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Severe heat waves in Southern Australia: synoptic climatology and large scale connections

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Abstract This paper brings a new perspective on the large scale dynamics of severe heat wave (HW) events that commonly affect southern Australia. Through an automatic tracking scheme, the cyclones and anticyclones associated with HWs affecting Melbourne, Adelaide and Perth are tracked at both the surface and upper levels, producing for the first time a synoptic climatology that reveals the broader connections associated with these extreme phenomena. The results show that a couplet (or pressure dipole) formed by transient cyclones and anticyclones can reinforce the HW similarly to what is observed in cold surges (CS), with an obvious opposite polarity. Our results show that there is a large degree of mobility in the synoptic signature associated with the passage of the upper level ridges before they reach Australia and the blocking is established, with HW-associated surface anticyclones often initiating over the west Indian Ocean and decaying in the eastern Pacific. In contrast to this result the 500 hPa anticyclone tracks show a very small degree of mobility, responding to the dominance of the upper level blocking ridge. An important feature of HWs is that most of the cyclones are formed inland in association with heat troughs, while in CS the cyclones are typically maritime (often explosive), associated with a strong cold front. Hence the influence of the cyclone is indirect, contributing to reinforce the blocking ridge through hot and dry advection on the ridge's western flank. Additional insights are drawn for the record Adelaide case of March 2008 with fifteen consecutive days above 35°C breaking the previous record by 7 days. Sea surface temperatures suggest a significant air-sea interaction mechanism, with a broad increase in the meridional temperature gradient over the Indian Ocean amplifying the upstream Rossby waves that can trigger HW events. A robust cooling of the waters close to the Australian coast also contributes to the maintenance of the blocking highs locally, which is a fundamental ingredient to sustain the HWs.

Keywords Cyclones · Anticyclones · Heat waves · Cold waves · Climate variability

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1 Introduction

Synoptic activity in the Southern Hemisphere (SH), particularly extratropical cyclone and anticyclone behaviour, is strongly associated with large-scale climate variability. Cyclones and anticyclones are important because they arise from a manifestation of wave patterns in the upper levels, transporting heat and momentum between the equator and the poles and driving most of the mid-latitude weather. A particular area of study that has become very important is weather extremes, as they pose a very significant (increasing) threat to life and property in times of accelerated population growth and climate change. In fact, the Intergovernmental Panel on Climate Change (IPCC) has strengthened the notion in its Fourth Assessment Report that the effects of temperature increases have been well documented with "some aspects of human health, such as heat-related mortality, infectious disease vectors, and allergenic pollen in high and mid-latitudes" becoming more prevalent (IPCC 2007).

Many areas of the world have become increasingly under threat of suffering the consequences of widespread heat wave (HW) events, as their likelihood of occurrence grows. Europe has had many recent instances of unprecedented HWs affecting large populated areas with a very high mortality rate, particularly in the summers of 2003 and 2006 (e.g. Black et al. 2004; Fink et al. 2004; Fouillet et al. 2006; Fischer et al. 2007). The August 2003 HW alone was the worst natural disaster in Europe of the last 50 years, with an estimated death toll exceeding 30,000 people (De Bono et al. 2004). The effect of extended periods of extreme heat can be devastating on human activities and mortality rates increase substantially during and after a HW (Medina-Ramón et al. 2006; Nogueira and Paixão 2007). A link between hot temperatures and an increase in violent behaviour is also observed (Anderson 1987), as well as a decline in mental health (Hansen et al. 2008). The structural integrity of buildings and utilities are affected, with the melting of tarmac and excessive expansion of metal structures such as railway lines. There is also a higher stress on the electricity supply, due to the increase in air conditioning use and increased resistance in the power lines during high temperatures. As noted by Kysely (2009) the probabilities of very long HWs have already risen by an order of magnitude over the last 25 years, and the projections under different emission scenarios is for this trend to continue (Meehl and Tebaldi 2004; IPCC 2007).

In Australia the situation is particularly sensitive primarily because of the natural dryness inherent to the continent. This has been exacerbated over the southern areas due to a record-breaking drought (coined the "Big Dry Drought") that lasted at least 13 years, from about 1997 to 2009 (e.g. Cai and Cowan 2008a; Verdon-Kidd and Kiem, 2009). The Big Dry Drought is currently giving signs of breaking down as of the end of 2010, but only further analysis will be able to determine whether the drought will break down in the long term or if the relative wetness of 2010 is an isolated response to the strong La Nina conditions that developed over that year.

The isolation of Australia and its limited resources also mean that the agriculture as a whole has been severely affected by the combination of high temperatures and very dry weather (Cai and Cowan 2008b), as the relative humidity can drop to values in the order of 1% during a HW. With vegetation drying out the enhanced potential for catastrophic bushfires is enormous. One such bushfire event occurred in the state of Victoria in February 2009 killing 173 people with an economic impact of at least $1.02 billion Australian in insurance claims, becoming known as Black Saturday (BS) (Cai et al. 2009). Black Saturday was the worst bushfire in the recorded history of Australia. The BS event was preceded by a record-breaking HW in Victoria with temperatures hitting near 49°C for the first time in recorded history.

A crucial aspect of extreme weather is the large scale connections (known as teleconnections) which give dynamic support for the establishment of local weather extremes. For instance, research shows that for cold waves in the SH the atmospheric anomalies responsible for the cold pattern can originate many days earlier on the opposite side of the hemisphere [e.g. cold waves in Australia can be triggered by a signal travelling from South America, and South American cold waves can be triggered by anomalies arising from the Australian region mainly through Rossby wave propagation (Pezza and Ambrizzi 2005; Ashcroft et al. 2009)].

In the case of HWs a blocking pattern usually prevents cold fronts from bringing relief to the hot weather, leading to the persistence of warm advection from inland areas under clear skies allowing for substantial warming during the day and little relief during the night. While persistence (duration of the event) is a key component, the dynamics is reliant on the synergy between a transient baroclinic wave train and the enhancement of the blocking. Solar heating, static stability and the dryness of the air also play fundamental roles. The dynamics of blocking highs are associated with an upper level meandering of the jet stream causing the winds to split, forming a cut off region from the mean flow for several days (Egger 1978). Blocking anticyclones have a high incidence of occurrence in the 140–180°E region (Wiedenmann et al. 2002), contributing to the warm advection into south-eastern Australia. However, we make the point that the perception of low mobility (or blocked pattern) associated with HWs does not give a complete description of how they form. In many instances the teleconnections associated with HWs can point to anomalies originating in regions far away from where the phenomenon took place similarly to what is observed during cold surges.

A better understanding of the large scale connections is essential to improve the forecasts of HWs. For instance, a preliminary compilation of Rossby wave propagation associated with conditions similar to the BS event reveal that the anomalies that produced the catastrophic bushfire conditions can be traced to a wave pattern arising from South America many days earlier (Reeder 2010). Certainly, the synoptic behaviour of cyclones and anticyclones is an important manifestation of how the large scale can interact with weather extremes. In this article we explore the large scale synoptic associations with HWs in Melbourne, Adelaide and Perth through the use of an automatic tracking scheme applied to the surface and 500 hPa geopotential height. We present a synoptic climatology of extreme HWs in those areas with a discussion of the large scale dynamics and climate variability.

2 Data and methods

The temperature data used is the daily maximum after 9 a.m. local time and minimum before 9 a.m. local time, provided by the Australian Bureau of Meteorology. The stations used in this study are Melbourne Airport (37.6°S, 144.8°E), Adelaide Airport (35.0°S, 138.5°E) and Perth Airport (31.9°S, 116.0°E). These stations were chosen because they have a long, robust recorded history and represent southern Australia's eastern, central and west regions respectively. Airport stations were chosen due to the good quality of the dataset and their proximity to the respective cities, yet still remaining light in urbanisation. The National Centers for Environmental Prediction/ National Center for Atmospheric Research (NCEP/NCAR) Reanalyses were used for the study of general circulation and cyclone and anticyclone trajectories. The period of analysis spans from January 1979 to March 2008.

HWs are defined as a period of 3 consecutive days in which a temperature threshold was met or exceeded. To avoid a seasonal bias, the 90th percentile of the monthly climatological mean maximum temperature was used (Simmonds and Richter 2000), making the temperature threshold dependant on month and the location of the station. This criterion is similar to alternative definitions used elsewhere (e.g. Trenberth et al. 2007; Della-Marta et al. 2007; Carril et al. 2008). In our definition we account for the fact that the effects of HWs are mostly severe (especially in terms of human mortality) when there is a lack of relief between hot days. Therefore a restriction was included in the definition to account for this effect in that the minimum temperature must be above or equal to the minimum temperature 90th percentile for the given month on the second and third days of the HW. The first day was not included because it is unlikely the HW would have started before 9 a.m. local time on the first day. A summary of the HW criteria used is as follows:

- Period: January 1979–March 2008
- 90th percentile using monthly climatologies.
- Maximum temperature ≥90th percentile of the maximum temperature for the month in which the heatwave begins for a minimum of 3 consecutive days.
- Minimum temperature ≥90th percentile of the minimum temperature for that month on the second and third days of the HW.

