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Climatic and synoptic characterization of heat waves in Brazil

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ABSTRACT: According to the latest global and regional circulation models, the probability of occurrence of large heat waves (HWs), such as the 2003 European or the 2010 Russian events will increase significantly in the following decades under most climate scenarios. Currently, there are numerous studies for the Northern Hemisphere characterizing HWs and evaluating their impacts in several areas such as public health, economy, and agriculture. However, over South America, and in particular for Brazil, similar analysis is lacking despite its large geographical extension and numerous population potentially affected. Here we perform an assessment of HW events and characteristics recorded in six large Brazilian cities during the last five decades. The performed analysis reveals the existence of positive and significant trends in HW frequency since the 1980s, particularly for the cities of São Paulo, Manaus, and Recife. Over the last decades, Brasília was the city that recorded the highest number of days per year under a HW regime, contrasting with Rio de Janeiro that recorded the lowest value. The assessment of the large-scale atmospheric circulation patterns associated with summer HWs, indicated for Porto Alegre, São Paulo, Rio de Janeiro, and Brasília the presence of well-marked concentric and positive 500 hPa geopotential height anomalies followed by positive 850 hPa temperature anomalies. These anomalies are likely associated with quasi-stationary anticyclonic systems promoted by anomalous westward displacements of the South Atlantic Subtropical High System which are related to a weakening of other transients (and non-transient) systems such the Intertropical Convergence Zone (ITCZ) and the South Atlantic Convergence Zone. For Manaus, the identified anomalies are linked to a northward displacement of the ITCZ. This configuration is compatible with an increase in solar radiative pattern and decreased soil moisture, enhancing surface temperature values, possibly associated with positive feedback mechanisms between soil and the atmosphere.

KEY WORDS heat waves; Brazil; atmospheric circulation patterns

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1. Introduction

Observational records reveal that the global average surface temperature has been increasing since the early 20th century, particularly after the 1970s decade (Intergovernmental Panel on Climate Change (IPCC), 2014). Future climate change scenarios based on global climate models show significant positive trends of surface temperature, accompanied by an increase in the frequency and intensity of hot extreme periods such as heat waves (HWs). According to the last IPCC report published in 2014, it is very likely that HW frequency has increased since the middle of the 20th century over large parts of Europe, Asia, and Australia. Several studies also suggest that anthropogenic forcing contribution was partially responsible for the occurrence of large HW's recorded in recent years, such as the 2003 European HW (Luterbacher *et al.,* 2004; Stott *et al.,* 2004; Coelho *et al.,* 2008; Zhu *et al.,* 2013) or the 2010 Russian HW, which were classified as mega-heat waves due to their spatial extent, magnitude and associated human, and socio-economic impacts (Barriopedro *et al.,* 2011; Dole *et al.,* 2011).

HWs are responsible for a wide range of effects in ecosystems (Bastos *et al.,* 2014) and in human health, including cardiopulmonary diseases, premature death, and other illnesses that occur when air temperature reaches unhealthy levels (Gosling *et al.,* 2009), impacting directly on public health (Linares and Diaz, 2008), and economy (García-Herrera *et al.,* 2010). Although HW impacts are mainly health-service-related (IPCC, 2014); they are also associated with settlement and social conditions, particularly for children and elderly people (Trigo *et al.,* 2009; Son *et al.,* 2016). Persistent unusual high temperatures may also induce the occurrence of vegetation fires (Pereira *et al.,* 2005; Silva *et al.,* 2016), losses for the agriculture sector, water supplies, food storage, and energy system (García-Herrera *et al.,* 2010).

