Author/s:
Jacobs, SJ;Pezza, AB;Barras, V;Bye, J

Title:
A new 'bio-comfort' perspective for Melbourne based on heat stress, air pollution and pollen

Date:
2014-03-01

Citation:
Jacobs, S. J., Pezza, A. B., Barras, V. & Bye, J. (2014). A new 'bio-comfort' perspective for Melbourne based on heat stress, air pollution and pollen. International Journal of Biometeorology, 58 (2), pp.263-275. https://doi.org/10.1007/s00484-013-0636-0.

Persistent Link:
https://hdl.handle.net/11343/283303

A new 'bio-comfort' perspective for Melbourne based on heat stress, air pollution and pollen

Stephanie J Jacobs, Alexandre B Pezza, Vaughan Barras, John Bye

Stephanie J Jacobs,
School of Earth Sciences
University of Melbourne
Victoria 3010
Australia
Email: stephanie.jacobs89@gmail.com

Alexandre B Pezza
University of Melbourne
Email: apezza@unimelb.edu.au

Vaughan Barras
Centre for Australian Weather and Climate Research
Bureau of Meteorology
Victoria 3008
Email: v.barras@bom.gov.au

John Bye
University of Melbourne,
Email: jbye@unimelb.edu.au

Abstract

Humans are at risk from exposure to extremes in their environment, yet there is no consistent way to fully quantify and understand the risk when considering more than just meteorological variables. An outdoor 'bio-comfort' threshold is defined for Melbourne, Australia using a combination of heat stress, air particulate concentration and grass pollen count, where comfortable conditions imply an ideal range of temperature, humidity and wind speed, acceptable levels of air particulates and a low pollen count. This is a new approach to defining the comfort of human populations. While other works have looked into the separate impacts of different variables, this is the first time that a unified bio-comfort threshold is suggested.

Composite maps of surface pressure are used to illustrate the genesis and evolution of the atmospheric structures conducive to an uncomfortable day. When there is an uncomfortable day due to heat stress conditions in Melbourne, there is a high pressure anomaly to the east bringing warm air from the northern interior of Australia. This anomaly is part of a slow moving blocking high originating over the Indian Ocean. Uncomfortable days due to high particulate levels have an approaching cold front. However, for air particulate cases during the cold season there are stable atmospheric conditions enhanced by a blocking high emanating from Australia and linking with the Antarctic continent. Finally, when grass pollen levels are high, there are northerly winds carrying the pollen from rural grass lands to Melbourne, due to a stationary trough of low pressure inland.

Analysis into days with multiple types of stress revealed that the atmospheric signals associated with each type of discomfort is present regardless of whether the day is uncomfortable due to one or multiple variables. Therefore, these bio-comfort results are significant because they offer a degree of predictability for future uncomfortable days in Melbourne.

Keywords

Apparent temperature, heat stress, PM_{10}, air pollution, pollen, thermal comfort

1. Introduction

Local environmental extremes can have many adverse health impacts on urban populations. Numerous studies have found links between high temperatures and hospital admissions (Basu and Samet 2002; Johnson et al. 2005; Linares and Díaz 2008; Pantavou et al. 2008; Loughnan et al. 2010; Li et al. 2012) and extreme temperatures with mortality (Curriero et al. 2002; Gosling et al. 2007; Anderson and Bell 2011; Laaidi et al. 2012; Schaffer et al. 2012; Son et al. 2012; Tobias et al. 2012). Air pollution is known to aggravate the respiratory system (Dockery and Pope 1994; Barnett et al. 2005; Simpson et al. 2005; Hansen et al. 2012) while grass pollen levels can negatively influence hayfever and asthma sufferers resulting in hospital admissions (Schäppi et al. 1998; Erbas et al. 2007). Furthermore, heat stress coupled with high levels of air pollution has been shown to increase mortality risk (Filleul et al. 2006; Ren and Tong 2006; Stafoggia et al. 2008). This study combines the impacts of heat stress, air pollution and pollen into one 'bio-comfort' threshold. This enables a broader classification of outdoor 'discomfort' where an average person will potentially experience heat stress, respiratory problems due to air particulate concentrations or hayfever symptoms.

There are many ways of describing human 'comfort', with the most popular using a thermal basis. These can be explored via different indices such as the Heat Index (Steadman 1979), Wind Chill Temperature (OFCM 2003), Wet Bulb Globe Temperature (WGBT) (Yaglou and Minard 1957) and the new Universal Thermal Comfort Index (UTCI) (Bröde et al. 2012). However, there is a distinction between indices that measure both thermal comfort and heat stress (e.g. UTCI) and indices that measure only stress such as the Heat Index. The Steadman (1994) apparent temperature (AT) equation is a universal index used in Australia by the Bureau of Meteorology to measure both thermal comfort and extremes such as heat stress. As discussed by Mendina-Ramon et al. (2006) there are significant variations among the population for how different people handle meteorological extremes, yet for a broad study and in the creation of the indices listed above parametrisations, such as for clothing thickness, are used to create models based on average populations.

Heat stress has been thoroughly studied with indices, such as the ones mentioned above, modelling and quantifying an average human's physiological response to different climatic variables. Thermal discomfort usually occurs on warm days coupled with high humidity, where a reduction in the body's ability to dissipate heat occurs. This can lead to an increased heart rate and hyperthermia (Pantavou et al. 2008). While there can be adverse health effects for humans in extreme heat and extreme cold (e.g. Curriero et al. 2002), Nicholls et al. (2008) and Bi et al. (2011) found that mortality in Melbourne due to extremely hot days is a significant issue for present and future generations. However, mortality rates due to cold temperatures are impacted by seasonal averages rather than extremely cold days (Nicholls et al. 2008). Therefore, this study has chosen to focus only on the potential for heat stress in Melbourne, as bio-comfort is discussed on a daily scale.

Climatic conditions relating to air pollution levels have also been investigated. For instance, a recent study shows that, in Greece, the sea breeze circulation is associated with an increase in particulate matter less than 10μm (PM_{10}) concentrations (Papanastasiou and Melas 2009; Papanastasiou et al. 2010). This is primarily due to the higher static stability associated with sea breezes, which do not favour the horizontal dispersion of pollutants. The dangerous synergy between air pollution and heat waves is well known in the literature. Warmer temperatures increase the rates of chemical reactions, enhancing natural emissions (e.g. nitrogen oxides from soil, volatile organic compounds from trees, etc.), increasing emissions from human sources (e.g. air conditioning use), the prevalence of bushfires and more frequent stagnation of hot air that alters the types of pollutants persisting in the urban boundary layer (see for instance Seguin and Berry (2008) and references therein). Moreover, Ren and Tong (2006) found a statistically significant relation between health, PM_{10} and temperature with PM_{10} having more adverse health effects on warm days than on cold days. This was quantified by Stafoggia et al. (2008) who used data from nine Italian cities and estimated that the risk of mortality increased by 2.54% in summer and 0.2% in winter when there was an increase in PM_{10} concentration of $10\mu gm^{-3}$.

Particulate matter is the biggest pollutant in Melbourne, Australia (Environmental Protection Agency (EPA) for the state of Victoria Air Monitoring Report 2011) and can travel large distances from rural areas to impact urban air quality (Hansen et al. 2012). This is due to Australia being an inherently dry, dusty country subject to very high temperatures. The majority of epidemiological studies focus on PM_{10}, which encompasses both coarse (2.5-10μm) and fine (less than 2.5μm) grains (World Health Organisation (WHO) global update 2005). The association between air pollution and human respiratory problems has been well documented (Barnett et al. 2005; Simpson et al. 2005) and is of specific concern to this study as the fine particles can be inhaled easily, thereby negatively affecting the throat and lungs (Dockery and Pope 1994).

Exposure to airborne grass pollen during the spring months is another concern in Australia. Ong et al. (1995) found that the grass pollen count in Melbourne is comparable to other temperate climates in Europe and this is associated with severe seasonal outbreaks of hayfever symptoms (Schäppi et al. 2007) and a dramatic increase in hospital admissions due to asthma (Erbas et al. 2007). Moreover, as discussed by Ong et al. (1995), the atmosphere of Melbourne during spring and summer contains approximately 70% of the total annual pollen count, with more than twenty different types of pollen identified over the two year study period. Tree pollen is the most common type of pollen in late winter and early spring, while grass pollen dominates the second half of spring and early summer. Ong et al. (1995) confirmed that grass pollen is the major source of allergenic pollen in the environment where most of the pollen is transported from pasture areas in the north to Melbourne. de Morton et al. (2011) studied airborne pollen variability finding that in Melbourne days with high or extreme pollen levels had winds of a continental origin (northerly winds) while days with low pollen levels had winds of a maritime origin.

This paper presents an assessment of the combined atmospheric and biological conditions that would result in an average person feeling uncomfortable, or ‘stressed’ outdoors. We define ‘bio-comfort’ as an overall concept that encompasses not only the variability of heat stress given by the apparent temperature (AT), but also incorporates concentrations of airborne pollutants known to have deleterious effects on human health. Using known thresholds of heat stress, PM_{10} and pollen, this study investigates the large-scale atmospheric circulation conducive to events in Melbourne when a bio-comfort threshold has been exceeded. From this, we show that robust large-scale anomalies are associated with the different types of ‘discomfort’, allowing us to draw a conceptual model of the synoptic circulations leading to their occurrence. This method differentiates itself from other common measures of human comfort such as the WBGT and the UTCI because it considers more than just meteorological variables. Furthermore, the results from this study offer a degree of predictability for future uncomfortable events in Melbourne.

2. Materials and methods

In order to measure the bio-comfort thresholds in Melbourne, meteorological data involving temperature, wind speed and humidity, as well as air pollution and grass pollen count data, were obtained.