The Melbourne University automatic tracking scheme (Murray and Simmonds 1991) was used to calculate the cyclone and anticyclone trajectories and their statistical properties. This algorithm utilizes a totally automatic approach for diagnosing low and high pressure centres on a sphere and calculating their tracks (Simmonds and Murray 1999). The scheme was chosen because of its proven reliability in capturing very accurately the weather patterns and synoptic climatology of the transient activity in the Southern Hemisphere (Jones and Simmonds 1993, 1994; Simmonds et al. 1999; Simmonds and Keay 2000; Pezza and Ambrizzi 2003, 2005), and because it deals directly with sea level pressure, giving a synoptic focus to the analyses.

This tracking scheme consists of a two step process of identification and tracking. The algorithm firstly uses an input of gridded reanalysis data and processes the information using a bi-cubic spline fit to a 90 × 90 polar stereographic array. Using this pressure field, minima (maxima) are identified through the maxima (minima) pressure laplacian relative to a specified threshold for 8 neighbouring grid points. Inflexions in the pressure surface are used to identify troughs. The second stage of the scheme then tracks centres using a prior movement and probability weighted identification of centres between analyses. Tracking data is then compiled for the identified cyclones, and descriptive statistics recorded. The identification of each cyclone and anticyclone associated with HWs was completed by diagnosing the systems *geostrophically* associated with each heat wave on a case by case basis on a similar principle as in Pezza and Ambrizzi (2005). All the in built parameters such as Laplacian thresholds and scheme calibration were equivalent to the ones tested by Pezza and Ambrizzi (2003) for mid-latitude systems. Only tracks lasting more than 48 h were included in the analysis.

3 Results

3.1 Heat wave variability

Figure 1 shows (a) the monthly maximum temperature 90th percentile for January over the period 1950–2005 and (b) the rainfall deciles for the period October 1996 to May 2009, respectively. This figure helps set up the climatological environment to understand the impact of HWs in Australia. All capital cities and important regional centres are shown in Fig. 1a, with the cities of Melbourne, Adelaide and Perth lying to the south-eastern, south and south-western corners of the country respectively. The 90th temperature percentile shown in Fig. 1a indicates that most of the country can frequently experience average maximum temperatures above 30°C during the summer, with values as high as 42°C inland. Note that these are not the percentiles of daily maximum temperatures, but of monthly average of the daily maxima. From this perspective it is obvious that most of Australia can experience very hot conditions on a persistent basis throughout summer.

The 90th percentile values for Perth and Adelaide are similar, with slightly warmer values than Melbourne. This

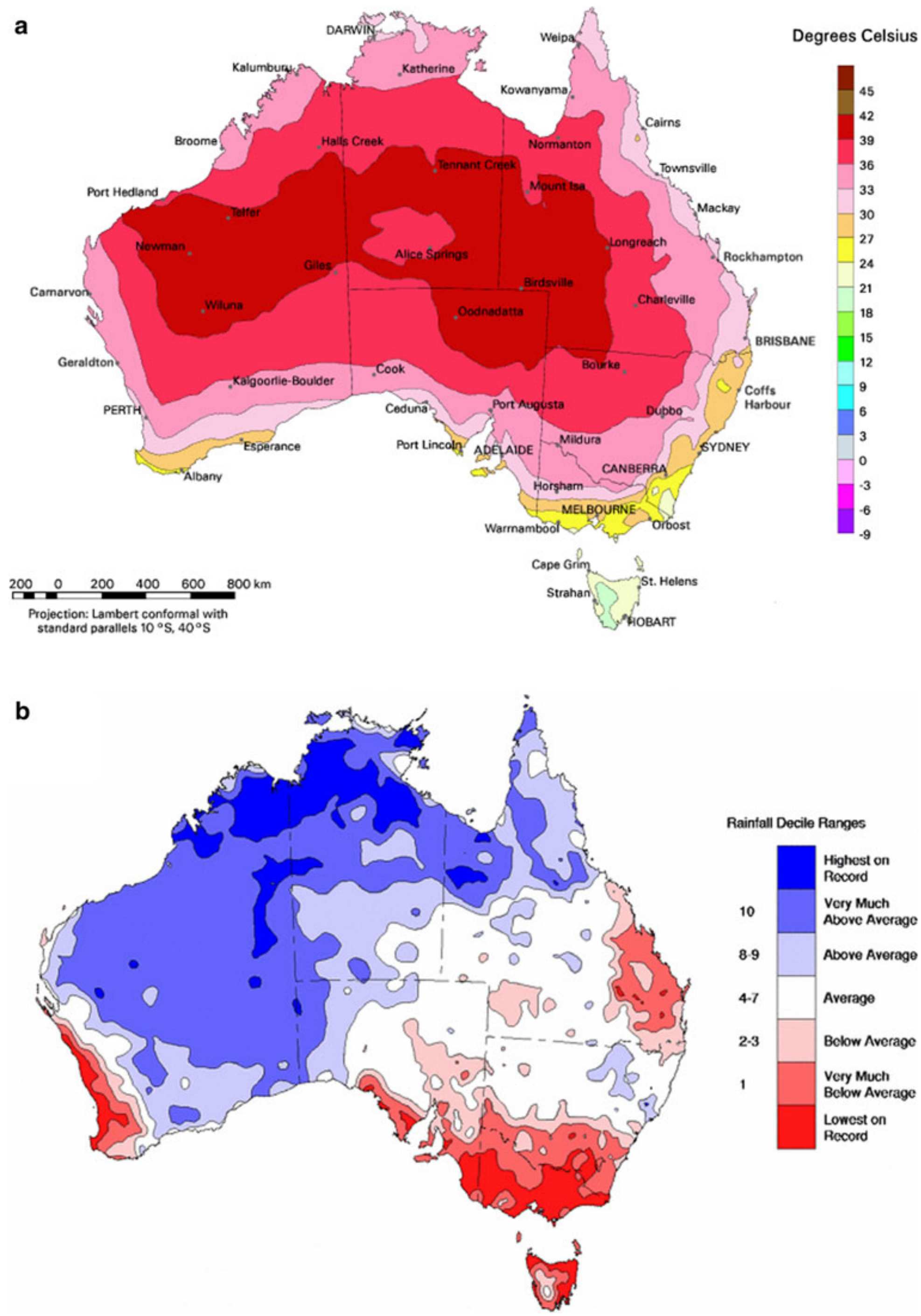


Fig. 1 **a** Monthly maximum temperature 90th percentile for January over the period 1950–2005 and **b** rainfall deciles for the period October 1996 to May 2009. Courtesy of Australian Bureau of Meteorology

panorama highlights why the southern regions of the country were chosen in this research. Being cooler areas closer to the Southern Ocean the southern areas can experience a dramatic temperature contrast over the summer months driven by the temperature gradient between coastal and inland areas evident in the figure. Under these conditions the occasional establishment of a blocking high to the east will create favourable conditions for persistent advection of inland air to the south affecting the area to the west of the blocking. Temperatures as high as 45°C can be measured almost anywhere on the southern coast, except in Tasmania or over high elevated areas in the south-eastern ranges. Inland Australia, where the climate responds to desert conditions, has less variability and a higher frequency of hot days, and the impacts of HWs are less relevant.

As discussed at the introduction, Australia is a naturally dry continent with average annual rainfall below 500 mm in most of the country except near the coastal areas. Within this distribution a large interannual variability is observed, but as shown in Fig. 1b in the last 13 years many areas along the southern and eastern coasts have experienced the lowest rainfall on record. This anomaly was measured over a 13 year period using high quality station data that in many instances span for about a century of data, indicating an unprecedented decline in rain measured over such a long period without breaks. The extensive drought regions have affected the most productive agricultural areas of the country and the locations where the largest state capital cities lie. This is important as it sets the context for HWs as the impacts over drought-stricken areas have been amplified, and the probability of bushfires and other weather-related disasters has increased substantially (Cai et al. 2009). It is also interesting to observe that the rainfall has increased over the northern regions of the country, where the most important regional centre is the city of Darwin. Often it is observed that the enhanced convection occurring over the northern areas during the summer monsoon can amplify the subsidence in the south of the country, acting to worsen the HW intensity via increasing the dryness of the air, the static stability and the vertical depth of the HW.