Accordingly, there is a global demand for understanding and characterizing HW events, considering the associated social, economic, and environmental impacts. However, the widespread interest in characterizing the occurrence

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of extreme temperatures in various continents has not attained the same level in South America and particularly in Brazil, despite few exceptions (Cerne and Vera, 2011; Renom *et al.,* 2011; Rusticucci, 2012; Hannart *et al.,* 2015; Bitencourt *et al.,* 2016; Ceccherini *et al.,* 2016; Rusticucci *et al.,* 2016, 2017). Nevertheless, South America and Brazil, in particular, are no exception to the global positive trend of surface temperature in the last decades (Vincent *et al.,* 2005; Alexander *et al.,* 2006; Skansi *et al.,* 2013; Soares *et al.,* 2017). In particular, Brazil has been affected by a marked increase in both minimum and maximum temperatures since the 1960s (Marengo and Camargo, 2008). The northeast Brazilian region, which is characterized by a semi-arid climate and for being historically affected by dry and extreme hot periods, has registered a gradual increase of extreme heat events, especially since the 1990s decade (Moura, 2016). Moreover, most models (either at the global or regional scale) point to a significant warmer future in South America, with air temperature increasing between 2 and 5 °C by the end of the current century (IPCC, 2014).

Currently, there are several HW definitions and, to some extent, all present advantages and caveats. A certain definition is in most cases effective solely to the group affected and/or to the respective study reporting the analysis (Perkins and Alexander, 2013). Nevertheless, a common denominator rises among all the definitions, considering that an HW can be interpreted as an extreme climate event characterized by a period of consecutive days with daily temperatures expressively higher than the climatological background values (Frich *et al.,* 2002).The most hazardous effects of climate change are related to a potential increase of extreme weather and climate events (Rusticucci, 2012). The vulnerability of the society and ecosystems to most climate extreme events depends crucially on the location and area affected, on the temporal extent of the event and naturally on the ecosystems and crops at risk (Costa *et al.,* 2015). From a human perspective on the potential rise in morbidity or mortality rates, these impacts also depend on the type of population affected, namely the age structure and overall adaptation of society to extreme temperatures (Son *et al.,* 2016).

In mid-latitude, HW genesis is generally associated with the establishment of a large-scale anticyclonic atmospheric circulation pattern (Black *et al.,* 2004; Dole *et al.,* 2011) characterized by quasi-stationary 500-hPa anomalies that induce descending vertical air motion (subsidence) leading to clear sky conditions, light surface winds, advection of warm air masses and prolonged hotter than usual conditions (Xoplaki *et al.,* 2003; Meehl and Tebaldi, 2004). Over Brazil, these patterns can be induced by a westward migration of the South Atlantic Subtropical high in association with sea surface temperature (SST) anomalies over the South Atlantic Ocean. In equatorial regions, hot and dry episodes can be associated with the northward migration of the Intertropical Convergence Zone (ITCZ) in association with warmer than normal SST over the North Tropical Atlantic Ocean and also with the warm phase of El Niño Southern Oscillation (ENSO) phenomena in the equatorial Pacific (Zeng *et al.,* 2008; Coelho *et al.,* 2012).

Given the relatively unexplored characterization of HWs in Brazil, this study aims to depict the decadal evolution of HW events for a number of important Brazilian cities, analysing in particular possible frequency changes and also investigating trends of HW events. The second objective of this work is to establish the relationship between summer HW events for each city and the main large-scale atmospheric circulation patterns associated with these prolonged temperature anomalies at the surface.

2. Data and methodology

Daily values of both minimum and maximum surface air temperatures from different meteorological stations were analysed for the period of 1961–2014. The six stations used here are located within the urban area of six major Brazilian cities, namely, São Paulo, Rio de Janeiro, Brasília, Porto Alegre, Manaus, and Recife. Each city/station belongs to one macro region, namely: North (Manaus), Northeast (Recife), Central-West (Brasília), South (Porto Alegre), and Southeast (São Paulo and Rio de Janeiro), covering the whole country (Figure 1). The macro regions were defined according to the Instituto Brasileiro de Geografia e Estatística (IBGE). Data were obtained from the meteorological station network of INMET (National Meteorology Institute of Brazil) and of ICEA (Air Traffic Control Institute of Brazil). Despite the quality control provided by INMET and ICEA, the temperature data are affected by missing data. We have analysed the temperature records and computed the percentage of missing values along the time series. The obtained percentage of missing values varies from 0.56 to 8.10% for each station, not hindering the HW index computation.