The Australian Bureau of Meteorology measures outdoor thermal comfort using the Steadman (1994) AT, which incorporates the effects of dry bulb temperature (T), vapour pressure (e) and wind speed (|U|) and is calculated as follows:

$$AT = T + 0.33e - 0.7|U| - 4 \quad (1)$$

where T is the dry bulb temperature (°C), e is the vapour pressure of air (hPa) and |U| is the 10m wind speed (ms^{-1}).

To calculate the AT for Melbourne, 1.2m temperature (°C), 10m wind speed (ms^{-1}) and 1.2m dew point temperature D (°C) data from Melbourne Airport weather station (37.7°S, 144.8°E) were obtained. Vapour pressures were derived from the dew point temperature D (°C) using the moisture equation:

$$e(hPa) = \exp\left(1.8096 + \frac{17.269D}{237.3+D}\right) \quad (2)$$

Melbourne Airport weather station was selected due to its close proximity to the city of Melbourne, the length of the observational record and the homogeneity in its wind speed measurements.

To identify heat stress conditions in relation to the Melbourne climate a percentile approach was implemented. Percentiles are commonly used in the literature for region dependent analysis and to identify heat waves (e.g. Pezza et al. 2012). Gaffen and Ross (1998) found that the 85th percentile of AT is closely correlated with weather related mortality, where the 85th percentile was defined using AT data from the two warmest months of the year over a reference climatology. This study has adapted the method from Gaffen and Ross (1998) with heat stress conditions in Melbourne defined as when the daily 3pm AT exceeds the 85th percentile. The 85th percentile was derived using the 3pm AT from

January and February (the two warmest months in Melbourne) over the reference climatology of 1981-2000. This resulted in an AT heat stress threshold of 27.2°C.

Daily 3pm AT data from Melbourne Airport weather station were used to assess the number of days during which people felt thermal discomfort due to heat stress conditions. While the maximum temperature can occur at a different time in the day, obtaining accurate dew point temperature and wind speed data at this time is difficult, therefore 3pm data was chosen to represent the daily maximum temperature. The study period for heat stress conditions in Melbourne was taken from 1 January 1973 to 31 December 2011.

Continuous 10m observational wind speed datasets in Australia have come under scrutiny since the replacement of pressure tube anemometers (Dines) with rotating cup anemometers (Synchrotac) in Automatic Weather Stations. Dines anemometers do not record very low wind speeds (Gold 1936), while Synchrotac anemometers are known to overestimate wind speeds due to instrumental inertia (Gorman 2004). This has resulted in a discontinuity in many wind speed data sets, which is highlighted when the wind speeds are averaged over time (Jakob 2010). Melbourne Airport weather station 10m observational wind speeds were independently checked and proved to be continuous. Therefore, Melbourne Airport weather station was deemed appropriate for thermal comfort AT analysis.

The World Health Organisation (WHO) daily average air quality concentration guideline for PM_{10} is $50\mu gm^{-3}$ (WHO global update 2005). However, this guideline is not a classification of safe or unsafe levels of PM_{10} and does not attempt to quantify the long-term risks from exposure to PM_{10}. Indeed, since there appears to be no threshold within the literature below which there are no adverse health effects from air pollution (Brunekreef et al. 2012), the WHO air particulates guidelines are based in the context of local constraints, capabilities and public health priorities. This study has classified any day that exceeds the WHO daily air quality guideline of PM_{10} as an uncomfortable day. It is expected that when this guideline has been surpassed, the short-term effects of PM_{10}, such as respiratory problems, may be felt immediately rendering the day uncomfortable to an average person.

Daily average PM_{10} (μgm^{-3}) data were obtained from the Footscray (37.5°S, 144.5°E) air pollution monitoring station. Footscray is an industrial/residential suburb of Melbourne with PM_{10} levels that are slightly higher than that of other urban air pollution monitoring stations in Melbourne. Nevertheless, Footscray air pollution monitoring station was chosen for comfort analysis due to the length of its dataset and for its close proximity to the Melbourne Airport weather station. Detailed analysis into the source of the PM_{10} in Melbourne can be found in Delaney and Marshall (2006) and shall be discussed briefly in the context of this research in section 4.

Hyde (1972) found that, in London, hayfever symptoms manifest themselves in 100% of sufferers when the grass pollen count exceeded 50 grass pollen grains m^{-3}. Moreover, Antépara et al. (1995) discovered that in Bilbao Spain 100% of hayfever sufferers experienced symptoms when exposed to grass pollen counts greater than 37 grass pollen grains m^{-3}. While grass pollen is not necessarily the most abundant type of pollen it is highly allergenic even when in small quantities compared to the total pollen count (Gioulekas et al. 2004). The Asthma Victoria Foundation, the local governing body for Melbourne regarding pollen counts and forecasts, defines a grass pollen count as high when it is greater than or equal to 50 grass pollen grains m^{-3}. Therefore, when the pollen count in Melbourne is high, the day will be deemed uncomfortable due to the likelihood of havfever sufferers experiencing symptoms.

Grass pollen count data are collected daily by the School of Botany at the University of Melbourne, in conjunction with the Asthma Victoria Foundation, from October to December each year. The study period for air pollution and grass pollen spans the period 1 January 1997 to 31 December 2011. Figure 1 shows a map with the locations of Melbourne Airport weather station, Footscray air pollution monitoring station and the University of Melbourne.

European Centre for Medium-Range Weather Forecasts ERA Interim reanalysis (Dee et al. 2011) daily 6Z (or 6GMT, which corresponds to 4pm Melbourne time) mean sea level pressure (MSLP) data were used to investigate the large scale atmospheric circulations of when an uncomfortable day occurred in Melbourne. 6Z MSLP data was chosen as this is the closest available reanalysis time step to when the maximum temperature and, hence, heat stress is most likely to occur in Melbourne.

The one-sample two-tailed Students t test was employed to calculate whether the atmospheric averages and anomalies calculated with ERA Interim were statistically significant.

3. Results

Comfort condition	AT > 27.2°C (1997-2011)	$PM_{10} > 50 \mu gm^{-3}$ (1997-2011)	Pollen > 50 grains m^{-3} (1997-2011)
AT > 27.2°C	231	14	20
$PM_{10} > 50 \mu gm^{-3}$	14	62	0
Pollen> 50 grains m^{-3}	20	0	289

Table 1 The number of uncomfortable days in Melbourne due to the three bio-comfort thresholds over the period 1997-2011

Table 1 shows the total number of uncomfortable days in Melbourne due to the three different bio-comfort thresholds over the period 1997-2011. It highlights that pollen is the most common form of discomfort in Melbourne with 289 days observed over the whole period, followed by ATs greater than 27.2°C (i.e. heat stress, 231 days) and PM_{10} (62 days). Table 1 also shows that there are only 34 days over the analysis period 1997-2011 where Melbourne simultaneously experiences two types of discomfort. Throughout the study period, uncomfortable days due to pollen are not observed simultaneously with uncomfortable days due to PM_{10} meaning that there are no days that experience all three forms of discomfort during 1997-2011.

3.1 Heat stress

Figures 2a and 2b show the number of days per year in which the 3pm temperature and AT exceed 27.2°C at Melbourne Airport weather station over the period 1973-2011. It can be seen that there are no long term trends with either variable, but a marked interannual variability is present with the temperature values ranging from 22 to 54 days per year, and the AT values varying from 3 to more than 29 days per year. There is a short statistically significant increasing trend in the temperature days from 1995-2010 (seen in Figure 2a) which is not reflected in the AT values, showing that in Melbourne the impact of wind and humidity are responsible for maintaining relatively unchanged thermal comfort conditions despite the number of warm temperature days increasing in recent years. This is further highlighted by the trend in Figure 2c, showing the increasing difference between the number of days per year where the temperature exceeds 27.2°C and the number of days per year where the AT is greater than 27.2°C. Furthermore, Figure 2c illustrates that there are significantly more days in Melbourne where the temperature exceeds 27.2°C than when the AT exceeds 27.2°C. This indicates that, on average, the AT in Melbourne is almost always cooler than the temperature highlighting the greater influence of cooling winds on Melbourne weather and thermal comfort conditions.

Figure 3, which shows the MSLP average and anomaly for the days in which the AT exceeds 27.2°C in Melbourne, allows us to understand the atmospheric conditions that are conducive to a high AT day (i.e. heat stress conditions). For consistency with other bio-comfort variables (PM_{10} and pollen) to be explored later in this section, this MSLP analysis period was reduced to 1997-2011.

Figure 3a shows an average high pressure system located over the Tasman Sea, with a continental low pressure anomaly highlighting the passage of warm air from the Australian interior to Melbourne (Figure 3b). Heat waves often occur in southeast Australia due to the presence of an anticyclone over the Tasman Sea (Pezza et al. 2012). Here, anticyclones draw hot dry continental air from the north to Melbourne.

To assess the origins and dynamics of the anticyclone, polar stereographic plots of the MSLP anomaly for the 5 days preceding and day of an uncomfortable day due to heat stress in Melbourne are shown in Figure 4. This figure is different from Figure 3 in that it only includes days that do not have any other forms of discomfort. Therefore this plot is mutually exclusive from the other bio-comfort variables. This separation is useful because, as shown in Table 1, the total counts associated with different indicators are not independent. Figure 4 shows a slow moving anticyclone that acts to amplify the inland trough and the geostrophic circulation arising from this combination enhances the northerly winds. From Figure 4 it is also clear that the weather systems to create heat stress conditions in Melbourne are part of atmospheric wave trains originating over the Indian Ocean. This is similar to the results of Pezza et al. (2012) during a heat wave.

3.2 PM_{10}

Footscray air pollution monitoring station recorded 62 days in which the WHO daily average concentration guideline level for PM_{10} (50μgm^{-3}) was exceeded during the study period 1997-2011. Figure 5 shows the number of uncomfortable days per year due to PM_{10}. According to Australian legislation (EPA Victoria), the maximum number of days that can exceed regulation levels is five, marked by the horizontal line in Figure 5. Years with active bushfire seasons (2003, 2006, 2009) had total numbers of days exceeding this limit. This confirms that bushfire is a major source of particulate pollution in Melbourne, which raises the PM_{10} well above the background level in active years (Delaney and Marshall 2006).