Figure 2 shows the time series of the length of HWs for (a) Melbourne, (b) Adelaide and (c) Perth over 1979–2008 with different seasons given by the colours. In Melbourne (Fig. 2a) there is a greater frequency of winter HWs in the second half of the analysed period, with an almost complete absence in the first half. This complements the results of Ashcroft et al. (2009) who showed a strong reduction of cold surges in Melbourne over the winter season. For the remaining seasons no trends can be discerned, with a pronounced interannual variability. The longest HW lasts between 10 and 13 days for any season, but years without occurrence of HWs in any season were also observed.

Adelaide (Fig. 2b) shows HWs in all seasons with no evidence of trends in the duration of the events. The longest event on record occurred in the autumn of 2008 with a duration of 15 days. A pronounced variability is also evident, with less activity towards the end of the 1990s and more activity in the 1980s and after 2000. In Perth (Fig. 2c) there are very few HWs in winter, but during summer and autumn the events can be quite protracted with a length of up to 12 consecutive days. A marked interannual variability is present but no signs of interdecadal variability, or trends, are apparent.

It is also of interest to study the intensity of HWs. Figure 3 shows the time series of the summer (DJF) average maximum and minimum temperatures during HWs measured as a function of the amount of degrees exceeding the monthly 90th percentile for (a) Melbourne, (b) Adelaide and (c) Perth. In this figure, and for the remaining of the paper, we restrict the analysis to DJF because this is the

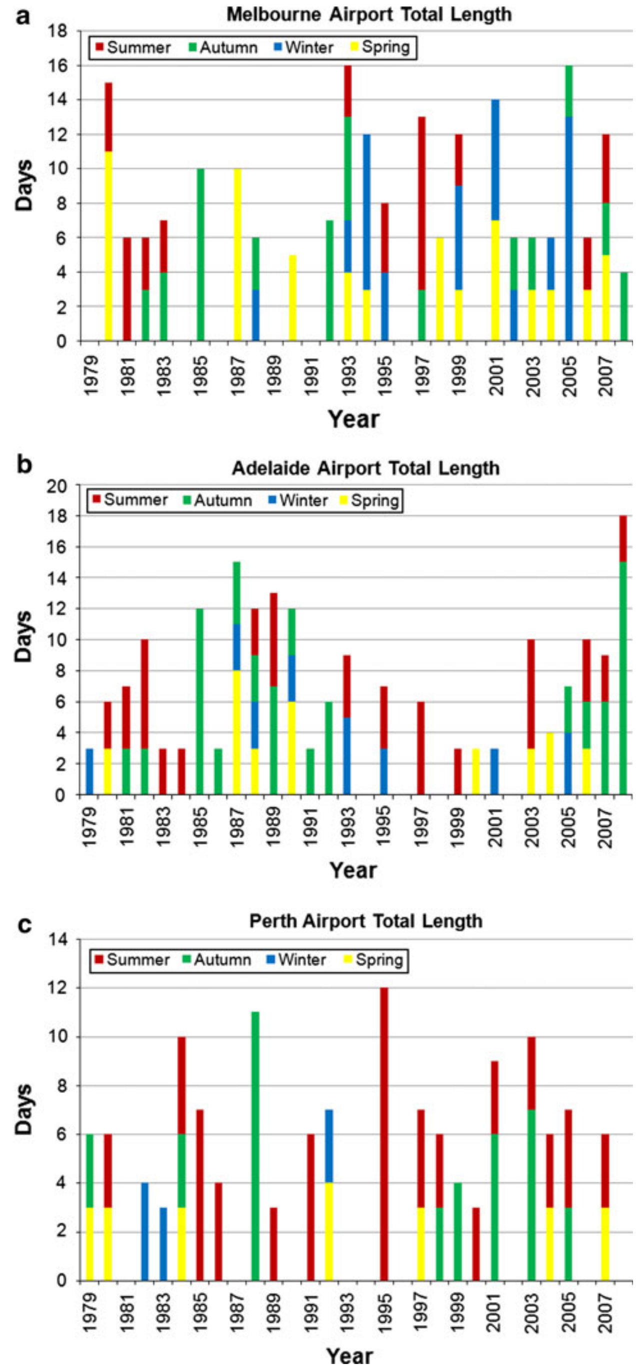


Fig. 2 Time series of the length of HWs over **a** Melbourne, **b** Adelaide and **c** Perth over 1979–2008. Different seasons are given by *colours*

season where the greatest impacts on human mortality are felt. The month of HW occurrence is indicated on top of the bars in the graph. Where multiple HWs occurred in the same season, an average was taken. Figure 3a shows that the minimum temperature anomalies during HWs in Melbourne are usually greater than the HW-associated maximum temperature anomalies, implying that HWs in that locality can offer very little respite during the night. An apparent increase of the relative minimum temperature, in relation to the maximum temperature, was observed during the 1990s.

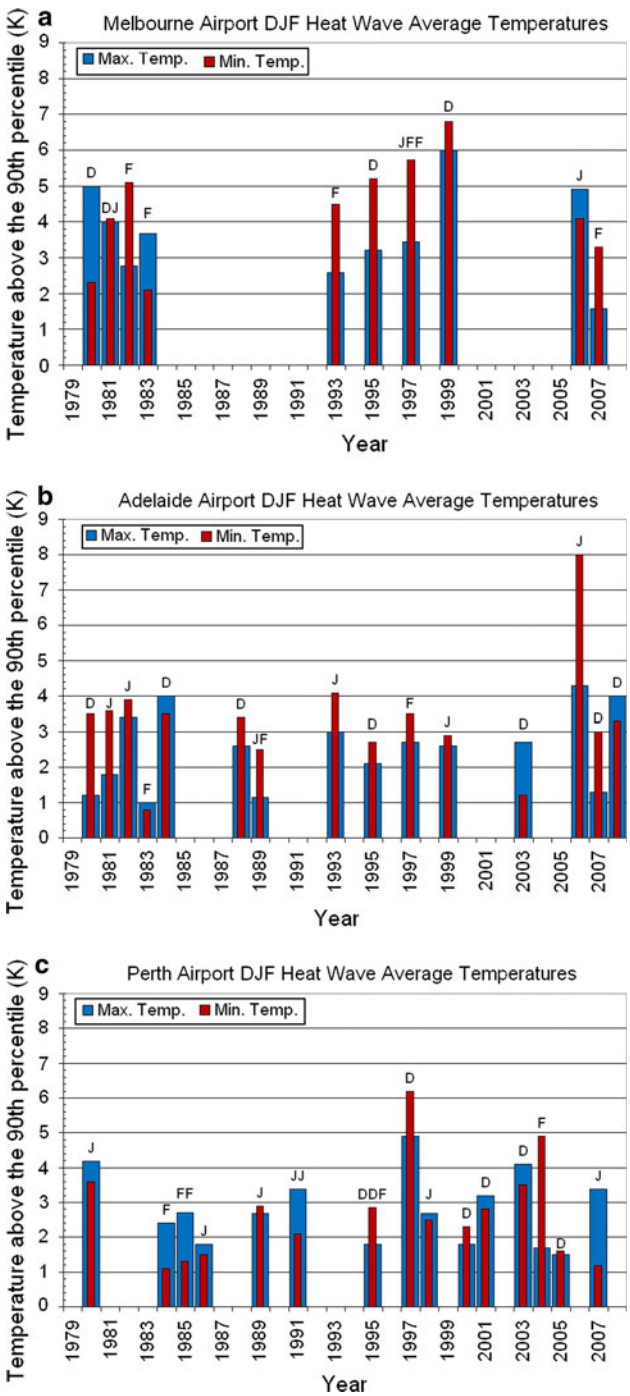


Fig. 3 Time series of the summer (DJF) relative maximum (*blue*) and minimum (*red*) temperature averaged during HWs measured as a function of the amount of degrees exceeded in relation to the monthly 90th percentile for **a** Melbourne, **b** Adelaide and **c** Perth. The letters above the *bars* indicate the month(s) of occurrence of HW(s)

In Adelaide the distribution is more uniform than in Melbourne, but the relative minimum temperatures also have a tendency to be greater than the maximum. January 2006 appears as an outstanding example in which the minimum temperature was 8° above the 90th percentile, about twice the value of any other event recorded within the period of analysis. In Perth the situation is different with a greater number of cases in which the relative minimum temperature is lower than the relative maximum, possibly indicating a higher tendency for an occurrence of a sea breeze. In the remainder of the paper we will discuss the large scale circulation and physical processes associated with summer heat waves, showing the dynamical causes for the persistence of very high temperatures on the southern coast.

