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Large scale and sub-regional connections in the lead up to summer heat wave and extreme rainfall events in eastern Australia

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ABSTRACT

Australia has been exposed to a vast array of extreme weather regimes over the past few years, and the frequency and intensity of these events are expected to increase as a result of anthropogenic climate change. However, the predictability of extreme droughts, heat waves (HWs), bushfires and floods, is still hampered by our inability to fully understand how these weather systems interact with each other and with the climate system. This study brings new insight into the regional and large scale dynamics of some extreme events in Australia, by describing and comparing the climate signature of summer HWs and extreme rainfall events which have occurred in the states of Victoria and Queensland respectively, during 1979-2013.

Our analyses highlight the importance of mid-latitude dynamics operating during HWs, in contrast with more tropical interactions at play during extreme rainfall events. A 'common' blocking high pressure system is observed over the Tasman Sea during the two types of extreme events, and may explain why some southeastern HWs (only about 25%) occur in close succession with floods in Queensland. However, our results suggest that there is no dynamical link between these two types of events, since the HW-related anticyclone evolves as part of a baroclinic wave train, whereas in the case of rainfall events, this structure emerges as an equivalent barotropic response to tropical convection.

Sub-regional surface temperatures and air-sea fluxes also suggest that distinct processes may be operating in the lead up to these two events. Indeed, HWs tend to occur when the wave train propagates from the south Indian to the Pacific Ocean, inducing a quasi-stationary blocking high system over the Tasman Sea. This anticyclonic anomaly can then advect hot dry air towards the southern Victorian coast, where it produces HW conditions. On the other hand, extreme rainfall events mostly occur when the background conditions correspond to a La Niña state. The convection induced in the western Pacific can trigger a tropical-extratropical teleconnection over Queensland. This may generate an anticyclonic anomaly over the Tasman Sea, able to divert air parcels over a warm and humid area where conditions are, this time, favorable for more extreme rainfall along the Queensland coast.

Keywords: Heat Wave; Extreme Rainfall; Sea Surface Temperature; Synoptic Climatology; Blocking; Australian climate.

1. Introduction

Considered the driest inhabited continent on Earth, Australia’s climate is harsh and vulnerable to the devastating effects of weather extremes. Whether it be droughts, prolonged periods of extreme high temperatures (heat waves (HWs)), bushfires, cyclones or floods, these events share the common ability to cause severe strain on the population’s health and resources, especially when they occur simultaneously or in succession across the country.

In southeastern Australia, where the country’s population and agricultural production are highly concentrated, bushfires, HWs and droughts are a regular occurrence during austral summer. Severe high temperatures pose a significant threat to the community, causing damage to infrastructure, often impacting the energy, water and transport sectors, and contributing to an increased rate of human mortality (Nicholls, 2008; Bi et al., 2011; Jacobs et al., 2014). The north and northeastern coasts are also regularly under the threat from tropical cyclones and extreme rainfall. With high river levels, these extensive rains can produce major flooding, causing widespread damage and loss of life in some of Australia’s major cities and most populated states (Evans and Boyer-Souchet, 2012).

In some years, HWs and floods have occurred together across Australia, leading some investigators to suggest there may be a connection between these two types of weather events (Sumner and Bonell, 1986). Sturman and Tapper (2005), for instance, noted that a blocking high in the Tasman Sea, characteristic of southeastern HWs, may also be associated with a trough to the north, which is favourable for bringing rainfall to the northern coastal region of Australia. The process of anticyclonic Rossby wave overturning was also proposed to explain this connection, as it may produce the low-level anticyclone and dry conditions over southern Australia, while simultaneously producing an upper-level trough and often precipitation in northeastern Australia (Reeder, 2010). An example of this were the severe floods observed across much of Queensland in February 2009, coincident with the Black Saturday bushfires that caused havoc and devastation in the southern state of Victoria (Engel et al., 2013). During the recent 2012-13 summer, Australia also faced unprecedented extreme conditions, with record-breaking HWs inland starting in

January 2013, while heavy rain extended over much of the eastern coast during the second half of the month (Bureau of Meteorology, 2013a, b).

It is clear that improved predictions could provide an important tool in adaptation and in minimizing the adverse impacts of such extreme events, especially since the frequency and intensity of these events are expected to significantly increase in coming decades as a result of climate change (Hennessy et al., 2007; Alexander and Arblaster, 2009, Gallant and Karoly, 2010; Perkins et al., 2012; Perkins and Alexander, 2013). As such, there has been an increasing urgency to improve our understanding of weather extremes and their potential associations in Australia, not only with respect to the synoptic characteristics of these events, but also the broader role of the ocean and other global climate drivers in providing the dynamical support for their establishment.