In order to study potential seasonal effects on the circulation leading to polluted days in Melbourne we have split the air pollution analysis into warm months (November to April) and cool months (May to October). Figures 6a and 6b show the MSLP average and anomalies for when an uncomfortable PM_{10} day occurs during the warm period and Figures 6c and 6d show the MSLP average and anomalies for when an uncomfortable day due to PM_{10} occurs during the cool period. Analogous to Figure 3a, Figures 6a and 6c show a region of high pressure present over the Tasman Sea. However, in the cool months the high pressure is larger and extends onto the continent, indicating that the high concentration of PM_{10} in cool months is associated with stable, stagnant air masses over Melbourne. Moreover, Figures 6b and 6d display an anomalous low pressure to the south of the continent. This is indicative of a cold front approaching, a signal not seen in the days with heat stress conditions. Figure 6b also highlights the passage of continental northwesterly winds approaching Melbourne, bringing dust and particulates from inland during the warm months.

Polar stereographic plots of the MSLP anomaly for the 5 days before and the day of an uncomfortable event due to PM_{10} in Melbourne during the warm months are shown in Figure 7. These plots are mutually exclusive from other bio-comfort variables and the PM_{10} events that occur during the cooler months. From Figure 7 it is clear that, like heat stress in Melbourne, these systems are not stationary and are part of wave trains that originate over the Indian Ocean. The high pressure system (shown on Figure 7) intensifies and becomes mobile three days before the uncomfortable event. Two days before the uncomfortable PM_{10} event a trough begins to form and travel towards Melbourne bringing a cold front that reaches Melbourne on the day of the uncomfortable event. Cold fronts bring a change in wind direction, which can then spread bushfires creating more airborne particulate matter and, hence, result in events where the PM_{10} concentration exceeds guideline levels.

Figure 8 shows polar stereographic plots for the MSLP anomaly of the 5 days before and the day of an uncomfortable event due to PM_{10} in Melbourne during the cool months. Like Figure 7, the days used in these plots are mutually exclusive from the other bio-comfort variables. In contrast to the moving wave train weather systems associated with warm PM_{10} events, Figure 8 shows stable and stagnant air masses present when an uncomfortable day due to PM_{10} occurs during the cooler months in Melbourne. A very strong blocking high is present covering most of Australia from five days before the uncomfortable event. This high evolves projecting a crest to the south which links up with another blocking high emanating from the Antarctic continent two days before the uncomfortable event. The blocking highs reinforce each other and contribute to the complete stagnation of the flow, preventing the westerly changes from arriving into Melbourne and dispersing the pollutants.

3.3 Grass pollen

Figure 9 shows the number of uncomfortable days per year due to the pollen count being greater than or equal to 50 grass pollen grains m^{-3} in Melbourne. It should be noted that this study period largely coincides with the ‘Big Dry’, a severe drought that affected southeastern Australia from 1997-2009 (e.g. Ummenhofer et al. 2009). This drought slowed plant growth resulting in four consecutive years (2006-2009 inclusive) of below average numbers of uncomfortable days due to pollen. However, once the drought ended, the number of uncomfortable days per year nearly tripled from eight days in 2009 to 22 days in 2010.

Figure 10 shows the MSLP average and anomaly for when a high grass pollen count day occurs in Melbourne. Consistent with uncomfortable heat stress and PM_{10} days, Figure 10a has an area of high pressure over the Tasman Sea; however, the magnitude is not as large as in Figures 3a, 6a and 6c. Moreover, Figure 10b features a low pressure anomaly over the continent, with another low pressure anomaly east of New Zealand. Figure 10b demonstrates that winds on a high grass pollen day in Melbourne are of a continental (northerly) origin, agreeing with de Morton et al. (2011). Analysis into the five days preceding an uncomfortable day due to pollen (figure not shown), indicate that the circulation conducive to high grass pollen days is relatively stationary. This is in contrast to the heat stress and warm month PM_{10} bio-comfort atmospheric signals, which presented a high degree of mobility.

3.4 Simultaneous types of discomfort

As shown in Table 1, there are a small number of days that simultaneously experience two types of discomfort. Incidentally, the 14 days that are uncomfortable due to heat stress conditions and PM_{10} are between December and March and, hence, use PM_{10} days from the warm period only, while the 20 uncomfortable days due to heat stress and grass pollen are between October and December. This is due to the seasonality of extremely warm weather in Melbourne and grass pollen levels.

Figures 11a and 11b show the MSLP average and anomaly for the uncomfortable days in Melbourne that have heat stress conditions and above guideline concentrations of PM_{10}. Interestingly, Figure 11a is similar to Figures 3a and 6a where there is a high pressure system present over the Tasman sea suggesting that the average atmospheric structure over the continent is very similar for both uncomfortable heat stress and PM_{10} days. However, in Figure 11b the MSLP anomaly appears to be a hybrid between Figures 3b and 6b. Indeed, there is a high pressure anomaly over the Tasman sea and, similar to days with heat stress conditions, there is a low pressure anomaly over the continent. However, similar to the warm month PM_{10} uncomfortable days, there is also a low pressure anomaly below the continent. Moreover, the weather systems in Figure 11b are again part of wave trains originating from the Indian Ocean.

Figures 11c and 11d show the MSLP average and anomaly for uncomfortable days with heat stress conditions and high grass pollen levels in Melbourne. Interestingly, the average atmospheric structure in Figure 11c is similar to Figure 3a i.e. the average MSLP for all days in Melbourne with heat stress conditions, since both figures have a distinct high pressure system located over the Tasman Sea. However, in Figure 11d the atmospheric MSLP anomaly for uncomfortable days due to heat stress and grass pollen is similar to Figure 10b (the MSLP anomaly for all uncomfortable days due to grass pollen in Melbourne) albeit Figure 11d has larger high pressure anomalies over the Tasman Sea.

The results in Figure 11 suggest that the three different atmospheric bio-comfort signals identified for uncomfortable days in Melbourne due to heat stress conditions, PM_{10} during warm months and grass pollen are robust. Therefore, when a particular form of bio-comfort threshold is exceeded, its atmospheric signal will be present regardless of whether the day has two forms of discomfort or only one.

4. Discussion and conclusions

This study looked at biological as well as atmospheric variables to understand conditions that could make a person feel uncomfortable outdoors in Melbourne. Three 'bio-comfort' indicators were defined: the AT when it exceeds 27.2°C creating heat stress conditions, PM_{10} when it exceeds the WHO regulation daily average concentration of 50µgm^{-3}, and when the pollen count is greater than or equal to 50 grass pollen grains m^{-3}. The large-scale atmospheric structure conducive to an uncomfortable day was then investigated using MSLP averages and anomalies, with each of the three bio-comfort variables exhibiting a different signal. On uncomfortable days due to heat stress conditions the wind patterns in Melbourne were found to be northerlies from the hot and dry continental interior of Australia. This is due to a non-stationary anticyclone located east of Melbourne over the Tasman Sea. When PM_{10} exceeds regulation levels during warm months it was found that a trough located below the continent indicated a cold front is approaching Melbourne. This trough would bring a change of wind direction that could spread bushfires creating more airborne particulates. In contrast, uncomfortable PM_{10} days during the cool months tend to have more stagnant/stable air masses, yet still with a trough located below the continent. This is due to the PM_{10} accumulating in the boundary layer prior to the arrival of a cold front and the shift of the winds from northerlies to southerlies. Finally, high pollen days in Melbourne were found to have northerly winds that originate inland from a stationary weather pattern given by an inland trough without necessarily being associated with passing cold fronts.

The majority of uncomfortable days due to heat stress and/or PM_{10} occur during summer and autumn due to the warm dry conditions in these seasons that create a favourable setting for heat waves and bushfires. In contrast, uncomfortable days due to grass pollen occur only during late spring and early summer, since this is when grass pollen, the most allergenic pollen, is most prominent. It is notable that the study period (1997-2011) largely coincides with a severe drought in southeastern Australia called the Big Dry (as mentioned in section 3). This may have affected the number of airborne particles in the atmosphere during this period, as top soil is drier and dust is more common in drought, yet pollen levels decrease.

There are no significant differences in atmospheric structure for uncomfortable days due to PM_{10} when the air pollution is from local or non-local sources. Years with active bushfire seasons (2003, 2006, 2009) produce 47% of the total number of uncomfortable PM_{10} days in Melbourne and 63% of the warm month uncomfortable PM_{10} days over the period 1997-2011. This suggests that more than half of the warm month uncomfortable PM_{10} days in Melbourne are due to a non-local source of particulates such as smoke and dust from bushfires that are brought to Melbourne by northerly winds, as shown in Figure 6a. However, when comparing warm month atmospheric composites from uncomfortable days during bushfire years to uncomfortable days during non-bushfire years, both composites reveal an almost identical atmospheric structure to Figures 6a and 6b, the composite of all warm month uncomfortable days due to PM_{10}. This shows that regardless of whether the PM_{10} in Melbourne is from local or non-local sources, the atmospheric structure on uncomfortable days due to PM_{10} during the warm months will be the same. Moreover, this implies that the seasonality between warm month and cool month PM_{10} days is associated with much more variation in the atmospheric structure than the source of the particulates.

A limitation of this study is that the Steadman (1994) AT formula implies that winds always act to decrease the AT, such that when wind comes in contact with a warmer body, it acts to withdraw heat from that body to the environment. However, when the air temperature exceeds the skin temperature the wind no longer has a cooling effect, except for the evaporation induced by the sun. In Australia, the surface temperature can greatly surpass the body temperature in the warm season, therefore the use of the Steadman (1994) AT equation can lead to a severe underestimation of the heat stress. Hot dry winds commonly observed in Australia during extreme heat waves can also result in rapid loss of water from the body posing very dangerous dehydrating conditions for anyone exposed to such extremes, even for a short exposure time.