3.2 General circulation

Figure 4 shows the DJF composite of mean sea level pressure (MSLP) on the first day of HWs in (a) Melbourne and (b) Perth overlaid with the 925 hPa winds. The stippling shows the areas where the MSLP is statistically significant above the 95% confidence level using a two-tailed Student's t test. The contours show the composite of surface temperature anomalies. The total number of summer events is 13 in Melbourne and 19 in Perth. This figure gives the key circulation conducive to HWs in extratropical Australia, revealing that a significant pressure couplet (or dipole) is responsible for sustaining the events in both cases.

The circulation associated with HWs in Adelaide is very similar to that of Melbourne just slightly shifted to the southwest, and is omitted in the interest of space. Figure 4 also shows that the temperature anomalies form a large scale warming region associated with the advection from inland Australia. For Melbourne this area of warm anomalies is very widespread and intense, while for Perth the HW has a more modest spatial signature.

Ashcroft et al. (2009) calculated the signature of the circulation associated with cold surges in Melbourne and Perth. Their results show that an intense pressure couplet is the main driver where both the cyclone and anticyclone are part of a baroclinic wave located over the ocean during the day of the cold surge (their Fig. 1). Our results show an approximate opposite pressure couplet (H and L) associated with HWs, but the fundamental difference is that the main driver of HWs is the anticyclone, while the cyclone is related to the monsoonal climatological trough (or heat low) normally observed over the summer months (Sturman and Tapper 2008).

These results also agree with Murphy and Simmonds (1993) and Kysely (2007) in that the persistence of the large scale circulation is a fundamental component of both

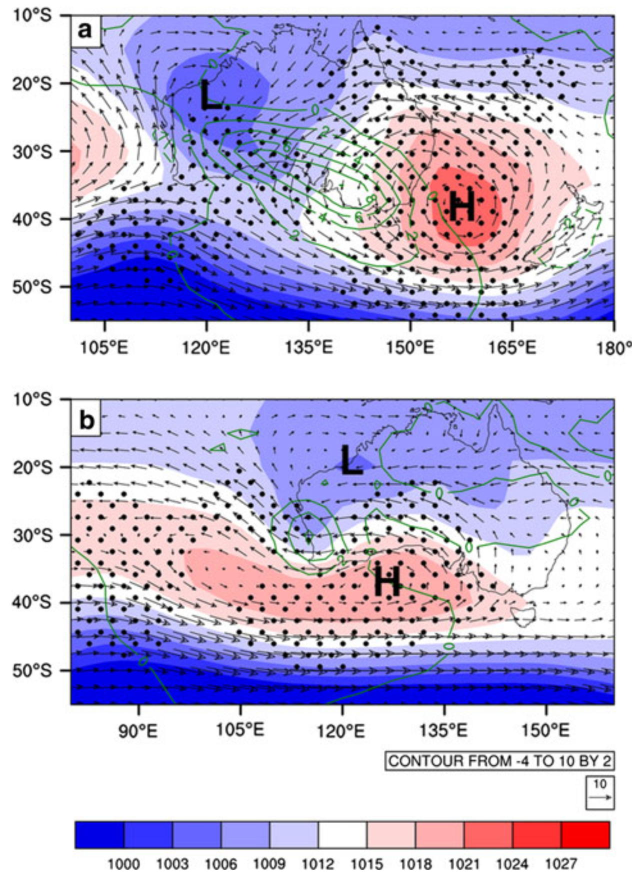


Fig. 4 DJF composite of MSLP (*shading*) and surface temperature anomalies (*contours*) on the first day of HWs in **a** Melbourne and **b** Perth overlaid with 925 hPa winds. Units are in hPa (*colour scheme*), K (*contours*) and wind magnitude in m s^{-1} given by vector size. Number of events is 13 for Melbourne and 19 for Perth. Statistically significant MSLP areas above the 95% confidence level are given by stippling

hot and cold events. In particular, Kysely (2007) also notes that the intensification of anomalies due to higher persistence of circulation patterns would likely be more important for warm temperature extremes than cold surges. Comparing Fig. 4a and b it is evident that while the locations of the lows are similar, in the Melbourne case the low (L) feeds from a strong band of north-easterly winds (warm and humid during the summer) on its eastern flank.

Figure 5 shows the hemispheric pattern of MSLP for Melbourne (a) and Perth (b) HWs respectively, superposed onto the composite of 1,000–500 hPa thickness. The statistically significant areas are given by the stippling. This figure shows that the HWs in Australia are associated with a hemispheric wavenumber 4 which is more symmetrical in the Melbourne case. The pattern in both cases conceptually suggests a relationship with the positive phase of the Southern Annular Mode, although correlation analysis with individual HWs does not show a significant association.

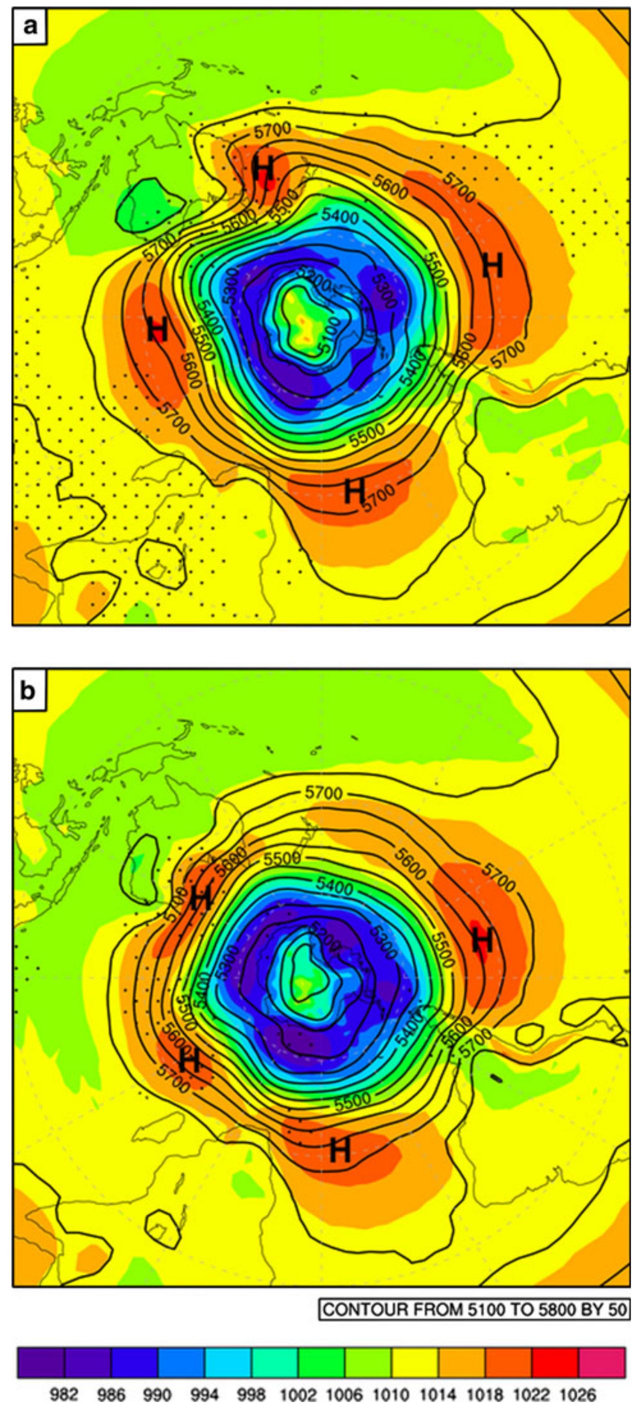


Fig. 5 As in Fig. 4, but showing the hemispheric pattern of mean sea level pressure (hPa) and 1,000–500 hPa thickness (m). The enhanced areas of subtropical ridge are indicated by *H*

The 1,000–500 hPa thickness shows that the dip associated with the Melbourne HW is the most pronounced feature in the hemisphere, with an axis directly to the west of the significant blocking ridge. In Perth, the statistically significant MSLP areas are associated with a prolonged trough extending from the Indian Ocean towards the Australian bight.

Figure 5b also shows that the subpolar trough is stronger during Perth HWs compared to Melbourne events, while the monsoonal trough over the northwest is more active during Melbourne HWs. In this case the tropical eastern coast is under the influence of a trough with lower thickness (Fig. 5a), which would bring the right ingredients for precipitation given the onshore flow to the north of the blocking high. This was observed during the BS bushfires in February 2009. Floods occurred on the north-eastern coast while a HW was experienced in Melbourne (Reeder 2010).

Figure 6 shows the composite of 500 hPa geopotential height anomalies from day −8 to day 0 in relation to the start of summer HWs in (a) Melbourne and (b) Perth for the period 1979–2008. The areas that are statistically significant are given by the stippling. These results indicate a striking large scale feature of Rossby wave amplification over the Indian Ocean particularly between day −5 and day 0, demonstrating that the main driver of HWs lies in high latitude dynamics associated with baroclinic instability. This assertion will be later shown to be corroborated by the fact that the meridional SST gradient in the Indian Ocean is shown to be significantly enhanced during HWs in both Melbourne and Perth (Sect. 3.4).