Indeed, while it is well known that some extreme events are caused by extremes in atmospheric circulation, such as blocking in the case of southeastern HWs (Pezza et al., 2012), these local circulation patterns may also be predisposed by underlying or remote sea surface temperature (SST) conditions, or more generally influenced by global modes of climate variability. For example, it is now recognized that El Niño Southern Oscillation (ENSO) influences much of the rainfall variability along the eastern coast of Australia, with generally drier than normal conditions during El Niño years and wetter than normal conditions during La Niña years (Risbey et al., 2009). The Indian Ocean variability has also been shown to play an important role in the climate variability of the southern part of the continent, and has been identified as a potentially key driver of some of the major southeastern droughts over the past 120 years, including the Federation Drought (1895-1902), the World War II Drought (1937-1945) and the Millennium Drought (1995-2009) (Ummenhofer et al., 2009). Cai et al. (2009) showed that positive phases of the Indian Ocean Dipole in austral spring may be particularly effective in preconditioning Victoria for bushfires in the following summer, by contributing to lower rainfall and higher temperatures, which exacerbate the dry conditions conducive to fire. Meanwhile, other recent works have argued that it is the *local* interaction with the ocean which is particularly important, as for instance for the generation and maintenance of HWs in southeast Australia (Pezza et al., 2012; Sadler et al., 2012).

Overall, it seems that the predictability of extreme events in Australia is still hampered by our inability to fully understand how these weather systems interact with each other and with the climate system. In this study, we attempt to unravel the physical processes leading to summer HWs in Victoria and extreme rainfall in Queensland, to gain a better insight into both the local and large scale climate variability associated with these extreme synoptic weather patterns. By exploring the entire 1979-2013 climatology of events, rather than some isolated cases, and by combining a global and a new Lagrangian perspective, we also examine whether there are common links or interactions between these two types of extremes.

The paper is organized as follows: Section 2 describes the data and methods we have used to define HWs in Victoria and extreme rainfall events in Queensland during the 1979-2013 period. In Section 3, we describe the global signature of each type of event and in Section 4 compare the climate precursors and physical processes which may be leading to such extreme weather patterns in the regions of interest. The results are then summarized and discussed in Section 5.

2. Data and Methods

To select HW and extreme rainfall events, we have used daily maximum and minimum temperature (maximum temperature after 9am local time and minimum temperature before 9am local time) and rainfall data provided by the Australian Bureau of Meteorology (BoM) observational stations in Victoria and Queensland (see Fig. 1). The details for each station are provided in Table 1. These stations were carefully chosen with regards to their location in each region of interest (*e.g.* Queensland stations located to the eastern side of the Great Dividing Range; Risbey et al., 2009), to their record history, and to the quality of the data, seeking to minimize missing data during the analysis period of 1979-2013. To test the robustness of BoM station temperature datasets, we have also compared the selection of extreme events using another high quality Australian dataset: the Australian Climate Observations Reference Network - Surface Air Temperature dataset (ACORN-SAT; Trewin, 2013).

- Selection criteria for Heat Waves

HWs can occur at any time during the year, however the conditions triggering these events, and their impacts may differ from season to season. In this study, we examine the occurrence of HWs in Victoria during austral summer, from December to February (DJF), as this is when their effects have been shown to be the most severe, especially in terms of human mortality (Loughnan et al., 2010). We then define a summer HW event occuring in Melbourne, Laverton or Moorabbin (see Fig. 1), as a period of (minimum) three consecutive days, when:

(i) daily maximum temperature (Tmax) remains above the 90th percentile of Tmax for the corresponding month of the HW; and

(ii) daily minimum temperature (Tmin) remains above the 90th percentile of monthly Tmin, during the second and third days of the HW.

These selection criteria, based on Pezza et al. (2012), enable us to measure several aspects of a HW and select the events with potentially the most devastating effects. First of all, the definition is based on a percentile threshold and is therefore relative to the area of interest and accounts for the seasonal variability of local temperature extremes (Perkins and Alexander, 2013). The use of a *monthly* percentile threshold helps us discriminate periods of excess heat, thus selecting the most extreme HWs in terms of temperature *intensity*, while the three day persistence of these heat conditions samples out the *longer-lived* events. Finally, we need to bear in mind that HWs can cause the most severe strain on the population when there is a lack of relief at night between two hot days. Consecutive nights of extreme high Tmin are usually less common over Australia due to the inherent dryness of the country: with less cloud cover and dry soils, the heat accumulated through solar forcing during the daytime tends to dissipate during clear nighttime conditions. The Tmin threshold in our definition reflects the extent to which this daily heat load is dissipated overnight during the HW, thus dictating the accumulating thermal load impacting people on the following day (Nairn et al., 2009).

We have applied this criterion to the daily Tmax and Tmin time series at Melbourne, Laverton and Moorabbin stations separately during 1979-2013. In spite of the potentially stronger urban heat island effect present in Melbourne, the list of HW events and composite patterns are robust from one station to the other (not shown). We thus only show results for HWs identified at the Melbourne station in this paper.

- Selection criteria for extreme rainfall events

We examine the occurrence of extreme rainfall events in the south, central and north coastal regions of Queensland. These events are also defined during the DJF season, as weeks of extremely heavy rainfall, meeting the following criteria:

(i) the weekly accumulated rainfall must exceed the 90th percentile of rain for the corresponding month; and

(ii) the selected calendar week is then recentered around the day of maximum rainfall (event = day of maximum rainfall +/- 3 days)

We apply these criteria to the daily rainfall timeseries of the nine Queensland stations (three stations per region, detailed in Table 1 and Fig. 1), and then construct our extreme rainfall events for the south, central and north regions by extracting the common weeks obtained from the three stations per region. This percentile-based definition thus allows us to select the most extreme summer rainfall episodes, as well as the most coherent patterns over various locations of a given region. The selected weeks have also been recentered to account for the local (small-scale) processes in the lead and follow-up to the peak of each rainfall episode.