Various HW indices are often constructed for different activity (e.g. human health, wildfire, agriculture, etc.). In a continental country such as Brazil, with a highly diverse population and regions with different atmospheric features, it is important to adopt an index that is versatile. Several indices are based on absolute thresholds, but these can be less suitable to be applied in some sub-regions (Perkins, 2011). Alternatives to absolute thresholds are percentile-based thresholds that define HW as events that exceed a threshold relative to the area of interest, not an absolute universal threshold. In particular, these percentile-based methods allow a more robust comparison of results between the different Brazilian regions and are better suited to be used in a climate change context. Taking into account all these aspects this work uses two indices, based on the 90th percentile of maximum (CTX90pct) and minimum (CTN90pct) temperatures. These types of indexes were also used in previous studies regarding HWs in South America (Rusticucci *et al.,* 2016). Thus we define HW as a period of three or more consecutive days characterized by daily T_{max} and daily T_{min} above the climatological (1961–2014 base period) calendar day 90th T_{max} percentile (CTX90pct) and 90th T_{min} percentile

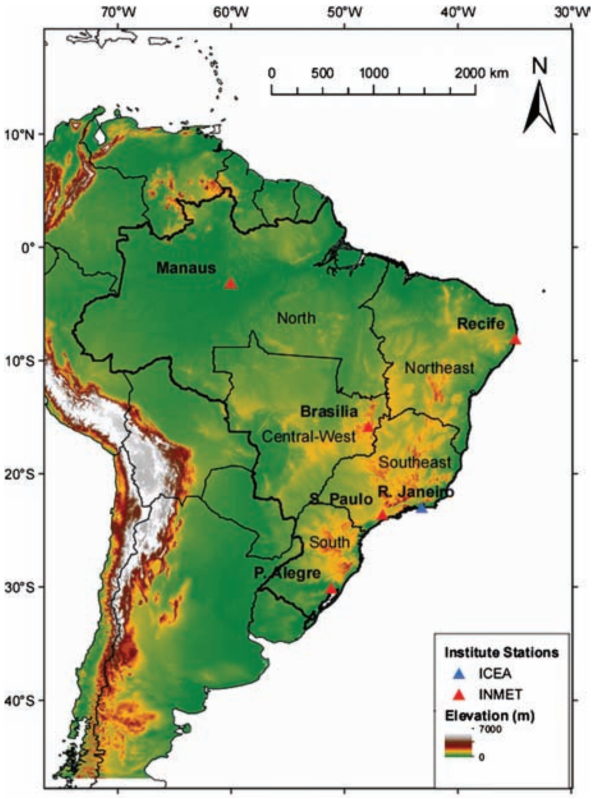

Figure 1. Map of South America highlighting Brazil (bold black line), the five Brazilian main geographical regions (black lines – North, Northeast, Central-West, Southeast, and South), the six Brazilian meteorological stations from ICEA and INMET, and the topography (m). [Colour figure can be viewed at wileyonlinelibrary.com].

(CTN90pct) calculated on a 15-day window (centred on the day in question). In this procedure a different percentile threshold value is computed for each day of the year in order to take into account the seasonal cycle. These two indices showed to be effective in defining and identifying HW events over the Australian territory, which is similar to Brazil in terms of spatial extent and ranges of regional climate variability (Perkins and Alexander, 2013).

The climatic characterization was conducted analysing for each city and for both indexes the number of HW days per year (NHWD), a value that is dependent on the annual number of HW's and also on the duration of each HW event. Any major variation on the annual number of HWs or on the duration of the events will impinge a change in the values of NHWD. Thus this metric represents a more inclusive assessment when compared to analysing separately the annual number of HW or the duration of all events recorded.