Figure 7 of Ashcroft et al. (2009) shows a wave train over the Indian Ocean for day −3 that strongly resembles the HW wave train observed in Fig. 6, but obviously with the opposite polarity (phase). This implies that the dynamics that initiates HWs is surprisingly similar to the processes behind wintertime cold surges, while the nuances of how the wave trains interact upon approaching the continent are different. In particular, the wave anomalies during HWs amplify and become semi-stationary, with a ridge building strongly over Tasmania from day −2. This ridge is responsible for the maintenance of the surface high over the Tasman Sea as indicated by the 'H' in Fig. 4a.

The upper level pattern also demonstrates that the heat trough shown in Fig. 4a presents little interaction with the baroclinic wavetrain to the south, although once the HW is established that feature will contribute to reinforce the pattern. This is further discussed in Sect. 3.3.1. The wave train can be followed up to day −8 (for Melbourne) but the ridge that builds over Tasmania is passing over Perth on day −5 emanating as a pulse from the subtropical high over the Indian Ocean (days −8 to −6). Over the south of Australia between days −8 and −6 we can see that the region was already under a ridge before the additional pulse from the Indian Ocean started to amplify, and that Tasmania stays under the influence of a high almost over the whole time of analysis. As we will discuss later this persistence of anticyclonic conditions over southern Australia is one of the key aspects that contribute to the establishment of the blocking over the Tasman Sea once the baroclinic wave train has arrived from the Indian Ocean.

For Adelaide the wavetrain anomalies leading up to HWs are very similar to the pattern discussed in Melbourne although slightly shifted to the west (figure not shown). In Perth (Fig. 6b) the main wavetrain is shifted towards the Indian Ocean. The downstream amplification in this case is less intense and can only be followed for about 3 days before onset. Hence we believe that the wavetrain amplification (or lack of) helps to explain why HWs in Perth are not as long-lasting as those in Melbourne and Adelaide. It follows that the empirical notion held by many practitioners that HWs mostly respond to a localised blocking pattern is not as accurate as one would have thought, in that the build up of planetary scale baroclinic energy is also associated with how long-lived HWs can be.

Figure 7 shows the 300 hPa average streamlines and wind magnitude for the first day of summer HWs in (a) Melbourne and (b) Perth. From this figure there is a clear enhancement of the subtropical jet to the south of Australia during HWs, with a potent jet streak of about 45 m/s. The jet is oriented towards the southeast for the Melbourne case, but it presents a slight bending towards the northeast in Perth. This configuration is a thermal wind response to the maximum temperature anomalies at the surface for each case, giving dynamical support for the establishment of the blocking high over the Tasman (Melbourne case).

The anomalous 300 hPa wind field for the Melbourne case (not shown) reveals a closed anticyclonic centre over the west of Tasmania, with strong upper level easterly anomalies in the south-eastern coast of Australia. While this local enhancement is part of the wave train propagation discussed in Fig. 6 covering the whole Indian Ocean, the maximum wind anomalies are observed in association with the anticyclonic cell that becomes established over south-eastern Australia. For HWs in Adelaide the pattern is slightly displaced to the west, but is qualitatively similar to Melbourne (figure not shown). To better understand the large scale connections and their impact on the transient synoptic systems we analyse in the next section the synoptic climatology of tracks.

3.3 Synoptic climatology

3.3.1 Surface tracks

Figure 8a shows the synoptic climatology of all MSLP cyclones (in blue) and anticyclones (in red and yellow) associated with summer HWs in Melbourne. While the whole duration of the tracks associated with the HW is

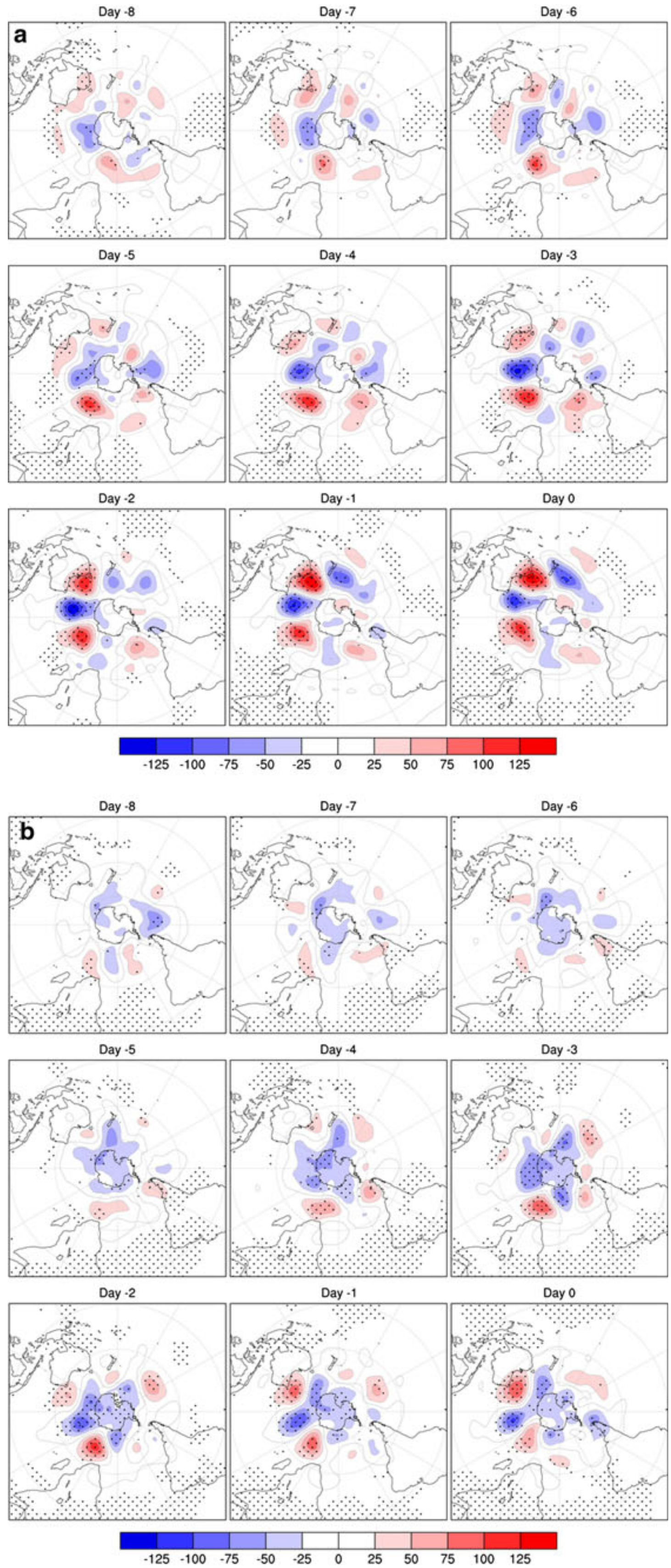


Fig. 6 Composite of 500 hPa geopotential height anomalies from day −8 to day 0 in relation to the start of **a** Melbourne and **b** Perth summer HWs. Units are in meters. Number of events is 13 in Melbourne and 19 in Perth, period 1979–2008. Statistically significant areas above the 95% confidence level are given by stippling