To examine the global signature of these selected HW and extreme rainfall events, we then perform composite analyses, where daily anomalies are computed based on the 1979-2013 climatology. We use global atmospheric and oceanic fields from the ERA-Interim reanalysis, which provides daily data at 1.5° resolution, and covers the period from 1979-2013 (Dee et al., 2011), as well as Outgoing Longwave Radiation (OLR) from the NOAA interpolated OLR daily dataset available since 1974 at 2.5° resolution (Liebmann and Smith, 1996). We have compared our results using other daily reanalyses products (*e.g.* NCEP-DOE Reanalysis 2; Kanamitsu et al., 2002), and other SST datasets which offer a higher spatial resolution than ERA-Interim but are available over a shorter time period, such as the NOAA High-resolution Blended Analysis of daily SST and ice, available on 0.25° global grid from 1982-2013 (Reynolds et al., 2007). Results are consistent among the various products, however to capture the maximum number of events, we show results only from the ERA-Interim reanalysis.

SST and atmospheric fields are generally linked with each other through processes at the air–sea interface such as surface turbulent and radiative fluxes. These fluxes are used to identify processes that may be important for the generation or attenuation of observed SST anomalies; such as heating of the surface layer by incoming solar (shortwave) radiation, or cooling of the surface by radiative (longwave) loss and/or thermal and evaporative processes (via sensible and latent heat fluxes). The surface heat fluxes analyzed here are derived from products of the objectively analyzed air–sea fluxes (OAFlux) for the Global Oceans project (Yu et al. 2008), obtained from the Woods Hole Oceanographic Institute.

Finally, we have used the Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT) to compute the trajectories of air parcels arriving at the location of stations on the first day of selected extreme events (Draxler, 1999). Using meteorological fields from the NCEP/NCAR reanalysis (available over 1948-2013), the model estimates the advection of a particle from the average of the three-dimensional velocity vectors for the initial-position, $P(t)$, and the first-guess position, $P'(t+\Delta t)$. The velocity vectors are linearly interpolated in both space and time, following an integration method commonly used for trajectory analysis (Petterssen, 1940), where the first guess position is:

$$P'(t+\Delta t) = P(t) + V(P,t)\Delta t \tag{1}$$

and the final position is:

$$P(t+\Delta t) = P(t) + 0.5\left[V(P,t) + V(P',t+\Delta t)\right]\Delta t \tag{2}$$

For a complete description of all the equations and model calculation methods for trajectories, see Draxler and Hess (1998).

3. Global signature of heat wave and extreme rainfall events

3.1. Heat waves

a) Selected events

Using the criteria specified in Section 2, we have identified 14 HW events occuring in DJF in Melbourne during 1979-2013. We note that only 12 and 13 events were found for Laverton and Moorabbin stations respectively (potentially linked to a weaker urban heat island effect in these locations), 10 of which were common to the Melbourne cases.

The characteristics of these Melbourne HW events are shown in Fig. 2 in the form of a histogram, where each bar captures the intensity of the HW through the average of Tmax during the three HW days, and the white line shows the average of Tmin during the second and third days. This figure illustrates how Melbourne HWs are comparably intense in terms of daytime heat (Tmax), but more variable in terms of the lack of relief they provide during nighttime (Tmin), which exacerbates HW conditions and renders some events more 'extreme' than others (*e.g.* the 19-01-1997 and 13-01-1981 events; see Fig. 2). Interestingly, Fig. 2 also shows an apparent tendency for these events to cluster in specific groups of years, with HWs in Melbourne occuring mainly in the early 1980s, mid-1990s and mid-to-late 2000s.

The color of each bar in Fig. 2 reveals the concurrent state of ENSO in the tropical Pacific for each HW, measured via SST anomalies averaged in the Niño3.4 region during DJF (list of years also given at http://ggweather.com/enso/oni.htm). HWs do not seem to occur preferrentially during El Niño (red) or La Niña (blue) events, and over half of the Melbourne events coincide with neutral ENSO conditions (grey), which suggests there is no synchronous/robust relationship during the DJF season between ENSO and extreme HW events in Melbourne, based on the definition used here (Sadler et al. 2012).

b) Composite analyses

In order to examine large scale conditions associated with Melbourne HWs, global composite analyses were performed during the first day of the 14 HW events listed in Fig. 2. The composite results in Fig. 3 suggest no relationship with ENSO in the tropical Pacific, as the most significant climatic signals are located in mid-to-high southern latitudes, as seen by the wave train signature to the south of Australia in Fig. 3a and b. Hence, in agreement with Pezza et al. (2012), the main drivers of HWs lie rather in mid-to-high latitude dynamics.