Operationally, weather forecasters could easily implement the three bio-comfort indicators and their MSLP signals identified in this study. As shown above, the signals are robust, even when there are two types of uncomfortable conditions acting simultaneously. While climate models cannot simulate reliable trends in grass pollen count and PM_{10} over specific areas, the knowledge of how these pollutants react to conventional meteorological parameters will place us a step further toward a more realistic impact assessment of future liveability conditions. Moreover, the use of known thresholds allows this method to be implemented anywhere in the world.

Acknowledgements

The authors would like to thank the three anonymous reviewers whose comments and suggestions greatly improved the text. We would also like to thank the Environmental Protection Agency of Victoria and the Australian Bureau of Meteorology for providing PM_{10} and meteorological data, respectively. We also thank Prof. Ed Newbigin from the School of Botany at the University of Melbourne for useful suggestions and discussions, and for sending the pollen data for Melbourne. A. B. Pezza would like to acknowledge the Australian Research Council for funding parts of this work.

5. References

Anderson GB, Bell ML (2011) Heat Waves in the United States: Mortaliry Ridk during Heat Waves and Effect Modification by Heat Wave Characteristics in 43 U.S. Communities. Environ Health Perspect 119:210-218

Antépara J, Fernández JC, Gamboa P, Jauregui I, Miguel F (1995) Pollen allergy in the Bilbao area (European Atlantic Seaboard Climate): pollen forecasting methods. Clin Exp Allergy 25:133-140

Barnett AG, Williams GM, Schwartz J, Neller AH, Best TL, Petroeschevsky AL, Simpson RW (2005) Air pollution and child respiratory health: a case-crossover study in Australia and New Zealand. Am J Respir Crit Care Med 171:1272–1278

Basu R, Samet JM (2002) Relation between elevated ambient temperature and mortality: a review of the epidemiologic evidence. Epidemiol Rev 24:190-202

Bi P, Williams S, Loughnan M, Lloyd G, Hansen A, Kjellstron T, Dear K, Saniotis A (2011) Heat on Human Mortality and Morbidity in Australia: Implications for Public Health. Asia Pac J Public Health 23:27S-36S

Bröde P, Fiala D, Błazejczyk K, Holmer I, Jendritzky G, Kampmann B, Tinz B, Havenith G (2012) Deriving the operational procedure for the Universal Thermal Climate Index (UTCI). Int J Biometeorol 56:481-494

Brunekreef B, Annesi-Maesano I, Ayres JG, Forastiere F, Forsberg B, Künzli N, Pekkanen J, Sigsgaard T (2012) Ten principles for clean air. Eur Respir J 39:525-528

Curriero FC, Heiner KS, Samet JM, Zeger SL, Strug L, Patz JA (2002) Temperature and Mortality in 11 cities of the Eastern United States. Am J Epidemiol 155:80-87

de Morton J, Bye J, Pezza A, Newbigin E (2011) On the causes of variability in amounts of airborne grass pollen in Melbourne, Australia. Int J Biometeorol 55:613-622

Dee DP, Uppala SM, Simmons AJ et al. (2011) The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Q J R Meteorol Soc. 137:553-597

Delaney W, Marshall A (2006) Clean Air Society of Australia and New Zealand. Proceedings 20th International Clean Air and Environment Conference, Auckland, New Zealand, August 2011

Dockery DW, Pope CA III (1994) Acute respiratory effects of particulate air pollution. Annu Rev Public Health 15:107-132

EPA Victoria (2011) Air Monitoring Report 2010 – Compliance With The National Environment Protection (Ambient Air Quality) Measure. epanote2.epa.vic.gov.au/EPA\publications.nsf/PubDocsLU/1390?OpenDocument. Accessed 27 Jun 2012

Erbas B, Chang J-H, Dharmage S, Ong EK, Hyndman R, Newbigin E, Abramson M (2007) Do levels of airborne grass pollen influence asthma hospital admissions? Clin Exp Allergy 37:1641-1647

Filleul L, Cassadou S, Médina S, Fabres P, Lefranc A, Eilstein D, Le Tertre A, Pascal L, Chardon B, Blanchard M, Declercq C, Jusot JF, Prouvost H, Ledrans M (2006) The relation between temperature, ozone, and mortality in nine French cities during the heatwave of 2003. Environ Health Perspect 4:1344-1347

Gaffen DJ, Ross RJ (1998) Increased summertime heat stress in the U.S. Nature 396:529-530

Gioulekas D, Papakosta D, Damialis A, Spieksma F, Giouleka P, Patakas D (2004) Allergenic pollen records (15 years) and sensitization in patients with respiratory allergy in Thessaloniki, Greece. Allergy 59:174-184

Gold E (1936) Wind in Britain. Q J R Meteorol Soc 62:167-206

Gorman J (2004) The conservation equation of the Synchrotac 706 anemometer: Instrumental test report 677. Bureau of Meteorology (Australia)

Gosling S, McGregor G, Páldy A (2007) Climate change and heat-related mortality in six cities Part 1: model construction and validation. Int J Biometeorol 51:525-540

Hansen A, Bi P, Nitschke M, Pisaniello D, Ryan P, Sullivan T, Barnett A (2012) Particulate air pollution and cardiorespiratory hospital admissions in a temperate Australian city: A case-crossover analysis. Sci Total Environ 416:48-52

Hyde HA (1972) Atmospheric pollen and spores in relation to allergy. Clin Allergy 2:153-179

Jakob D (2010) Challenges in developing a high-quality surface wind-speed data-set for Australia. Aust Meteorol Oceanograph J 60:227-236

Johnson H, Kovats RS, McGregor G, Stedman J, Gibbs M, Walton H, Cook L, Black E (2005) The Impact of the 2003 heat wave on mortality and hospital admission in England. Health Statistics Quart 25:6-11

Laaidi K, Zeghnoun A, Dousset B, Bretin P, Vandentorren S, Giraudet E, Beaudeau P (2012) The Impact of Heat Islands on Mortality in Paris during the August 2003 Heat Wave. Environ Health Perspect 120:254-259

Li B, Sain S, Mearns L, Anderson H, Kovats S, Ebi K, Bekkedal M, Kanarek M, Patz J (2012) The Impact of extreme heat on morbidity in Milwaukee, Wisconsin. Climatic Change 110:959-976

Linares C, Díaz J (2008) Impact of high temperatures on hospital admissions: comparative analysis with previous studies about mortality (Madrid). Eur J Public Health 18:317-22

Loughnan ME, Nicholls N, Tapper N (2010) When the heat is on: Threshold temperatures for AMI admissions to hospital in Melbourne Australia. Appl Geogr 30:63-69

Mendina-Ramón M, Zanobetti A, Cavanagh DP, Schwartz J (2006) Extreme Temperatures and Mortality: Assessing Effect Modification by Personal Characteristics and Specific Cause of Death in a Multi-City Case-Only Analysis. Environ Health Perspect 114:1331-1336

Nicholls N, Skinner C, Loughnan M, Tapper N (2008) A simple heat alert system for Melbourne, Australia. Int J Biometeorol 52:375-384

OFCM (2003) Report on Wind Chill Temperature and extreme heat indices: Evaluation and improvement projects. U.S. Department of Commerce / National Oceanic and Atmospheric Administration, Office of the Federal Coordinator for Meteorological Services and Supporting Research, FCM-R19-2003, Washington D.C

Ong E, Singh M, Knox R (1995) Seasonal Distribution of pollen in the atmosphere of Mebourne: an airborne pollen calendar. Aerobiologica 11:51-55

Pantavou K, Theoharatos G, Nikolopoulos G, Katavoutas G, Asimakopoulos D (2008) Evaluation of thermal discomfort in Athens territory and its effect on the daily number of recorded patients at hospitals' emergency rooms. Int J Biometeorol 52:773-778

Papanastasiou D K, Melas D (2009) Climatology and impact on air quality of sea breeze in an urban coastal environment. Int J Climatol 29:305-315

Papanastasiou DK, Melas D, Bartzanas T, Kittas C (2010) Temperature, comfort and pollution levels during heat waves and the role of sea breeze. Int J Biometeorol 54:307–317

Pezza A, van Rensch P, Cai W (2012) Severe heat waves in Southern Australia: synoptic climatology and large scale connections. Climate Dynamics 38:209-224

Ren C, Tong S (2006) Temperature modifies the health effects of particulate matter in Brisbane, Australia. Int J Biometeorol 51:87-96

Schaffer A, Muscatello D, Broome R, Corbett S, Smith W (2012) Emergency department visits, ambulance calls, and mortality associated with an exceptional heat wave in Sydney, Australia, 2011: a time-series analysis. Environ Health 11:3

Schäppi G, Taylor P, Kenrick J, Staff I, Suphioglu C (1998) Predicting the grass pollen count from meteorological data with regard to estimating the severity of hayfever symptoms in Melbourne (Australia). Aerobiologia 14:29–37

Séguin J, Berry P (2008) Human Health in a changing climate: A Canadian Assessment of Vulnerabilities and Adaptive Capacity. Synthesis Report, Climate Change and Health Office, Safe Environment Directorate, Health Canada

Simpson R, Williams G, Petroeschevsky A, Best T, Morgan G, Denison L, Hinwood A, Neville G (2005) The short-term effects of air pollution on hospital admissions in four Australian cities. Aust NZ J Public Health 29:213-221

Son JY, Lee JT, Anderson GB, Bell ML (2012) The Impact of Heat Waves on Mortality in Seven Major Cities in Korea. Environ Health Perspect 120:566-571

Stafoggia M, Schwartz J, Forastiere F, Perucci CA, SISTI Group (2008) Does temperature modify the association between air pollution and mortality? A multicity case-crossover analysis in Italy. Am J Epidemiol 167:1476–1485