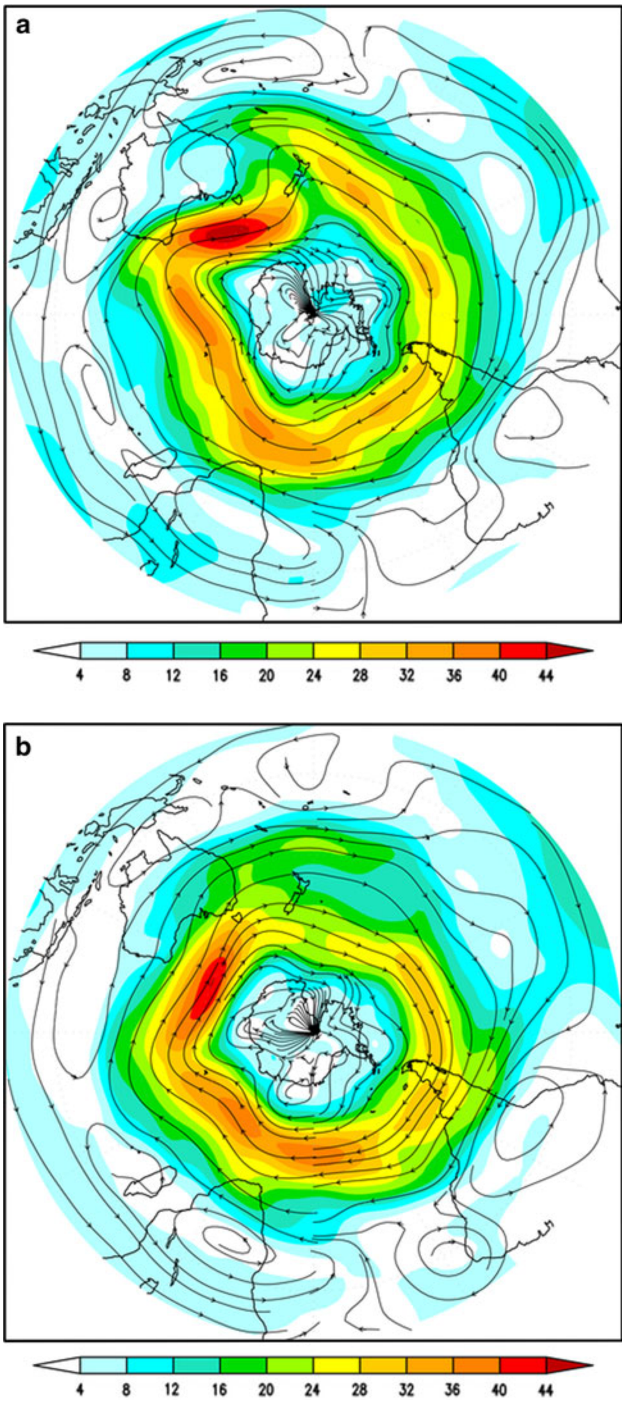


Fig. 7 300 hPa average streamlines and wind magnitude for the first day of summer HWs in **a** Melbourne and **b** Perth. Units are in m s^{-1}. Number of events is 13 in Melbourne and 19 in Perth, over the period 1979–2008

shown, the tones of red and dark blue represent the location of the systems while the HW is occurring (as defined in Sect. 2). This figure is very revealing, showing that there is a large scale hemispheric connection with HWs. During the occurrence of HWs the anticyclones concentrate over the Tasman Sea while the cyclones are displacing from inland Australia towards the coast. This complements the pattern discussed in Fig. 4a, showing that although the MSLP for the first day of the events show an association with the inland heat trough towards the western coast (Fig. 4a), in reality it is the interaction with the baroclinic trough to the southwest of Australia that gives the mobility associated with HWs. The wider scattering of anticyclones in red also implies that the transient systems become temporarily blocked during the HW events, continuing their eastward progression several days later.

Figure 8a also reveals that most cyclones continue to travel to the southeast after the HWs are finished, undergoing cyclolysis around Antarctica, while some of the anticyclones can reach as far as the eastern Pacific Ocean. While the origin of cyclones is predominantly local (a synergy between the heat trough and the wave train arriving from the Indian Ocean) many of the anticyclones initiate in the Indian Ocean.

The behaviour of synoptic tracks for Adelaide HWs (not shown) is similar to that of Melbourne but slightly shifted to the west, with an equally-spread group of systems throughout the hemisphere. However, the interaction with the inland trough appears more pronounced than in Melbourne, with a greater density of cyclones observed inland. Some of the anticyclones associated with Adelaide HWs also emerge from the South American coast. Figure 8b shows the behaviour of Perth's synoptic tracks, where it is evident that there is an equally important participation of the couplet cyclone-anticyclone while the HWs occur (tones of red and dark blue). The orientation of the couplet is different to the Melbourne case, presenting a more north–south alignment rather than an east–west alignment (i.e., cyclones to the north and anticyclones to the south). This is in agreement with the MSLP pattern discussed in Fig. 4b, showing that the couplet has a fundamental role in bringing the hot continental easterly winds into Perth.

The interaction with the heat trough on the west coast as shown in Fig. 4b is not simply a by-product of the MSLP observed over the summer. The synoptic tracks display a wide pattern of cyclones interacting with the ridge as in a blocking pattern over the east Indian Ocean. Compared to Melbourne the cyclones are less mobile, with only a few cases continuing to travel towards the southeast after the demise of the HW. However, the anticyclones present an equally large displacement with many tracks crossing at least half of the Pacific Ocean after causing the HW. In short, Fig. 8 demonstrates from another perspective the large scale connection with hemispheric Rossby waves associated with HWs discussed earlier, contrary to the notion that HWs arise as a simple manifestation of a local blocked pattern.

We also note that while all HW cases were associated with at least one anticyclone trajectory at the sea level, not

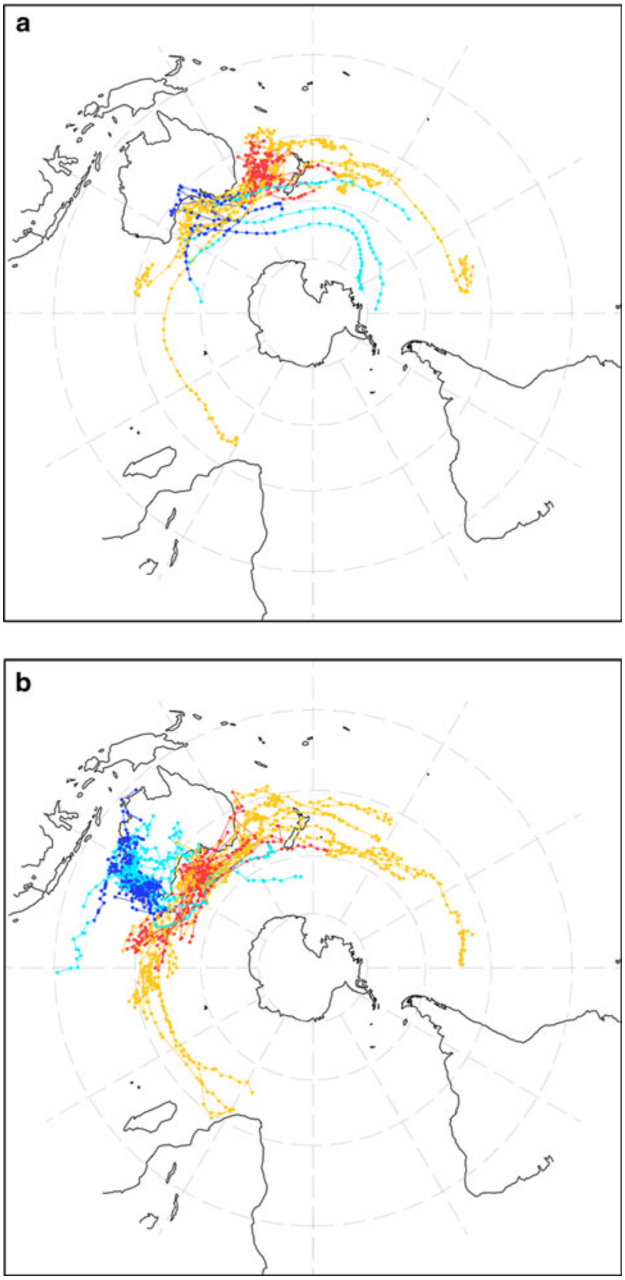


Fig. 8 Mean sea level cyclone and anticyclone synoptic tracks (every 6 h) describing the whole lifecycle of each system associated with summer HWs in **a** Melbourne and **b** Perth. Anticyclones are shown in *red* and *yellow* and cyclones are shown in *blue*. The area traversed by systems while the HW is occurring is given by darker tones (*red* for anticyclones and *darker blue* for cyclones). Number of HW events is 13 in Melbourne and 19 in Perth, over the period 1979–2008

all cases were accompanied by cyclones. In fact only 55% of Melbourne HWs had a cyclone track associated with the geostrophic flow conducive to the advection of warm air over Melbourne. This is another difference from the case of cold surges, where almost all cases studied by Ashcroft et al. (2009) presented a couplet. This implies a lesser degree of mobility associated with HWs.