On the first day of the HWs, this wave train pattern is characterized by a significant zonal pressure dipole centered over southern Australia (see Fig. 3b). The cyclonic anomaly to the west has been related to a strengthening of the monsoonal climatological trough (Sturman and Tapper, 2005), while the (quasi-stationary) large anticyclonic anomaly to the east has been identified as a key driver of HWs contributing to the establishment of blocking over the Tasman Sea (Sadler et al., 2012). Indeed, this anticyclonic cell can produce subsidence (consistent vertical velocity field not shown) and clear skies over southeastern Australia (Fig. 3d), while advecting warm dry inland air towards the southern coast (Fig. 3b), where it produces the prolonged hot surface conditions characteristic of HWs (see Fig. 3a; Xoplaki et al., 2003; Black et al., 2004; Meehl and Tebaldi, 2004). Foehn winds may also be contributing to this rapid rise in temperatures through adiabatic warming of the air coming from the northeast mountanous region. The generation and maintainance of these hot conditions along the southern coastal regions in Fig. 3a may then be due to a higher persistence of the dipole-like circulation patterns (as is seen in many contexts, *e.g.*, Murphy and Simmonds, 1993; Kysely, 2007), but may also involve an interaction with surrounding SST conditions.

The global SST composite analysis suggests that the ocean may indeed play a significant role in the dynamical processes involved with, or leading to, HWs. The SST signature in Fig. 3c is marked by a general high latitude warming centered around 60°S, and also seems to highlight the importance of sub-regional SST conditions, with significant cold anomalies prevailing over the Tasman and Coral Seas, contrasting with anomalously warm waters along the southern coast of Australia and Great Australian Bight. We have tested the robustness and relative importance of some of these key SST signals (mean SST anomalies in each colored box in Fig. 3c), by comparing their values separately during the first day of *each* HW. The bar plot in Fig. 4a illustrates how SST anomalies over the Tasman Sea are predominantly cold, while warm conditions prevail over the Great Australian Bight region. Interestingly, most of the HWs are also characterized by a warming of the Southern Ocean, and generally warm anomalies over the southwest Indian Ocean, a key area of wave amplification and high cyclogenesis (Ashcroft et al., 2009; Pezza et al., 2012). The yellow bars in this plot also indicate that during most HWs there is a negative anomalous SST gradient between tropical (10°S-30°S) and extratropical (40°S-60°S) latitudes of the Southern Hemisphere (Fig. 4a).

These *large-scale* SST conditions remain constant thirty days before and after the HWs (see black, green and yellow curves in Fig. 4b), suggesting they may reflect the typical ‘background’ HW anomalies. However, it is interesting to note that these conditions were inversed (or perturbed) during the most recent HWs (HW11 to HW14, shaded in Fig. 4a) – events which have incidentally (mostly) occurred during La Niña years (see Fig. 2, Kosaka and Xie, 2013).

The *sub-regional* SSTs are also quite intense (red and blue curves, Fig. 4b) but the strength of these anomalies varies over time: they increase in magnitude significantly six days before the HW, peak one day after the HW, and then remain significant for another few days before decreasing towards their initial value. We suggest that these sub-regional SST anomalies have an influence on the initiation and development of the HW, by providing additional memory to the system and playing the role of a positive feedback conducive to extreme HW conditions. Indeed, the anomalously warm Great Australian Bight SSTs, located within the widespread area of hot surface air conditions (Fig. 3a), may result from the southward advection of hot air induced by the Tasman Sea high (Fig. 3b), and could then also reinforce the HW surface conditions by modulating the temperature gradient across the southern coastal region. Meanwhile, the cold SST anomalies in the Tasman Sea may contribute to the establishment of blocking via induced subsidence (Sadler et al., 2012), and may also be reinforced by the cool southern air advected along the eastern flank of the anticyclone (Fig. 3b).

By examining SST, air-sea fluxes and atmospheric conditions in the lead up to the HWs, we deduce that these sub-regional SST anomalies have both become significant a few days before the onset of the HWs, in association with a transient anticyclone over the Tasman Sea (figure not shown; Pezza et al., 2012; Takaya et al., 2001). The sequence of events suggests that the passing of this anticyclone prior to the HW induces cold conditions locally over the Tasman Sea, while also generating warmer SSTs to the south of Melbourne. The SST induced pattern is then amplified a few days later, once the blocking high is established over the Tasman Sea and the HW is initiated.

Overall, although both the cold and warm sub-regional SST anomalies associated with HWs may have been induced by previous circulation anomalies, we suggest here that they also play a significant and active dynamical role in the maintenance and intensity of these HW events, through local air-sea interaction and in particular through a modulation of air-sea fluxes (as discussed in Section 4).

Finally, note that the OLR composites during the first day of Melbourne HWs indicate areas of enhanced cloudiness and rainfall over the tropics and northwest coast of Australia, associated with the monsoonal low, but also extending towards the eastern coast of Queensland (Fig. 3d). These OLR anomalies may at least partially result from onshore winds due to the HW anticyclone (Sumner and Bonnel, 1986), and illustrate how HWs in Melbourne may coincide with increased rainfall over coastal Queensland (for 10 out of the 14 Melbourne cases); see also Sturman and Tapper (2005).

