correlation between temperature and latitude, but the scatter indicates low maximum temperatures in Melbourne are not necessarily associated with air originating from far south. As can be seen from Fig. 15, the lowest temperature did indeed correspond to the highest latitude five days earlier. This day was found to have the highest latitude origin for the three winters and was selected as a cold outbreak. However, the next highest latitude event resulted in an above average July temperature of 14.0°C, while the next coldest day was associated with air originating from around 44°S. Air parcels originating from higher latitudes between 60° and 70°S display a large amount of scatter in terms of their corresponding Melbourne maximum temperatures. Very few events could be said to be of high latitude origin. Only two events in 1986 originated (at six days) south of 70°S whereas the most southerly starting points were around 65°S in 1972 and 1980.
Fig. 15  Temperature versus latitude scatter plots for one (top left) to six (bottom right) days before the air arrives over Melbourne, on the 1000 hPa surface, during winter 1986.
Fig. 16  Correlation coefficient profiles of the latitude of air parcels with maximum temperatures experienced in Melbourne for winter 1972, 1980 and 1986 on the 1000 hPa (a) and 850 hPa (b) atmospheric pressure levels.

To quantify these associations, Fig. 16 presents the correlation between the latitude of the air parcels N days before reaching Melbourne and the eventual maximum temperature for each of the three winters. The 1986 case shows a maximum at four days whereas for 1972 the maximum occurs at three days. The magnitudes of the coefficients are modest, with the greatest just exceeding 0.5 (0.26 is required for significance at the one percent level), and hence reinforce the point that cold temperatures experienced in Melbourne are not exclusively related to the influx of air of high latitude origin.

In a final analysis of trajectories, we compare the mean trajectory from the three winters with that derived from the thirteen outbreak cases. The average trajectories were constructed from the calculated mean (centre of gravity) air parcel locations for each day from one to six days before the time of arrival over Melbourne using all the winter (276) and all the outbreak (13) days. The results are presented in Fig. 17 for both the 1000 and 850 hPa levels. On all days, and at both levels, the mean outbreak trajectory was to the south and the east of that of the mean of all days in the three winters although the southerly distance between corresponding days was rather small. The fact that this difference was so small appears to be the result of the compositing of the differing outbreak types.

Fig. 17  Average cold outbreak (+) and combined winter 1972, 1980 and 1986 (*) air parcel trajectories on the 1000 hPa (a) and 850 hPa (b) atmospheric pressure levels.
Anomaly MSLP patterns and spectral analysis

In an endeavour to gain a greater understanding of the dynamical characteristics associated with these events, it is essential to establish the statistical significance of the synoptic patterns that appear to be related to the onset of cold air outbreaks. This is especially important for understanding whether a cold outbreak will always occur when the MSLP conditions resemble any of the three previously determined general cold outbreak synoptic patterns and when considering the high atmospheric variability experienced in the study region. The compositing of MSLP analyses, similar to that used previously, is a useful method of investigating the statistical significance of differences from the long-term climatology of the region. Since we are also interested in the characteristics of the atmosphere in the lead up to a cold outbreak event, composite outbreak synoptic patterns were produced for the days leading up to the outbreaks.

The composite cold outbreak MSLP analyses were derived from the eight Melbourne July events and compared against the July long-term average. The anomalies are shown in Fig. 18 and the stippling denotes regions over which the differences are statistically different from zero at the 95 per cent confidence level using a two-tailed t-test (Simmonds 1981). An important feature is the large positive anomaly to the south of Western Australia extending down to over the Antarctic continent three days before the outbreak day. This anomaly is seen to move steadily eastwards becoming centred south of the Bight on the outbreak day. The ridge of high pressure extending into the Bight is a common feature of many of the individual Melbourne outbreaks, especially the classic-type outbreaks which are strongly represented in the July composite patterns. This appears to be one of the main mechanisms behind the movement of cold, possibly high latitude air towards Melbourne.