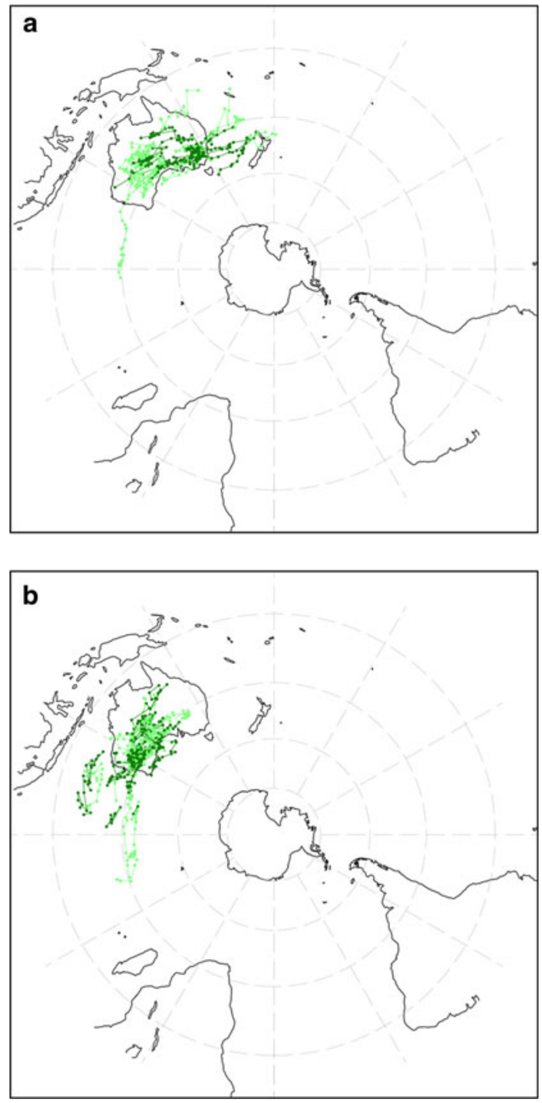


Fig. 9 As in Fig. 7 but for the tracks of 500 hPa geopotential height maxima

3.3.2 500 hPa tracks

Figure 9 shows the synoptic climatology of 500 hPa geopotential height maxima tracks associated with summer HWs in (a) Melbourne and (b) Perth. The darker tones of green indicate the positioning of the tracks while the HWs are occurring. It is interesting to note that the mobility associated with the mid-level ridge is much lower compared to that of the surface tracks. This suggests that most of the enhancement associated with the wave train that originates in the Indian Ocean (Fig. 6) occurs locally over inland Australia, possibly as a response of teleconnective features such as the monsoonal circulation to the north of the ridge.

It is also remarkable that after the end of the HW the 500 hPa anticyclones do not continue further east, regardless of the wave train continuing to propagate with a detectable anticyclone at the surface. A possible dynamic interpretation is that the transient signal that initiates the HW resonates with the Australian continent when there are favourable conditions for a blocking ridge to be established. When the blocking loses intensity the HW finishes and the transient pulse continues to travel to the east as shown by the surface tracks.

3.4 Oceanic effects

Sea surface temperature (SST) can have an influence on the strength and development of synoptic systems. As noted by Ashcroft et al. (2009), a colder than average SST tends to inhibit convection promoting anticyclone development or intensification. Similarly, a warmer than average SST increases the instability in the lower atmosphere, leading to an intensification of cyclonic systems. Even more importantly, an enhanced meridional gradient in SST can lead to a greater amplification of Rossby waves upstream from the triggering areas of both cold surges and HWs. One of the new key results that we bring in this paper is that, indeed, there is evidence that such process plays a role in HW formation.

To explore the association of SSTs with HWs the SST anomalies for the week before the day of the event were examined on a case by case basis and the results were composited. These anomalies at each grid point were calculated by comparing SST data to a quadratic regression curve fitted to the data for a 90 day period centred over each event day, then taking the average for the 7 days before each HW. This technique is the same as the one employed by Ashcroft et al. (2009). It ensures that global SST warming trends did not influence our results, nor did the time of year in which the HWs occurred.

Figure 10 shows the SST anomalies associated with summer HWs in (a) Melbourne and (b) Perth. Areas with at least 90% statistical significance are indicated by the crosses. The pattern reveals that large areas of the subtropical Indian Ocean are significantly warm while HWs are occurring in Australia, while the mid-latitudes tend to be colder than normal. This pattern tends to enhance the baroclinicity and can help explain the development of long-lasting wave trains coming from the Indian Ocean before the onset of the HWs.

Most importantly the areas where the blocking anticyclone is established during the HWs are significantly cold for both Melbourne and Perth cases, meaning that the Tasman Sea is colder than average during Melbourne HWs (Fig. 10a) and that the Southern Ocean to the south of Perth is significantly cold during Perth HWs (Fig. 10b). This significant result hints that the cold SSTs have an important role in contributing to the establishment of the blocking high via induced-subsidence, which is often observed over areas of negative SST anomalies. It also demonstrates that the average oceanic conditions associated with HWs in Melbourne and Perth are completely different, in fact they are almost the opposite pattern. Hence if the oceanic conditions are not favourable the probability of a very significant or extended HW should decrease. For instance, Melbourne would be unlikely to experience a very prolonged summer HW if the Tasman Sea is warmer than normal. The unusually wet and cool La Nina summer of 2011 is a recent example for the validity of this hypothesis.

The magnitude of the anomalies is small, but all the areas discussed above are significant. These anomalous areas can alter the heat fluxes associated with migratory cyclones and anticyclones, influencing the baroclinicity of the HW-associated trajectories noted in Fig. 8. While the coastal areas tend to amplify the blocking that leads to the HWs when the waters are colder than normal the greater meridional temperature gradient in the Indian Ocean would also contribute to amplify the wave train beforehand, resulting in a greater probability that when the anticyclone reaches the area where the HW will be triggered, it is already intense.

Remarkably Ashcroft et al. (2009) showed a similar increase in the meridional temperature gradient in the Indian Ocean during cold surges (see their Fig. 9), suggesting that the ocean's control of the dynamical processes intrinsic to baroclinic growth leading to extreme events is significant regardless of it being a cold surge or a heat wave. Our result also brings to light that the fundamental origin of HWs lies (surprisingly) in high latitude (baroclinic) dynamics, for without this preliminary development it is unlikely the blocking would have enough energy to sustain a prolonged HW event. One must still be cautious, without further analysis, of attributing direct causal physical mechanisms between the SSTs and HWs as individual cases might occur under a different synoptic pattern. Our findings offer a new factor for consideration when examining the dynamics of HWs, highlighting the important interplay given by the air-sea interaction.

3.5 Mobility of the wave train and HW persistence

In this section we present a short case study to exemplify the association between the wave train amplification and the persistence of the HW, a mechanism that, as discussed earlier, became evident via the composite analysis of hemispheric geopotential height several days before the onset. For this discussion we chose an extremely long-lived event in Adelaide where the HW was defined by a period of 15 days. As discussed next, the revealing feature of this case was the very significant mobility associated with the transient pulse that originated the event, as revealed by the trajectory of the anticyclone formed over the Weddell Sea.

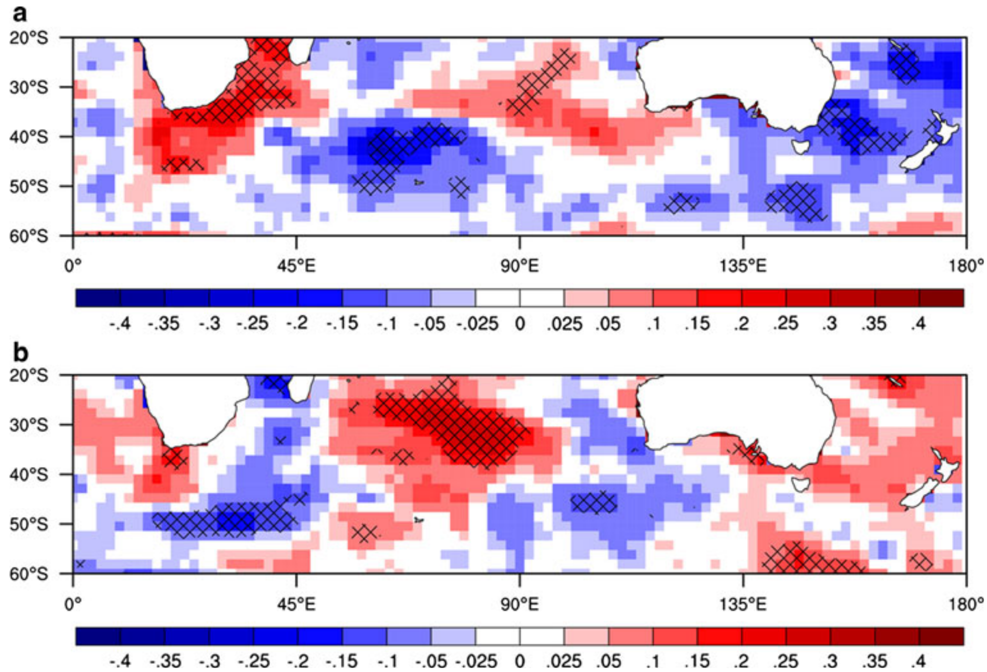


Fig. 10 Average SST anomalies (°C) over the ocean for the 7 days before a HW in Melbourne (**a**) and Perth (**b**). *Hatched areas* indicate regions of 90% statistical significance. Number of events is 13 in Melbourne and 19 in Perth, over the period 1979–2008

Figure 11 shows the evolution of maximum and minimum temperatures for the longest on record HW in Adelaide, occurring in March 2008. In this impressive autumn event the maximum temperatures remained above 34°C for fifteen consecutive days, making March 2008 the hottest month of March on record by a far margin. It can also be observed that the minimum temperatures remained above 20°C for most of the duration of the event. This case exemplifies remarkably well how the concept of mobility can be misleading in HWs. Certainly the synoptic pattern conducive to warm advection in Adelaide was very persistent, but a detailed synoptic analysis reveals that the anticyclone presented a remarkable degree of mobility associated with the baroclinic build up that triggered the event.