Regional atmospheric circulation of summer corresponding to December, January, and February (DJF) HW periods was analysed through ERA-Interim reanalysis fields from European Centre for Medium-Range Weather Forecast (ECMWF) for the period spanning from 1979 to 2014 and over an area of 85–30°W and 13°N-60°S. The meteorological variables used are daily time series of sea level pressure (SLP), 500 hPa geopotential height (H500), 850 hPa level temperature (T850), maximum and minimum air temperature at 2 m (Tmax and Tmin respectively), zonal and meridional wind components at 10 m (U10 and V10 respectively), relative humidity at surface (HRsup), precipitation rate (Prec), solar radiative balance at surface (RadS) and thermal radiative balance at surface (RadTerm).

All values correspond to daily mean averages, except for Tmax, Tmin, RadS, and RadT. Regarding Tmax (Tmin) the daily values correspond to the maximum (minimum) temperature recorded on each day. Regarding RadS and RadT, the daily values correspond to daily levels of accumulated radiation. The reanalysis data, although based on observed fields, depends also on the quality of the forecast model used. This caution note must be considered when analysing the Prec variable because it is particularly dependent on the forecast model, and thus, susceptible to model systematic errors. Nevertheless, the large-scale atmospheric circulation analyses performed in this paper were based on anomaly composites (mean field removed) as explained in the following paragraph, which filter considerably the impact of model biases (Trigo *et al.,* 2002, 2004; Pereira *et al.,* 2005).

Anomaly composite fields of different meteorological variables relative to each city were obtained by averaging the summer anomalies (with respect to the 1979–2014 climatology) for the dates identified as intense HW events (see definition below). In other words, an anomaly composite of intense summer HW events regarding a specific city is defined as the mean of the meteorological variable values recorded during the days identified as being part of an intense summer HW event. An intense summer HW event, relatively to a specific city and to a certain meteorological parameter was defined as an event whose temporal extension was longer than the 90th percentile of all the durations (of all summer events recorded over the period of 1979–2014) obtained for the same city.

3. Results

3.1. Climatic characterization

3.1.1. Number of HW days per year

As mentioned in Section 2, the climatic characterization was conducted analysing for each city and for both indices the NHWD. Figure 2 provides a full assessment of these various components for the city of São Paulo showing that the NHWD time evolution (Figure 2(c)) results from the annual number of HWs evolution (Figure 2(a)) as well as from the duration of the HW events recorded (Figure 2(b)).

Table 1 reveals a well-marked disparity in NHWD mean and standard deviation values between cities and even, for the same city, between both indices. Regarding the CTX90pct index, Brasília was the city showing the highest mean NHWD value of 20.5 days. On the other hand, Rio de Janeiro showed the smallest mean NHWD value of 7.8 days. The cities of São Paulo and Porto Alegre showed similar mean values (14.5 and 14 days year^{-1}, respectively) to what was obtained for the cities of Recife