A feature of considerable interest in the plots is the absence of any significant difference in the region of the Indian Ocean anticyclone. This anticyclone, a common feature amongst all the outbreak MSLP averages, was considered by Hannay (1959) and Elliott (1989) to be important in the establishment of a southern Australian cold air outbreak event. The absence of significance indicates that, although a regular climatological feature in the study region, its exact bearing on the onset of a cold outbreak is questionable. Another interesting feature of the anomaly plots is the large number of statistically significant regions in middle and high latitudes (apparent, in particular, for the outbreak day and one day before) which appear to be reasonably uniformly spaced, with regions of alternative negative and positive anomalies. Hence the atmosphere appears to organise itself in the lead up to and during a cold air outbreak event. The wavelike structure of this important result suggests that planetary-scale Rossby waves are associated with the establishment of a cold outbreak situation.

Rossby waves of differing wave number are related to contrasting synoptic arrangements, which may allow the cold air outbreak phenomena to be categorised in terms of the associated wave structure of the atmosphere. Spatial spectral analysis was performed on the composite July anomalies for each of the days considered above. The analysis was conducted at 50°S, the latitude showing greatest organisation. As expected from the anomaly plots, spectral analysis does indeed convey that planetary-scale Rossby waves and a significant amount of atmospheric organisation are associated with the July cold air outbreaks. A full analysis shows wave number 3 to be quite pronounced, with a strong contribution from wave numbers 1 and 4, for the day of the outbreak and one day before. The atmospheric organisation was restricted to these two days.

Whether or not conditions of this type are typically responsible for the onset of a cold air outbreak over Melbourne, and indeed whether these conditions are unusual compared to a number of days selected at random, is beyond the scope of this study. The usefulness of the discovery of the hemispherical organisation of the atmosphere surrounding the July cold air outbreaks is not diminished by this as it serves as another aspect to further characterise cold air outbreaks and hence provides an important stepping stone in the understanding of cold air outbreaks over Melbourne.

Conclusions

Melbourne cold air outbreaks are not as easily described (i.e. simply surges of Antarctic air) as may be at first thought. Indeed, just the distribution of months in which the thirteen outbreaks between May 1972 and June 1991 were deemed to have occurred was surprising, but explainable, when considering the relationship between the outbreak criterion and both daily temperature frequency analyses for each month and local warming trends. The selection of cold outbreak events is not an uncomplicated procedure. The criterion used here was found to be biased towards the selection of events in the cooler months and hence the conclusions reached are limited because of this.

The outbreak events examined show that, in general, the common preconception that out-
breaks are the result of surges of air of recent Antarctic origin is not correct for the majority of cases. Isobaric trajectory analyses for the events investigated show that only the July 1986 outbreak is conclusively the result of impinging Antarctic air. However, this might also be the case for the July 1982 event which shows an Antarctic origin for the day after the outbreak. Average outbreak trajectories show that, on the whole, outbreaks are associated with middle rather than high latitude air. On examination of the individual one to six-day travel air parcel trajectories for the winters of 1972, 1980 and 1986, it was found that the relationship between latitude of origin and Mel-
bourne temperature is not particularly strong and there exists no exclusive relationship between air of high latitude origin reaching Melbourne and 'cold' temperatures. When compared to mean trajectories for all days from the same winters, the outbreak trajectories do not differ greatly despite an obviously greater meridional influence.

Melbourne cold air outbreaks were able to be categorised into three broad types. Six of the thirteen outbreaks were termed 'classic' outbreaks and were established by a strong and quickly moving south to southwesterly airstream in the wake of a cold front with associated cloud and precipitation influences restricting increases in temperature during the day. The surging nature of this type of outbreak was apparent in many of the corresponding temperature versus time plots. Trajectories for this type were found to originate from high latitudes. The four outbreaks fitting into the 'warm front' category were the result of a returning maritime polar air mass across Melbourne ahead of a warm front with clouds and precipitation playing, as in the classic type, an important role in helping to keep the maximum temperature low. The third and least common category, in which only three events were grouped, is the 'blocking anticyclone' type which occurred as a result of pools of air from just southwest of the Bight moving over Victoria behind southwesterly cold fronts. These cool air masses remained almost stationary over Melbourne under the influence of very slow-moving blocked anticyclones which also led to slight easterlies from over the Tasman Sea. The easterlies served to humidify the cool pool leading to foggy conditions which severely reduced surface solar insolation and kept temperatures low.