3.2. Extreme rainfall events

a) Selected events

Using the criteria detailed in Section 2, we have identified 19 extreme rainfall events occuring in DJF in south Queensland, 17 in the central region, and 14 in the north. Only about 25% of these Queensland rainfall events co-occurred with HWs in Melbourne in the DJF season during 1979-2013 (see Figs. 3 and 5).

The characteristics of these selected rainfall events are shown for each Queensland region in Fig. 5, where each bar represents the total amount of rainfall accumulated over the week of the event, and the white line indicates the maximum daily rainfall recorded during that week. As expected, the intensity of events in terms of accumulated rainfall increases closer to the tropics (*e.g* most rain in north Queensland, see Fig. 5c). The white lines in Fig. 5 also indicate differences in the nature of the accumulation over the week, and identify shorter-lived intense events that are mainly due to extreme rainfall occuring over a single day of the week (representing approximately 50% of the cases). The comparison between the February and December 1995 events in south Queensland (ninth and tenth bars in Fig. 5a, respectively) clearly illustrates this notion of ‘continuous’ versus ‘flash’ rainfall episodes.

Finally, despite the relatively low number of events in each region, the general predominance of blue bars in Fig. 5 suggests that extreme rainfall events in Queensland during DJF tend to coincide with the occurrence of La Niña events in the tropical Pacific. This is particularly true for the events occuring after 1998 (Kosaka and Xie, 2013), and overall consistent with the teleconnection observed at the interannual timescale between ENSO and rainfall variability along the eastern coast of Australia during austral summer (Risbey et al., 2009).

b) Composite analysis

To further explore the large scale connections associated with extreme rainfall events in Queensland, global composite analyses were performed in each region during the weeks listed in Fig. 5. The results shown in Fig. 6 generally highlight the predominance of a tropical connection, in contrast with the dominant extratropical signals observed during Melbourne HWs.

In Fig. 6 (top panels), the most prominent and significant SST signal is observed in the tropical Pacific region, displaying a typical La Niña pattern. This suggests that the interannual ENSO-rainfall relationship remains valid in the case of more *extreme* rainfall episodes, occuring both in tropical (Fig. 6c) and subtropical regions of

Queensland (Fig. 6a). It is noteworthy that the high latitude SST warming observed during HWs is not present here and that, despite some regional differences, these three SST composites also show warm SST anomalies prevailing over the Tasman Sea, in contrast to the sub-regional HW conditions described previously (see Fig. 3c).

The OLR composites, shown in the middle panels, also clearly illustrate the predominance of a tropical connection during rainfall events, with only a small region of significant convective anomalies observed over the eastern (*northeastern*) coast of Australia in Fig. 6a-b (*Fig. 6c*), and weak signals elsewhere. During the south and central events, this negative OLR signal appears as part of a zonal dipole structure, with positive OLR anomalies (clear skies) prevailing over the rest of the Australian continent (Fig. 6a-b). But, more importantly, for each Queensland region, this OLR signal seems to mainly emerge from a broad area of convection centered over the Maritime Continent, consistent with a La Niña-induced pattern (Fig. 6a-c). The sea level pressure (SLP) and low-level wind composites are consistent with this tropical convective response, with a low pressure cell largely dominating the northern part of Australia (Fig. 6, lower panels). This figure also reveals the presence of an anticylonic anomaly over the Tasman Sea, particularly significant during south Queensland events (smaller significant region for central events, and no significance for north Queensland events) and reminiscent of the blocking anticyclone observed during Melbourne HWs (Fig. 3b). However, as we discuss next, the dynamical structure of this Tasman Sea anticyclone may be quite different during rainfall versus HW events.

In order to investigate this resemblance between HWs and extreme rainfall events in south Queensland, we examine the vertical structure of each type of event in Fig. 7, by comparing their composites of SLP and 500-hPa geopotential height anomalies. This figure clearly shows the presence at both levels of a significant anticyclonic anomaly over the Tasman Sea, although this cell is shifted slightly eastwards in the case of rainfall events (Fig. 7b). Nevertheless, our results suggest that this anomalous high may evolve and/or take part in two distinct dynamical configurations. On one hand, the HW-related anticyclone is part of a mid-latitude wave train in the Southern Hemisphere, clearly discernable here at 500 hPa (see markings in Fig. 7a), whereas in the case of rainfall events, this structure is much weaker and seems to emerge as a more equivalent barotropic response to tropical convection. Indeed, Fig. 7b indicates no clear wave train pattern (or at least not as organized in space), but suggests a possible tropical-extratropical teleconnection whereby La Niña-induced convection over northern Australia may impact higher latitudes (*i.e* the Tasman Sea region) through a modulation of the local Hadley cell in the southwestern Pacific.

4. Comparison of climate precursors during Melbourne HWs and south Queensland extreme rainfall events

The foregoing analyses have provided us with a general overview of the climatic signature of HWs and extreme rainfall events which occurred in Victoria and Queensland, respectively, during 1979-2013. Our results have highlighted the importance of mid-latitude dynamics during HWs versus a more tropical teleconnection operating during extreme rainfall events, while also identifying the presence of a significant persistent anticyclone over the Tasman Sea during both types of events. But what key physical processes are operating *in the lead up* to these events? Are there any common sources or potential connections between HWs and episodes of extreme rain in southern Queensland?