Steadman RG (1979) The Assessment of Sultriness Part I. J Appl Meteor 18:861-873

Steadman RG (1994) Norms of Apparent Temperature in Australia. Aust. Met. Mag 43:1-16

Tobias A, Armstrong B, Zuza I, Gasparrini A, Linares C, Díaz J (2012) Mortality on extreme heat days using official thresholds in Spain: a multi-city time series. BMC Public Health 12:133

Ummenhofer CC, England MH, McIntosh PC, Meyers GA, Pook MJ, Risbey JS, Gupta AS, Taschetto AS (2009) What causes southeast Australia's worst droughts? Geophys. Res. Lett., 36 L04706, doi:10.1029/2008GL036801

World Health Organisation (2005) WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide: Global Update 2005

Yaglou CP, Minard D (1957) Control of heat casualties at military training centers. Am Med Assoc Arch Ind Health 16:302–316

Figure captions

Fig. 1 Map of Melbourne showing the locations of Melbourne Airport weather station (square), Footscray air pollution monitoring station (triangle) and the University of Melbourne (circle)

Fig. 2 Number of days per year the 3pm (a) temperature and (b) AT exceeds 27.2°C and (c) the difference between (a) and (b) over the study period 1973-2011. The solid line indicates the average number of days for the total period. The dot-dashed lines indicate trends of statistical significance greater than 99%

Fig. 3 6Z MSLP (a) average and (b) anomaly of when the AT exceeds 27.2°C in Melbourne over the period 1997-2011 using ERA Interim daily data. 231 days were used in this composite. Anomalies were based on mean MSLP over the period 1997-2011. Stippling indicates regions of statistical significance greater than 95%

Fig. 4 Polar stereographic plots of the 6Z MSLP anomaly of the 5 days before and the day of an event where the AT exceeds 27.2°C (i.e. heat stress conditions) in Melbourne over the period 1997-2011 using ERA Interim. 197 days were used in this composite. Anomalies were based on mean MSLP over the period 1997-2011. Stippling indicates regions of statistical significance greater than 95%

Fig. 5 Number of days per year the PM_{10} exceeds WHO air quality guideline levels at Footscray air pollution monitoring station over the study period 1997-2011. Black columns indicate years with active bushfire seasons. The solid line indicates the number of days allowed by Australian legislation that can exceed WHO guideline levels per year

Fig. 6 6Z MSLP (a) average and (b) anomaly of when the PM_{10} at Footscray air pollution monitoring station exceeds WHO guideline levels in warm months (November to April, 46 days used in composites) and the (c) composite and (d) anomaly of when PM_{10} exceeds WHO guideline levels in cool months (May to October, 16 days used in composites) over the period 1997-2011. Anomalies were based on mean MSLP over period 1997-2011. Stippling indicates regions of statistical significance greater than 95%

Fig. 7 Polar stereographic plots of the 6Z MSLP anomalies of the 5 days before and day of an event when the PM_{10} exceeds guideline levels during warm months (November to April) in Melbourne over the period 1997-2011 using ERA Interim. 32 days were used in this composite. Anomalies were based on mean MSLP over the period 1997-2011. Stippling indicates regions of statistical significance greater than 95%. Note: the high is only traceable from 3 days before the uncomfortable event

Fig. 8 Polar stereographic plots of the 6Z MSLP anomalies of the 5 days before and day of an event where the PM_{10} exceeds guideline levels during cool months (May to October) in Melbourne over the period 1997-2011 using ERA Interim. 16 days were used in these composites. Anomalies were based on mean MSLP over the period 1997-2011. Stippling indicates regions of statistical significance greater than 95%

Fig. 9 Number of uncomfortable days per year in Melbourne due to the grass pollen count being greater than or equal to 50 grains m^{-3} over the study period 1997-2011. The solid line indicates the average number of days over the study period

Fig. 10 6Z MSLP (a) average and (b) anomaly of when the grass pollen count in Melbourne is greater than or equal to 50 grass pollen grains m^{-3} over the period 1997-2011. 289 days were used in the composites. Anomalies were based on mean MSLP over the period 1997-2011. Stippling indicates regions of statistical significance greater than 95%

Fig. 11 6Z MSLP (a) average and (b) anomaly of days in Melbourne that are uncomfortable due to heat stress conditions and above regulation PM_{10} concentrations and (c) average and (d) anomaly of days in Melbourne that are uncomfortable due to heat stress and high grass pollen levels over the period 1997-2011. Plots (a) and (b) include 14 days and (c) and (d) use 20 days. Stippling indicates regions of statistical significance greater than 95%

Tables

Comfort condition	AT > 27.2°C (1997-2011)	PM_{10} > 50µgm^{-3} (1997-2011)	Pollen > 50 grains m^{-3} (1997-2011)
AT > 27.2°C	231	14	20
PM_{10} > 50µgm^{-3}	14	62	0
Pollen> 50 grains m^{-3}	20	0	289

Table 1 The number of uncomfortable days over the period 1997-2011 in Melbourne due to the three bio-comfort thresholds

Figures

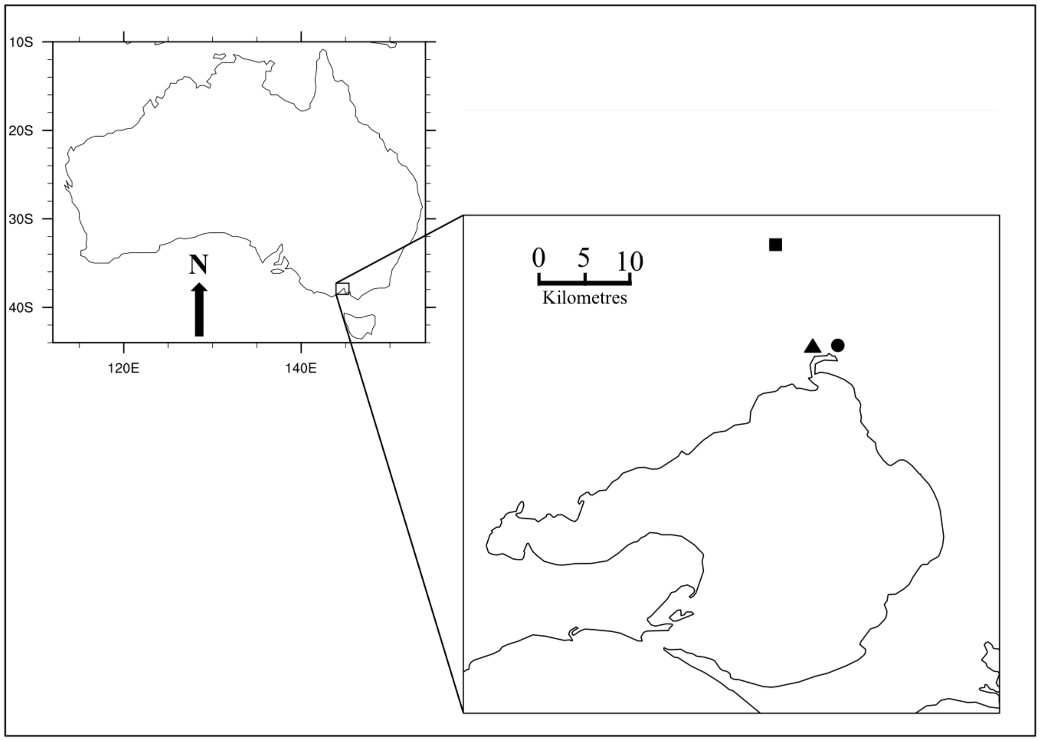

Fig. 1 Map of Australia with an inlet of the locations of Melbourne Airport weather station (square), Footscray air pollution monitoring station (triangle) and the University of Melbourne (circle)

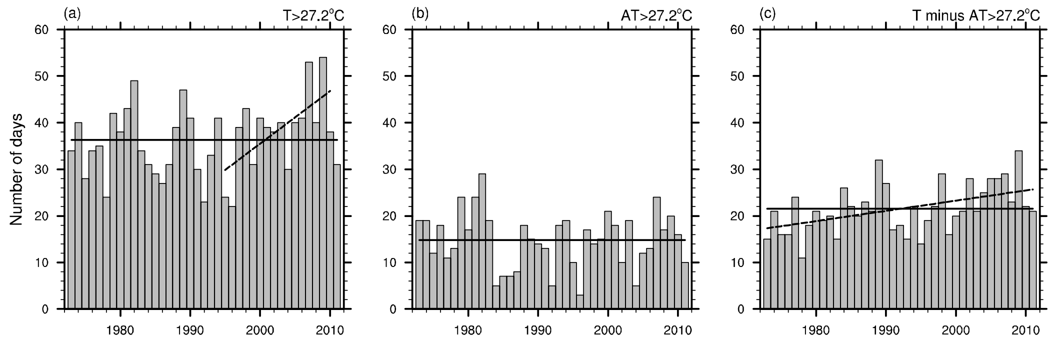

Fig. 2 Number of days per year the 3pm (a) temperature and (b) AT exceeds 27.2°C and (c) the difference between (a) and (b) over the study period 1973-2011. The solid line indicates the average number of days for the total period. The dot-dashed lines indicate trends of statistical significance greater than 99%