Figure 12 shows the trajectories of all surface cyclones and anticyclones (a) and of the 500 hPa anticyclones (b) associated with the Adelaide HW. As discussed earlier, this result shows that the surface anticyclone was originated in the sub-polar region close to the Antarctic Peninsula (Weddell Sea), traversing almost a full circle around the world in its total trajectory. Even in the portion related to the duration of the HW, shown in dark red, it can be observed that a great deal of mobility was still observed, indicating that the blocking high was formed by more than one single wave.

It is rather the local amplification of the incoming baroclinic waves in phase that explain the extremely large length of this event. In contrast, Fig. 12b shows that the trajectories at 500 hPa remained fairly local, restricted to inland Australia during the lifecycle of the event. This

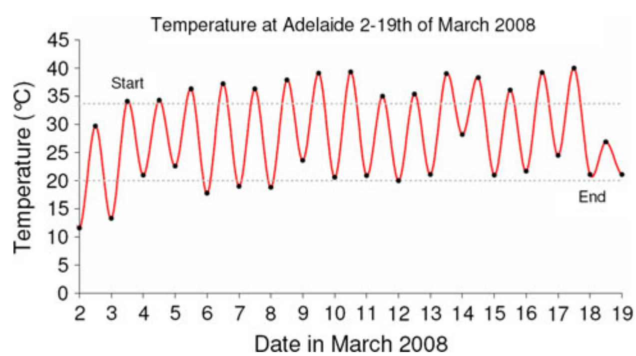
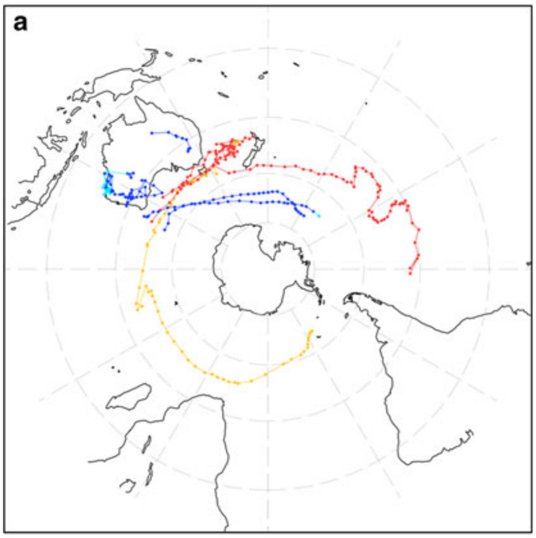


Fig. 11 Daily evolution of the maximum and minimum temperatures for the record-breaking HW of March 2008 in Adelaide. The *top* and *bottom dotted lines* indicate the 90th percentile of the maximum and minimum monthly temperature respectively

upper level pattern remains similar to the general outlook observed for the overall climatology in Melbourne and Perth (Fig. 9). It is also worth noting that the SST anomalies for this event were similar to the pattern shown in Fig. 10a, depicting colder than average SSTs around the blocking high.

Of relevance is that the surface anticyclone for this autumn case travelled a greater distance than any of the climatological summer cases discussed earlier (compare Figs. 8 and 12a), continuing its propagation to the east after enhancing the Tasman blocking (Fig. 12a). This aspect shows that the migratory baroclinic pulse does not disperse all of its energy during the heat wave until it dissipates. On the contrary, the wave train feeds from the marked temperature contrast of the event and continues to propagate towards South America. The cyclone tracks observed



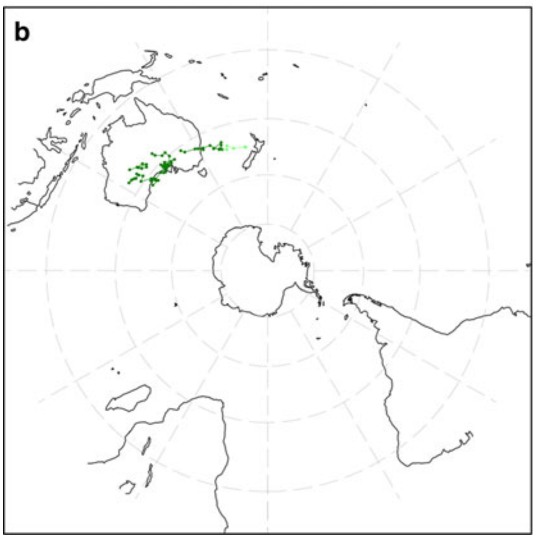


Fig. 12 **a** Mean sea level cyclone and anticyclone synoptic tracks (every 6 h) describing the whole lifecycle of the systems associated with March 2008 HW in Adelaide and **b** same as **a** but for 500 hPa geopotential height maxima. Anticyclones are shown in *red* and *yellow* and cyclones are shown in *blue* in **a**. The area traversed by systems while the HW is occurring is given by darker tones (*red* for anticyclones and *darker blue* for cyclones). The geopotential height maxima are given in *green* in **b**, with darker tones of *green* corresponding to the duration of the HW

during this case concentrate over the far west as well as in the Southern Ocean and on the eastern coast, showing a combination of the features associated with climatological HWs in Melbourne and Perth (compare with Fig. 8).

The combination of cyclonic features on the western and eastern coasts acted together to maximize the HW, helping to push hot air from the desert towards Adelaide. The cyclone track over the Southern Ocean is associated with baroclinic instability arising from the marked temperature contrast near the coast. While this particular result for Adelaide complements the previous climatological discussions for Melbourne and Perth it also highlights that most of the features seen collectively in the climatological maps (Figs. 8, 9) can also be present in a single case study, explaining why the March 2008 event was so extreme.

4 Concluding remarks

In this work we bring a large scale perspective to the heat events that occur in the southern parts of Australia. HWs, and the bushfires that are frequently associated with them, are a fundamental part of Australia's natural environment due to the inherent dryness of the country. This has been significantly aggravated by a long-term drought that has persisted for at least 13 years in south-eastern Australia (1997–2009), the Big Drought (Verdon-Kidd and Kiem 2009). The impact of increased average temperatures in Australia also means that HWs tend to occur in a background environment which has become more conducive to higher temperatures. Despite this, from the range of analyses used in this work we cannot infer that a statistically significant change in HW frequency and intensity has already occurred. A part of the problem in identifying a change in behaviour lies in the relatively short period used in our analyses, and also on the general problem of determining the significance of changes in rare and extreme events.

The fundamental mechanism of HWs was identified as a transient pulse arriving from the Indian Ocean which resonates with the Australian continent projecting a very strong ridge towards the south. The ridge becomes quasi-stationary during the events but the transient pulse continues to the east a few days later, forming a hemispheric pattern of baroclinic wave train that closely resembles the cold surge case except that it has the opposite polarity. There is a considerable degree of interaction with the semi-permanent heat trough near the western coast of the country for about half of the overall number of cases, with many heat lows moving towards the coast and interacting with a passing trough particularly in the Melbourne case. In fact, Melbourne HWs seem to be associated with a more enhanced monsoonal period in the tropical region of Australia when compared to Perth HWs. This agrees with the observation that many cases of Melbourne HWs have occurred at the same time when severe flooding was taking place in north-eastern parts of Australia.

The wave train amplification over the Indian Ocean is greater and more long-lasting for Melbourne events, explaining why HWs over the eastern part of Australia last longer than HWs over the western coast. This also seems to suggest that the eastern coast has a greater predictability because it relies more strongly on baroclinic processes for growth. The persistence of the HW also seems to be associated with an increased north–south SST gradient in the Indian Ocean (and hence an increase in baroclinicity) for both the Melbourne and the Perth cases. Most importantly the coastal areas where the anticyclones sit while the HWs are occurring coincide with negative SST anomalies, suggesting that the colder SSTs contribute to the establishment of the blocking high. While it is difficult to infer a definite causal relationship our results suggest that the interaction with the ocean is very important for HW generation and maintenance, highlighting the importance of baroclinic dynamics in high latitudes as a main precursor.

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