4.1. Transient activity associated with each event

To address these questions, and complement our initial global approach, we have explored the synoptic configurations which may lead to HWs or extreme rainfall. Using the HYSPLIT model, we have computed the trajectories of air parcels arriving in Melbourne on the first day of the selected HWs at both 925 hPa and 500 hPa levels (Fig. 8). A similar analysis is performed to back track the air parcels arriving in south, central and north Queensland on the rainiest day of each selected week (Figs. 9 and 10). This Lagrangian approach enables us to detect both the origin and the characteristics of key air parcels in the 15 days leading up to each type of extreme event. This approach is similar to that used by Brown et al. (2009) to track air parcels associated with cut-off lows across southeastern Australia.

The trajectories estimated for the 14 HWs are shown in Fig. 8a, in the case of air parcels arriving at 925 hPa in Melbourne. For most of these HWs, the air has originated from the deep southwest Indian Ocean 15 days prior, and has been channeled eastward through the 40°S-60°S latitudinal band for a couple of days, before reaching the Tasman Sea and being diverted anticlockwise towards Melbourne. Note that the location of this ‘loop’ is consistent with the anomalous high observed in Fig. 7a. The evolution of pressure along these tracks (right panels) also indicates that these air parcels either originate and remain at low-levels during 15 days, or else if they are initially higher in the atmosphere (*i.e* at lower pressure levels) they tend to all sink together five-to-seven days before reaching Melbourne, just as they are caught in the blocking anticyclone. The further advanced the HW conditions, the longer the air parcels remain blocked in this anticyclonic ‘loop’ (not shown).

Results for the air parcels arriving at 500 hPa on the day of a HW in Melbourne are shown in Fig. 8b and display a similar extratropical pathway for the parcels, originating in most cases from constant or higher levels in the southwest Indian Ocean, but moving directly towards Melbourne rather than the Tasman Sea. This is due to the more southwestward location of the anticyclone at 500 hPa compared to the near surface (925 hPa) or sea level anticyclone (see Figs. 8a, 7a). It is worth noting that for a limited number of HWs (*e.g.* the aqua blue traj_970205 event, Fig.8b), the 500 hPa air parcels can originate from the tropical Indian Ocean, an area known for the genesis of tropical cyclones and for potentially influencing certain types of hot events such as Black Saturday (Parker et al., 2013). However, this occurs for a minority of HW cases addressed in this study. Thereby we infer no substantial interaction or influence from the tropics in our analysis.

Interestingly, the trajectories leading to extreme rainfall in Queensland display a fairly similar preferential pathway to HWs for air parcels arriving at 950 hPa (Fig. 9). Indeed, most parcels again originate from the extratropical southwest Indian Ocean, are advected eastwards until they are diverted by the blocking high and subside over the Tasman Sea, in a slightly more eastward location compared to HWs, but again consistent with the anticyclonic anomaly observed in Fig. 7b. Note, however, that for a couple of events, the air originates from the tropical Pacific Ocean (*e.g.* the dark blue traj_101227 event in south Queensland, Fig. 9a).

The 500 hPa trajectories, on the other hand, exhibit more chaotic and significantly diverse pathways, which clearly differ from the HW tracks in Fig. 8b. Indeed, Fig. 10 indicates that, although some parcels still have a purely extratropical origin in the case of south Queensland events, there seems to be a subtantially larger influence from the tropics at 500 hPa, especially in the lead up to central and north Queensland events (for over 50% of the cases considered here). Most of the air parcels also tend to start rising a few days before the rainiest day (or ‘day 0’) of these extreme rainfall events.

Overall, this trajectory analysis has suggested there may be a similar preferential extratropical pathway in the lead up to HWs and to some cases of extreme rainfall especially in south Queensland, which contrasts with the larger tropical influence observed during most of the other extreme rainfall events in Queensland. But what conditions will pre-determine the occurrence of one type of event or the other? Our results indicate that in both situations, the trajectories are affected by the precise position of the anticyclonic anomaly in the Tasman Sea (see Fig. 7), but they may also be dependant on underlying and other large scale conditions.

4.2. Influence of underlying large scale conditions

To understand how larger scale conditions may impact the transient synoptic systems along the different trajectories, we have first compared the SST conditions typically observed during Melbourne HWs and rainfall events in south Queensland. Figs. 3c and 6a revealed that there may be contrasting SST anomalies prevailing locally over the Coral and Tasman Seas, and along the southern coast of Australia during both events. These regions have been shown to be important for the generation and maintenance of HWs (see Section 3), but have not yet been identified as playing a significant role in the occurrence of extreme rainfall in south Queensland.

To examine whether and how these opposite SST conditions may affect the various air trajectories, we have examined the variability of surface heat fluxes in the regions of interest, separately during HWs and extreme rainfall events (Figs. 11 and 12). The composite patterns during HWs illustrate how the blocking anticyclone in the Tasman Sea is associated with an acceleration of the wind speed along its eastern flank (Fig.