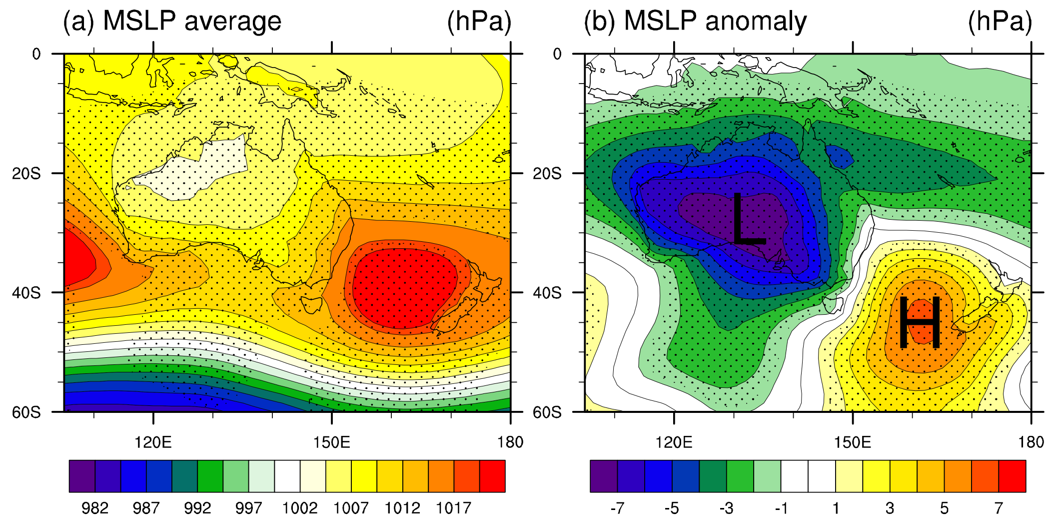

Fig. 3 6Z MSLP (a) average and (b) anomaly of when the AT exceeds 27.2°C in Melbourne over the period 1997-2011 using ERA Interim daily data. 231 days were used in this composite. Anomalies were based on mean MSLP over the period 1997-2011. Stippling indicates regions of statistical significance greater than 95%

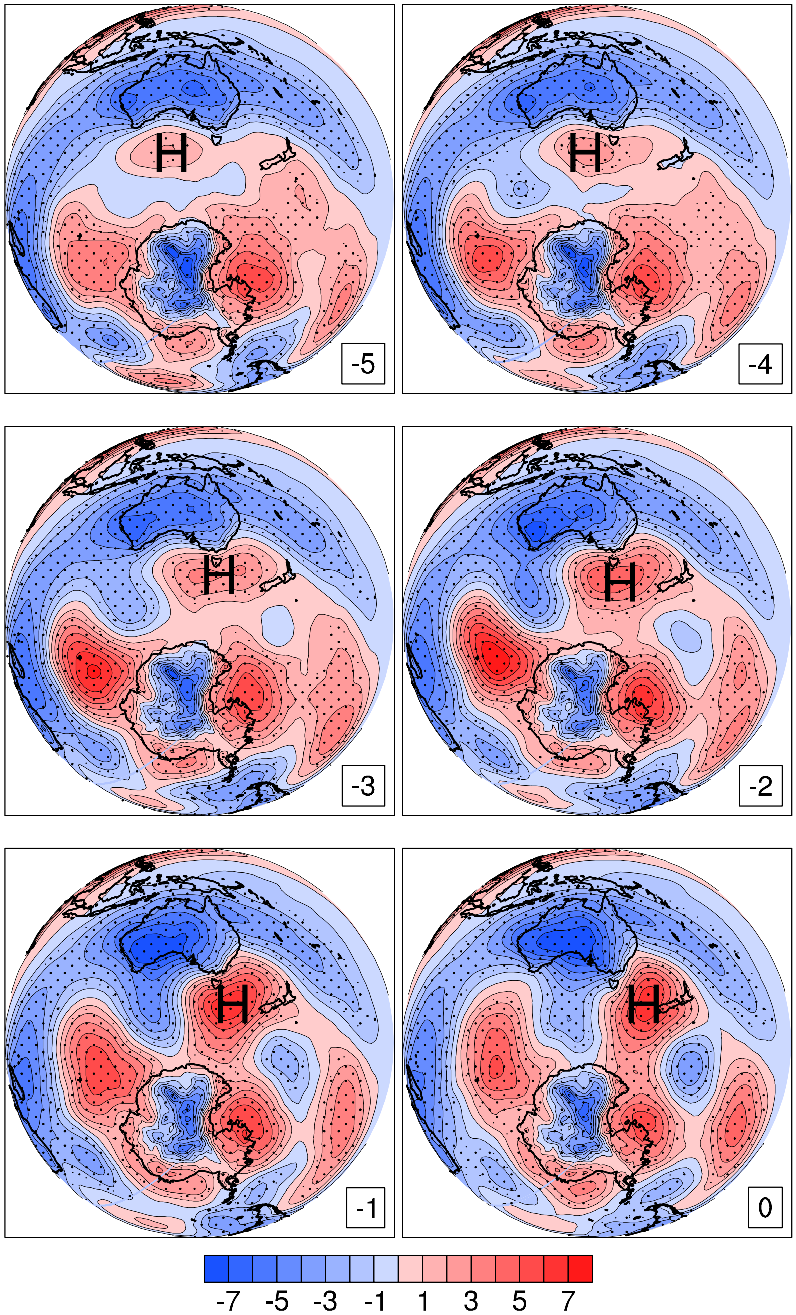

Fig. 4 Polar stereographic plots of the 6Z MSLP anomaly of the 5 days before and the day of an event where the AT exceeds 27.2°C (i.e. heat stress conditions) in Melbourne over the period 1997-2011 using ERA Interim. 197 days were used in this composite. Anomalies were based on mean MSLP over the period 1997-2011. Stippling indicates regions of statistical significance greater than 95%

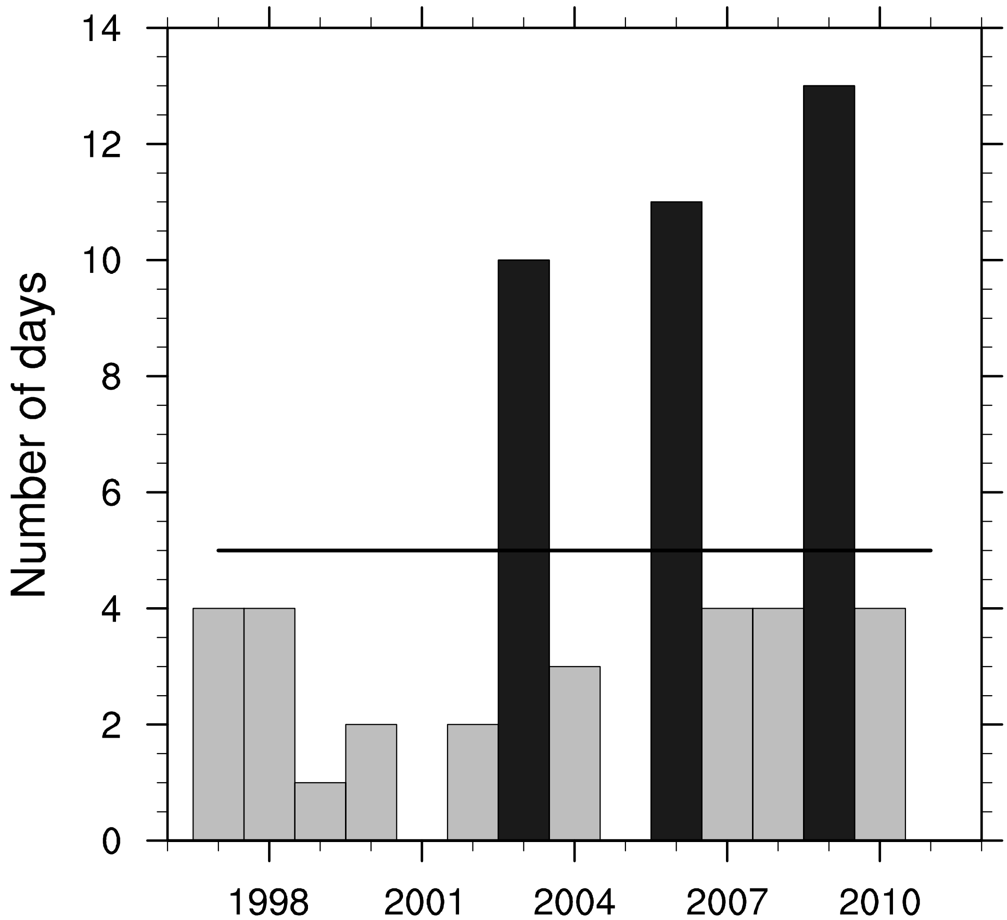

Fig. 5 Number of days per year the PM_{10} exceeds WHO air quality guideline levels at Footscray air pollution monitoring station over the study period 1997-2011. Black columns indicate years with active bushfire seasons. The solid line indicates the number of days allowed by Australian legislation that can exceed WHO guideline levels for PM_{10} per year