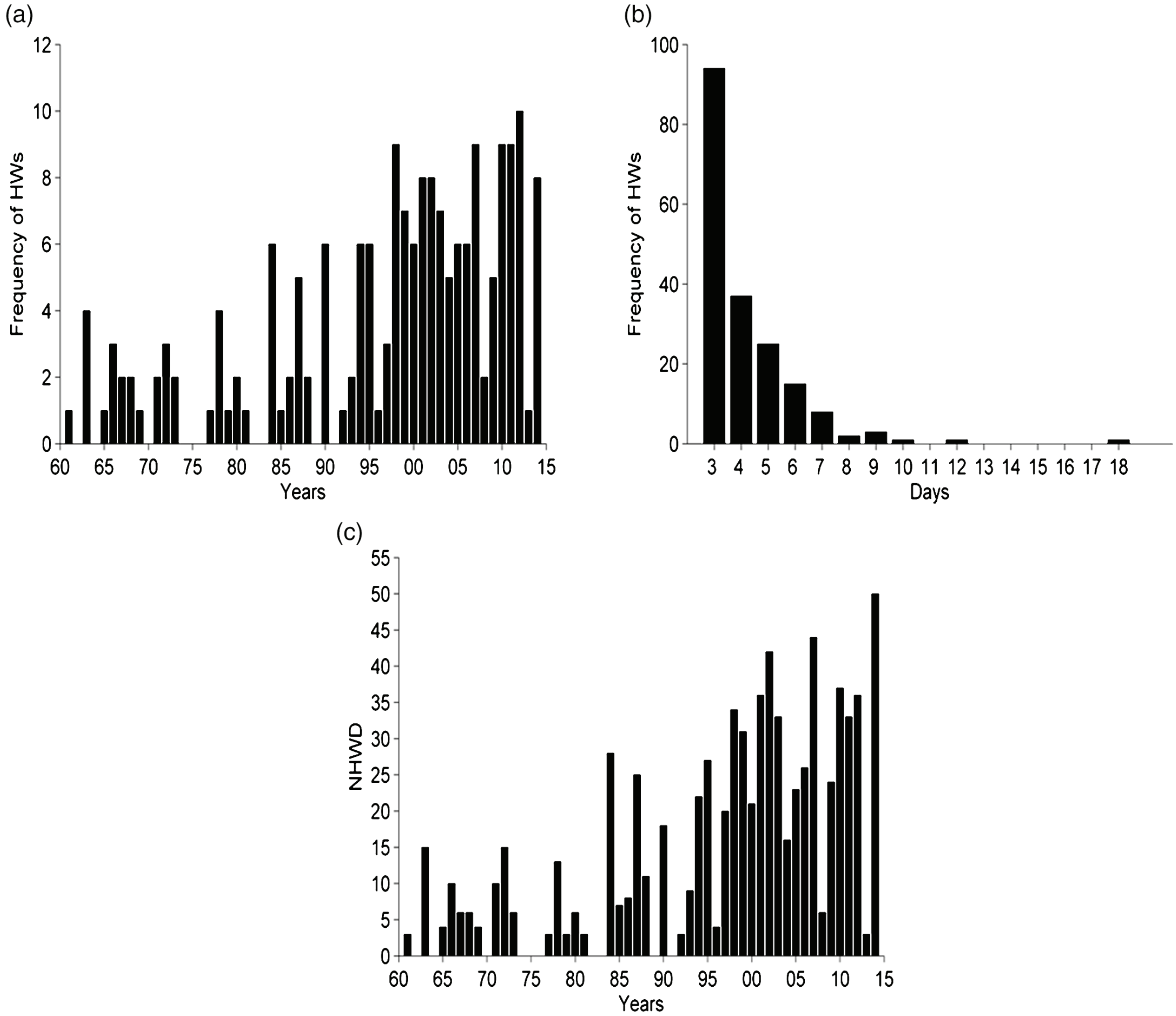

Figure 2. Time evolution (1961–2014) of the annual number of HW's for São Paulo (a). Histogram of the durations of all HW events recorded for São Paulo over the period of 1961–2014 (b). Time evolution (1961–2014) of the annual number of HW days (c). All values were recorded regarding the CTX90pct index.

Table 1. NHWD statistical values (means and standard deviation) for the 1961–2014 period for the six Brazilian cites and for both indices.