11b), which can enhance upward latent heat flux (Fig 11a) over the Tasman and Coral Sea regions, and is thus consistent with a cooling of the local SST (see Fig. 3c). The local radiative fluxes are also consistent with this SST cooling (not shown), and the specific humidity anomaly in this region is negative (Fig. 10c). The blocking high is therefore associated with cloud free and dry conditions during HWs (consistent with the low thickness values observed in this region, figure not shown).

On the other hand, during extreme rainfall events in south Queensland, the more eastward location of the anomalous high slightly shifts the positive wind anomaly over the Tasman Sea compared to the HW composites (Fig. 12b), although this anomaly is again associated with increased upward latent heat flux (Fig. 12a). However these anomalies are smaller than during HWs, and the radiative fluxes indicate cloudy conditions (not shown), which is consistent with the anomalously warm SSTs observed over the Tasman and Coral Seas during these events (Fig. 6a). More importantly, the specific humidity anomaly observed along the eastern Australian coast is opposite to the HW composites (Fig. 12c), thereby providing in this case both warm and humid conditions in the region (consistent with positive thickness anomalies, not shown).

Based on these observations, we argue that during the extreme rainfall events, the air parcels can be diverted by the blocking high in the Tasman Sea, and then advected along the eastward flank of the anticyclone over an area of anomalously warm and humid conditions. The underlying warm SSTs (and hot air column) tend to favor the convergence of moisture and onshore winds, both conditions conducive to extreme rainfall once these parcels reach the Queensland coast.

In contrast during HWs, the more westward position of the blocking anticyclone, the anomalously cooler SST conditions (colder air column) and the low values of specific humidity over the Tasman and Coral Seas, tend to divert the ‘drier’ air parcels inland sooner and thus create more favorable conditions for the development of extreme heat over southeast Australia. The evolution of specific humidity along the trajectories shown in Figs. 8a and 9a is consistent with this rise (*decline*) in humidity for most air parcels travelling over the Tasman Sea during extreme rainfall (*HW*) events (see Figs. 11d and 12d).

5. Concluding remarks

This study describes and compares the climate signatures of extreme HW and rainfall events which have occurred in Victoria and Queensland respectively, during 1979-2013. Results from our composite analyses have highlighed the importance of mid-latitude dynamics operating in the lead up to, and during, HWs, through the process of Rossby wave amplification over the south Indian and Pacific Oceans. These HWs are also characterized by a warming of the 60°S latitudinal band in the Indian Ocean and by significant sub-regional SST anomalies, which are negative over the Tasman Sea and positive along the southern coastal seas. These mid-latitude processes clearly contrast with the tropical interactions observed during extreme rainfall events, operating mainly through a La Niña teleconnection pattern, and characterized in the case of the events studied here, by warmer SSTs over the Tasman and Coral Seas.

An analogy is found between composites of HWs and extreme rainfall events in south Queensland, in the presence of blocking high systems over the Tasman Sea. This ‘common’ feature may explain why HWs and floods have sometimes been observed to occur simultaneously or in close succession during austral summer (in only about 25% of our extreme case studies). However, our results suggest no dynamical link between such events, since the HW-related anticyclone evolves as part of a mid-latitude wave train, whereas in the case of rainfall events, this much weaker structure emerges as an equivalent barotropic response to tropical convection.

The tracking analyses in Section 4 have helped us complete this comparison of Melbourne HWs and extreme rainfall events in south Queensland, by exploring the physical processes which may be operating in the lead up to these two types of events. Our results suggest again two distinct processes:

- HWs tend to occur when a Rossby wave train propagates from the south Indian to Pacific Ocean, inducing a quasi-stationary blocking high system over the Tasman Sea. This anticyclonic anomaly can then advect *hot and dry* air towards the southern Victorian coast, where it produces HW conditions.

- Extreme rainfall events predominantly occur when the background conditions correspond to a La Niña state (Cai and van Rensch, 2012). The convection induced in the western Pacific can trigger a tropical-extratropical teleconnection over Queensland. This may generate an anticyclonic anomaly over the Tasman Sea, which is able to divert air parcels over a *warm and humid area* where conditions are favorable for more extreme rainfall along the Queensland coast.

In conclusion, our results point towards no direct connection between HWs in Victoria and extreme rainfall in Queensland. Although there is evidence suggesting some extratropical influence on extreme rainfall (*i.e* that the HW-induced blocking may indirectly act to enhance rainfall over Queensland when the background conditions are already conducive to rainfall), our tracking experiment suggests that there is no substantial influence from the tropics during HWs.

Nevertheless, we need to bear in mind that these hypotheses rely on simple composite analyses, based on a limited number of observed cases, and perhaps may also be dependent on the specific definitions we have chosen to select these HW and extreme rainfall events (Perkins and Alexander, 2013). Our results will therefore need to be tested through various numerical experiments. It would be particularly useful to unravel the relative role of each of the key SST regions mentioned in this study to determine whether they play a direct or active role in the occurrence of extreme HW or rainfall conditions, and if so, to quantify their effect on the characteristics of these events. This modelling work would also provide an opportunity to examine some case studies of recent Victorian HWs and Queensland floods (*e.g.* the January 2009 events), and compare those which have occurred independently or simultaneously across the country. Perhaps a particular focus for this could be on the three last HWs identified in this study, which occurred during La Niña conditions and were characterized by perturbed or specific SST conditions (see Fig. 4a, shaded area). This ongoing work will help us address whether and how the signature of these extreme events observed during recent decades will evolve in a future global warming climate.