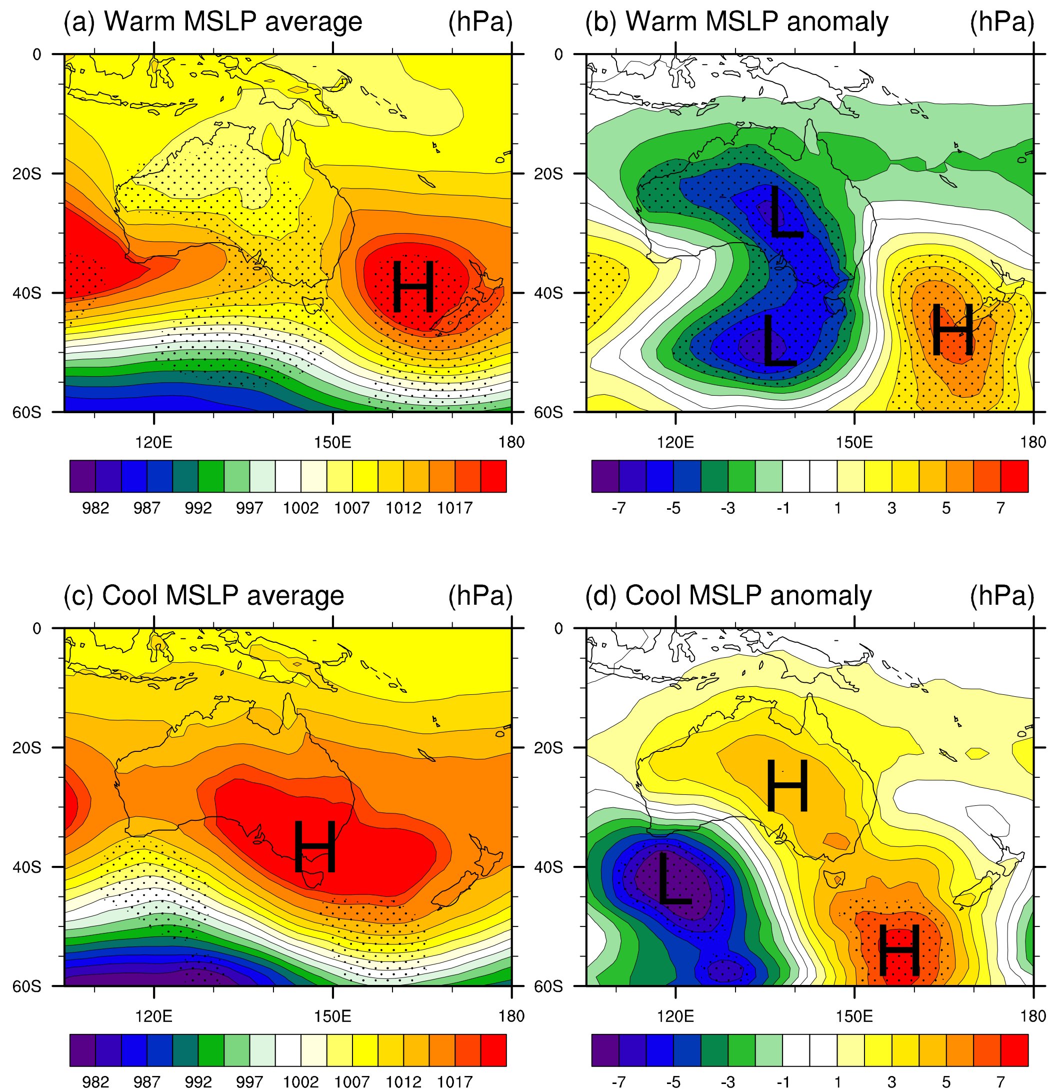

Fig. 6 6Z MSLP (a) average and (b) anomaly of when the PM_{10} at Footscray air pollution monitoring station exceeds WHO guideline levels in warm months (November to April, 46 days used in composites) and the (c) composite and (d) anomaly of when PM_{10} exceeds WHO guideline levels in cool months (May to October, 16 days used in composites) over the period 1997-2011. Anomalies were based on mean MSLP over period 1997-2011. Stippling indicates regions of statistical significance greater than 95%

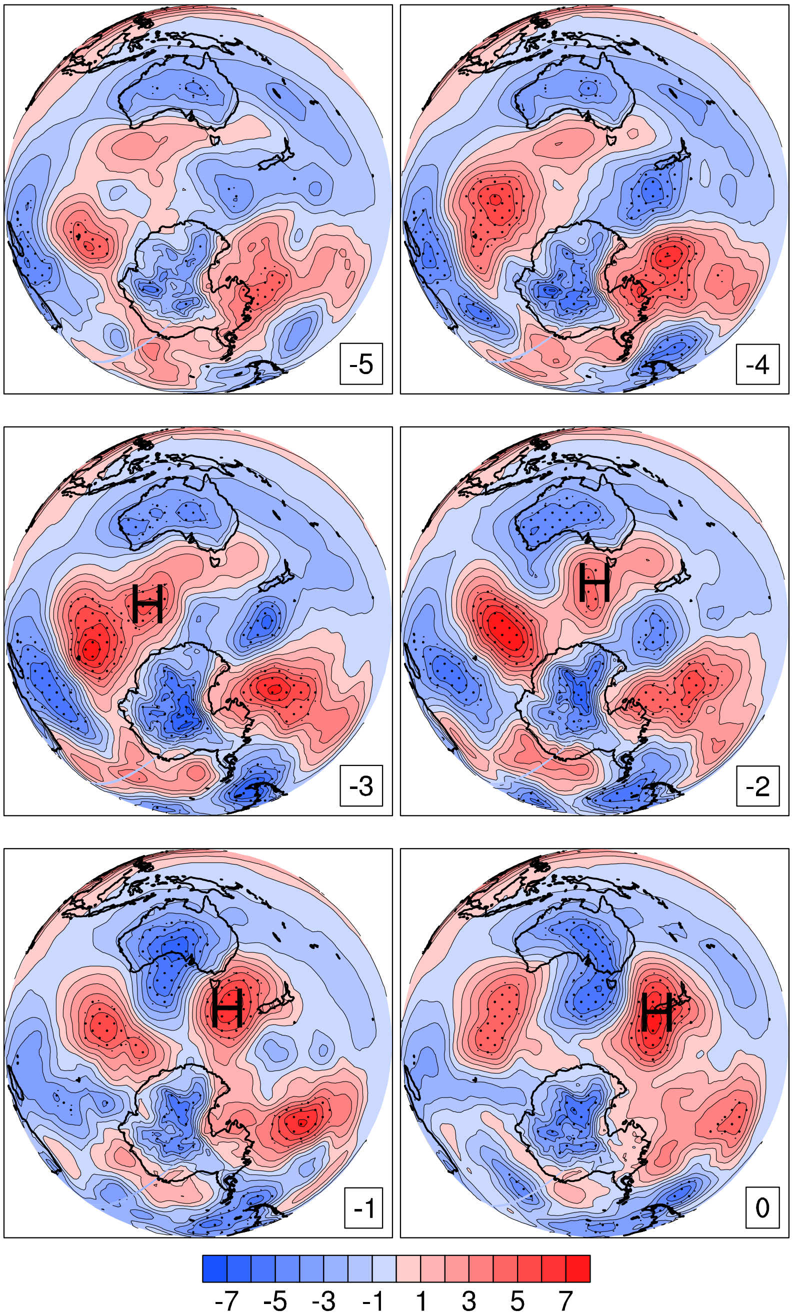

Fig. 7 Polar stereographic plots of the 6Z MSLP anomalies of the 5 days before and day of an event when the PM_{10} exceeds guideline levels during warm months (November to April) in Melbourne over the period 1997-2011 using ERA Interim. 32 days were used in this composite. Anomalies were based on mean MSLP over the period 1997-2011. Stippling indicates regions of statistical significance greater than 95%. Note: the high is only traceable from 3 days before the uncomfortable event

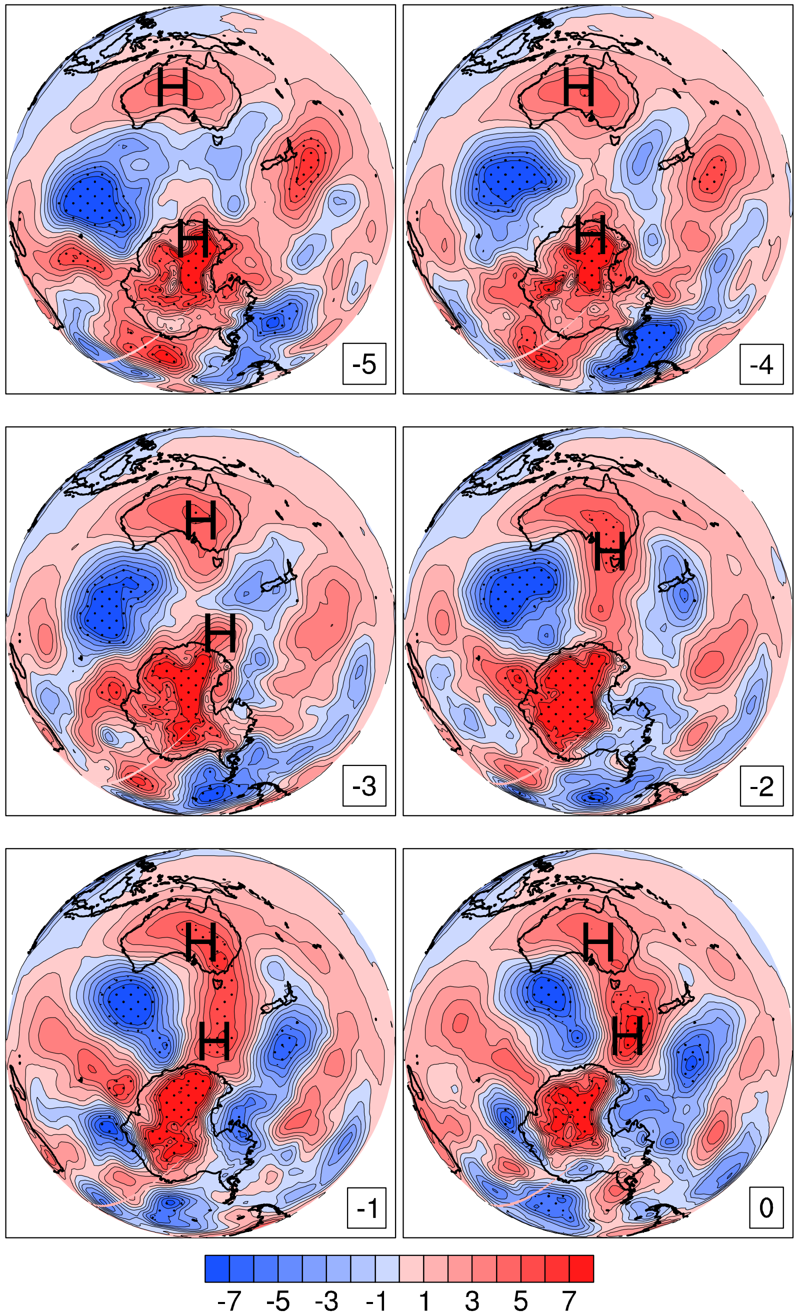

Fig. 8 Polar stereographic plots of the 6Z MSLP anomalies of the 5 days before and day of an event where the PM_{10} exceeds guideline levels during cool months (May to October) in Melbourne over the period 1997-2011 using ERA Interim. 16 days were used in these composites. Anomalies were based on mean MSLP over the period 1997-2011. Stippling indicates regions of statistical significance greater than 95%