In terms of prediction, difficulties could arise due to the individual peculiarities of many of the outbreaks. Although a knowledge of the broad synoptic structure may assist in the characterisation and understanding of outbreak events, there are indications that outbreaks do not necessarily occur in the presence of 'outbreak-type' synoptic conditions.

Composite anomaly MSLP patterns showed statistically significant atmospheric organisation around the hemisphere at mid-latitudes. Spectral analysis indicated that anomaly patterns with wave numbers 1, 3 and 4 were significant on both the outbreak day and the day before. This suggests that distinct planetary-scale Rossby waves may play an important role in the establishment of cold air outbreaks over Melbourne.

The relatively small sample size considered in this research, however, makes it impossible to conclude that all Melbourne 'outbreaks' display synoptic characteristics of the three types identified here. An analysis of Melbourne outbreaks over a longer period would be an important progress towards obtaining a more comprehensive understanding of these events.

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**References**


Appendix

Trajectory model

The trajectory model (developed by Dr Rachel Law) calculates horizontal parcel trajectories through cubically interpolating the wind fields in space and linearly in time using one-hour time steps over the 24 hours between data records. The new parcel location is found via a fourth-order Runge-Kutta method (Allam and Tuck 1984; Law 1993) which computes the two wind components as a weighted mean of the winds at approximate (since the exact trajectory is unknown) points along the trajectory. The distance travelled by the parcel and the direction of travel from north are used, via spherical geometry, to calculate a new parcel position following a great circle path.

The east-west \( u \) and north-south \( v \) wind components are used to calculate the distance travelled and the direction of travel from:

\[
\begin{align*}
\xi(u, v) &= (u^2 + v^2)^{1/2} \Delta t/r \quad \ldots \quad 1 \\
\alpha &= (\pi/2) - \tan^{-1} (v/u) \quad \ldots \quad 2
\end{align*}
\]

where:
- \( \xi = \text{distance travelled (in radians)} \)
- \( \alpha = \text{direction of travel (in radians)} \)
- \( \Delta t = \text{time step} \)
- \( r = \text{radius of the earth} \)

With a latitude, longitude starting point of \((\vartheta_1, \lambda_1)\) at time \( t_1 \), the trajectory end point \((\vartheta_2, \lambda_2)\) is determined via:

\[
\begin{align*}
\vartheta_2 &= \sin^{-1}(\cos\xi\sin\vartheta_1 + \sin\xi\cos\vartheta_1 + \cos\alpha) \quad \ldots \quad 3 \\
\lambda_2 &= \lambda_1 + (u/|u|)\sin^{-1}(\sin\xi\sin\vartheta_1/\cos\vartheta_2) \quad \ldots \quad 4
\end{align*}
\]

In Eqs 1 to 4, the \( u \) wind component is determined by the Runge-Kutta method via:

\[
u = 1/6(u_1 + 2u_2 + 2u_3 + u_4) \quad \ldots \quad 5
\]

where:

\[
\begin{align*}
u_1 &= u(\vartheta_1, \lambda_1, t_1) \quad \ldots \quad 6 \\
u_2 &= u(\vartheta_2, \lambda_2, t_1 + \Delta t/2) \quad \ldots \quad 7 \\
u_3 &= u(\vartheta_3, \lambda_3, t_1 + \Delta t/2) \quad \ldots \quad 8 \\
u_4 &= u(\vartheta_4, \lambda_4, t_1 + \Delta t) \quad \ldots \quad 9
\end{align*}
\]

with similar expressions for \( v \).

The positions \((\vartheta_2, \lambda_2), (\vartheta_3, \lambda_3), \) and \((\vartheta_4, \lambda_4)\) are separated from \((\vartheta_1, \lambda_1)\) by distances of \(1/2\xi(u_1, v_1), 1/2\xi(u_2, v_2)\) and \(\xi(u_3, v_3)\) respectively as calculated using equations 1–4. The Runge-Kutta method chosen is considered to be of greater accuracy and efficiency than many other schemes (Law 1993).