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Figure captions

Figure 1: Map of Australia showing the location of weather stations in Queensland and Victoria (listed in Table 1) and highlighting the key geographical features discussed in the text, such as the Great Australian Bight, and the Coral and Tasman Seas.

Figure 2: Characteristics of the 14 heat waves selected in Melbourne, illustrated through the average of maximum temperature observed during the three HW days *(bars)* and the average of minimum temperature during the second and third of these days *(white lines).* The concurrent state of ENSO in the tropical Pacific during the DJF season is shown in color for each bar.

Figure 3: Composite of **(a)** 2-m air temperature, **(b)** SLP (*shading*) and 850-hPa wind (*arrows*), **(c)** SST and **(d)** OLR daily anomalies during the first day of selected HWs in Melbourne. Composite anomalies that are significant at the 90% confidence level using the Monte-Carlo procedure of *Terray et al. (2003)* are shown in black contours. Boxes in panel (c) indicate key areas where SST indices (mean SST anomalies) are computed: over the Tasman Sea (blue box), the Great Australian Bight region (red box), a latitudinal band of the Southern Ocean (black box), and the southwest Indian Ocean (green box).

Figure 4: Characteristics of key SST indices (mean SST anomalies) computed for Melbourne HWs over the boxes shown in Fig. 3c, in terms of:

- **(a)** the value of each index during the first day of each HW; and
- **(b)** the daily evolution of each SST index averaged over all 14 HWs, from one month prior to one month following the start (day 0) of the HWs.

Figure 5: Characteristics of selected rainfall events in **(a)** south, **(b)** central and **(c)** north Queensland, in terms of weekly accumulated rainfall *(bars)* and maximum daily rainfall *(white lines)* recorded during each selected week. The concurrent state of ENSO in the tropical Pacific during the DJF season is shown in color for each bar.

Note the different ordinate scale for accumulated rain (in mm) in each Queensland region.

Figure 6: Composite of SST *(top panels),* OLR *(middle panels),* and SLP (shading) and 850-hPa wind (arrows) *(bottom panels)* daily anomalies during the extreme rainfall weeks selected in **(a)** south, **(b)** central and **(c)** north Queensland. Composite anomalies that are significant at the 90% confidence level using the Monte-Carlo procedure of *Terray et al. (2003)* are shown in black contours.

Figure 7: Composite of daily 500-hPa geopotential height *(top panels)* and SLP *(bottom panels)* anomalies during **(a)** the first day of HWs in Melbourne and **(b)** extreme rainfall events in south Queensland. Composite anomalies that are significant at the 90% confidence level using the Monte-Carlo procedure of *Terray et al. (2003)* are shown in black contours.

Figure 8: Three-dimensional air parcel back-trajectory calculations for the air parcels arriving at **Melbourne** at **(a) 925 hPa** or **(b) 500** hPa on the first day of the 14 selected HWs (one color per HW track). The backward trajectories, shown in the *left panels,* are calculated commencing on the first HW days (listed in Fig. 2) and ending 15 days before, with small diamonds every 24 hours. The *right panels* show the evolution of pressure along each of these trajectories.

Figure 9: Three-dimensional air parcel back-trajectory calculations for the air parcels arriving at **925 hPa** at **(a)** Brisbane, **south Queensland**, **(b)** Rockhampton, **central Queensland** and **(c)** Cairns, **north Queensland** stations on the rainiest day of the corresponding rainfall events. The backward trajectories, shown in the *left panels,* are calculated commencing on the rainiest day of each selected event (listed in Fig. 5) and ending 15 days before, with small diamonds every 24 hours. The *right panels* show the evolution of pressure along each of these trajectories.

Figure 10: Same as Figure 9, but for the air parcels arriving at **500 hPa** at **(a)** Brisbane, **south Queensland**, **(b)** Rockhampton, **central Queensland** and **(c)** Cairns, **north Queensland** stations on the rainiest day of the corresponding rainfall events.

Figure 11: Composite of **(a)** latent heat flux (positive upward), **(b)** wind speed and **(c)** 2-m air specific humidity daily anomalies during the first day of HWs in Melbourne (black contours show anomalies that are significant at the 90% confidence level using the Monte-Carlo procedure of *Terray et al. (2003))*. Panel **(d)** shows the evolution of specific humidity along the trajectories calculated for air parcels arriving at 925 hPa at Melbourne on the first day of these HWs (see tracks in Fig. 8a).

Figure 12: Composite of **(a)** latent heat flux (positive upward), **(b)** wind speed and **(c)** 2-m air specific humidity daily anomalies during the extreme rainfall events in south Queensland (black contours show anomalies that are significant at the 90% confidence level using the Monte-Carlo procedure of *Terray et al. (2003)).* Panel **(d)** shows the evolution of specific humidity along the trajectories calculated for air parcels arriving at 925hPa at Brisbane, on the rainiest day of the south Queensland rainfall events (see tracks in Fig. 9a).