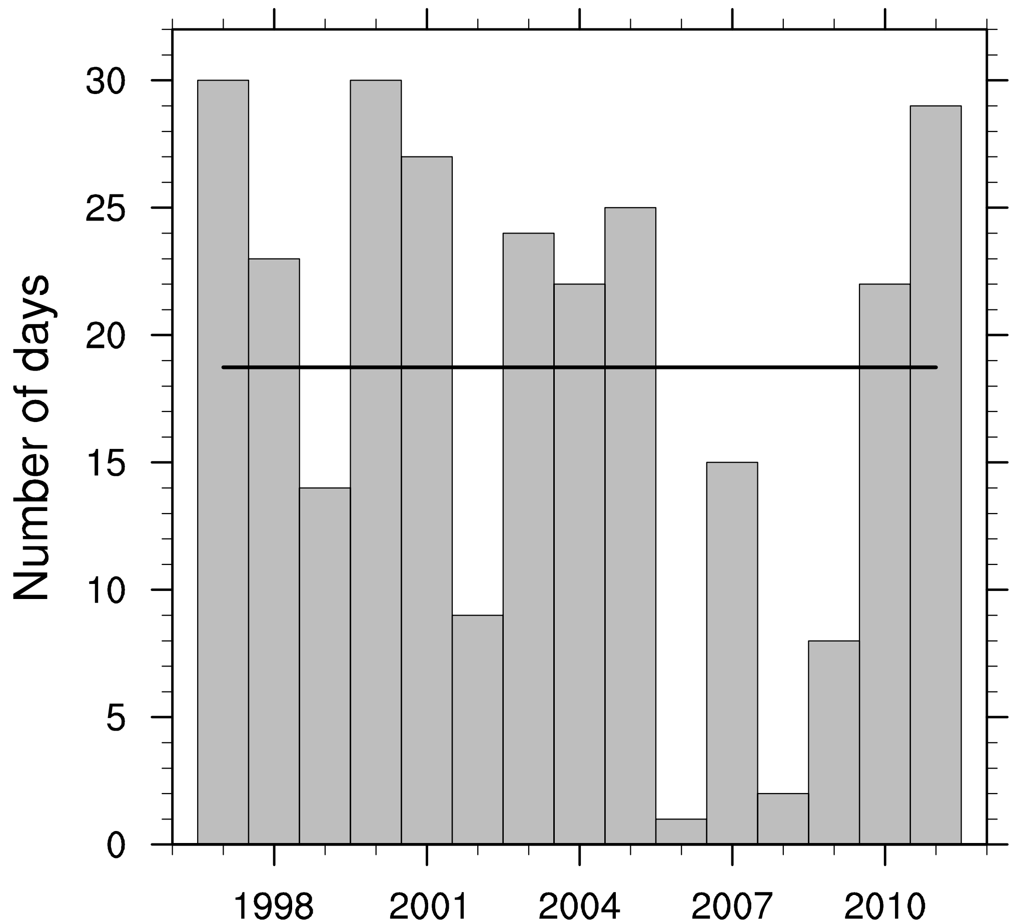

Fig. 9 Number of uncomfortable days per year due to the grass pollen count being greater than or equal to 50 grains m^{-3} over the study period 1997-2011. The solid line indicates the average number of days over the study period

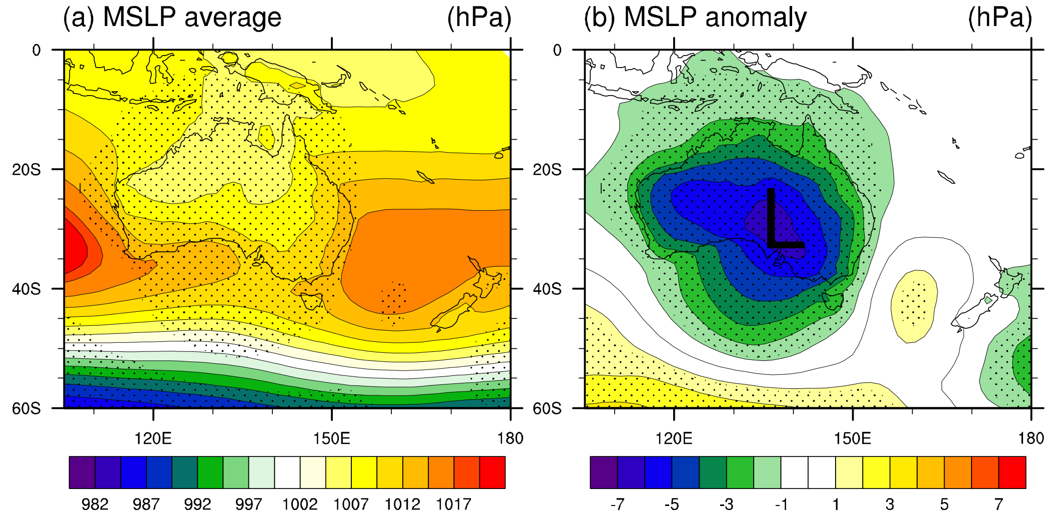

Fig. 10 6Z MSLP (a) average and (b) anomaly of when the grass pollen count is greater than or equal to 50 grass pollen grains m^{-3} over the period 1997-2011. 289 days were used in the composites. Anomalies were based on mean MSLP over the period 1997-2011. Stippling indicates regions of statistical significance greater than 95%

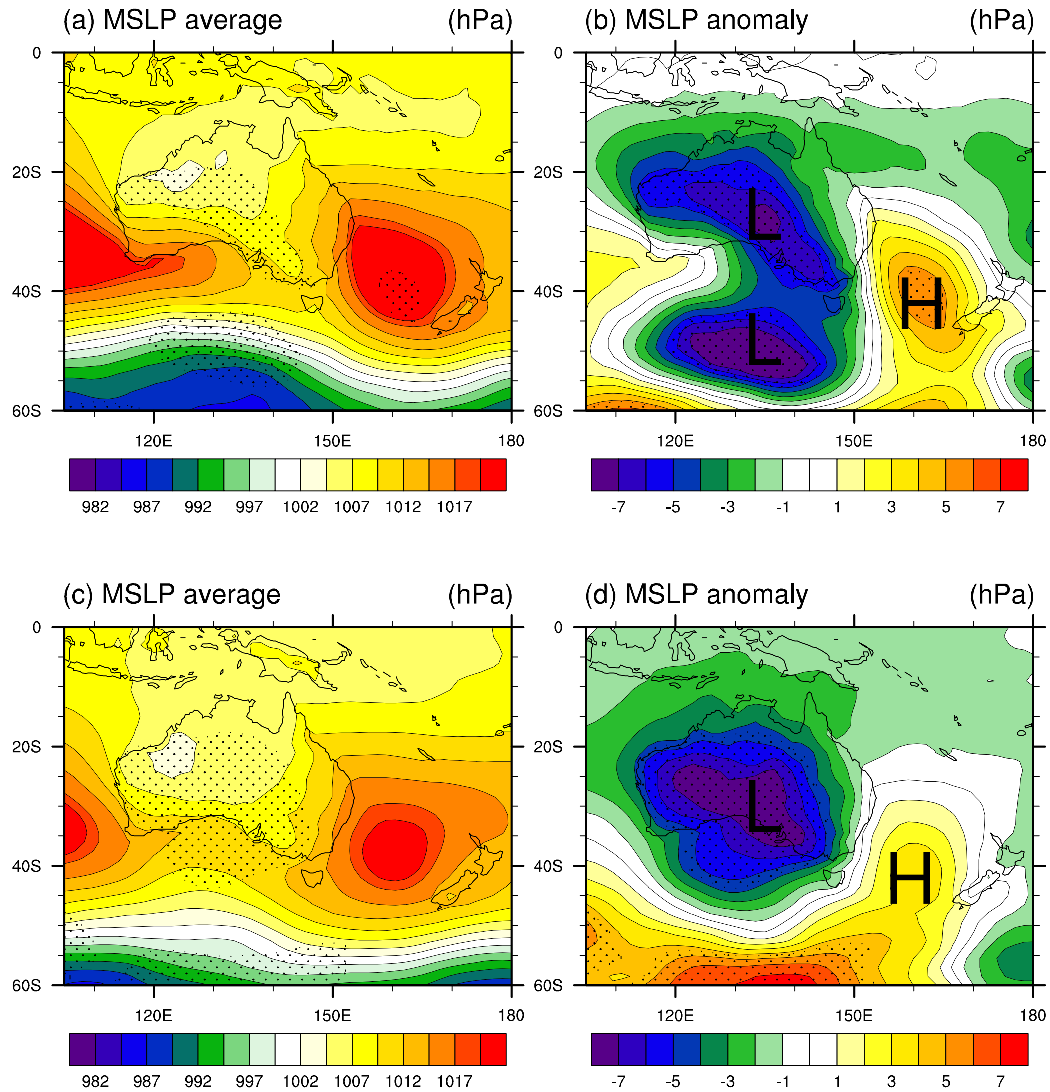

Fig. 11 6Z MSLP (a) average and (b) anomaly of days in Melbourne that are uncomfortable due to heat stress conditions and above regulation PM_{10} concentrations and (c) average and (d) anomaly of days in Melbourne that are uncomfortable due to heat stress and high grass pollen levels over the period 1997-2011. Plots (a) and (b) include 14 days and (c) and (d) use 20 days. Stippling indicates regions of statistical significance greater than 95%