NHWD	Mean (day year^{-1})		Standard deviation (day year^{-1})	
	CTX90pct	CTN90pct	CTX90pct	CTN90pct
Manaus	16.6	18.1	21.0	39.0
Recife	17.6	7.7	22.6	10.8
Brasília	20.5	14.1	15.9	17.2
São Paulo	14.5	12.5	14.1	12.7
R. Janeiro	7.8	16.7	6.1	16.6
P. Alegre	14.0	16.1	12.3	11.4

and Manaus (17.6 and 16.6 days year^{-1}, respectively). Regarding the CTN90pct index, Recife showed, in contrast with the large mean value for the CTX90pct, the smallest mean NHWD value, just 7.7 days year^{-1}, confirming the disparity of results often observed between the two computed indices. Likewise, contrary to what was noticed for CTX90pct, Rio de Janeiro was one of the cities with the highest value (16.7 days year^{-1}) with CTN90pct index. Finally, Manaus recorded the highest values (18.1 days year^{-1}) with CTN90pct index.

This disparity between indices is also noticed in the NHWD standard deviation values. For both indices, Manaus showed the highest results, including the exceptional value of 39 days year^{-1} for the CTN90pct. Regarding CTX90pct index, Recife was the city with the highest value (22.6 days year^{-1}) while Rio de Janeiro showed the smallest (6.1 days year^{-1}). Again, results for the CTN90pct show a very different picture with Rio de Janeiro presenting the highest value and Recife the smallest (10.8 days year^{-1}).

This contrast over the analysis period between indices is also observed in terms of the NHWD historical time series, as shown in Figure 3. Regarding the NHWD values obtained by applying the CTX90pct index (Figure 3(a))

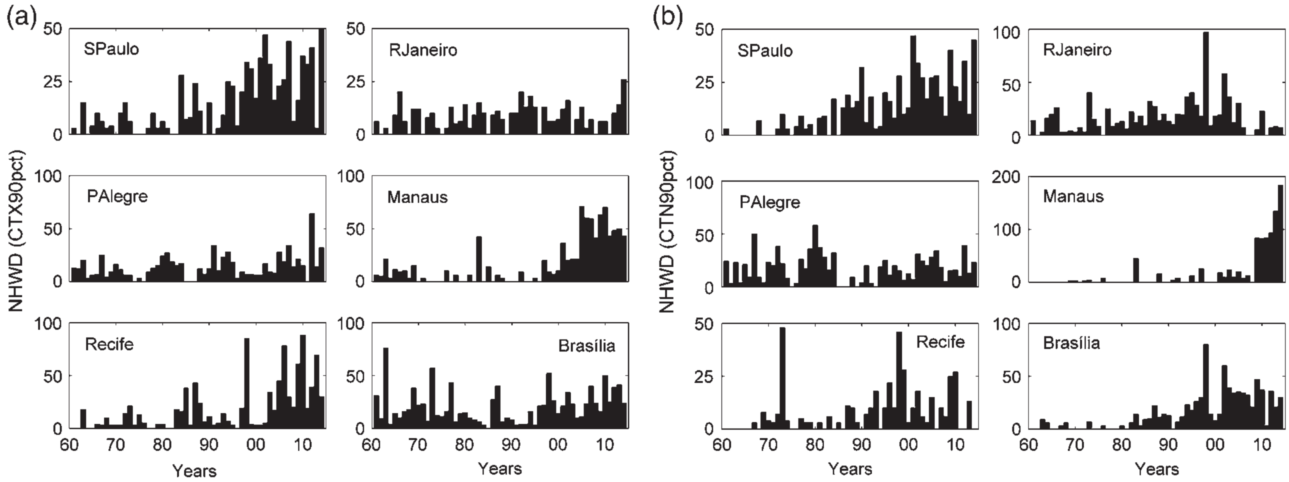

Figure 3. NHWD time series for the 1961–2014 period: (a) CTX90pct index and (b) CTN90pct index.

two different behaviours are noticed for the cities of São Paulo, Recife, and Manaus throughout the 1961–2014 period. During the first half of the period, especially until the 1980s, fairly stable NHWD values were noticed, contrasting with the second half, where a sustainable increase is identified in the NHWD values. This increment was particularly remarkable and intense for Manaus (for both indices shown in Figure 3), where the contrast between the high (low) NHWD values recorded during the second (first) half of the analysis period contributes to the large standard deviation values for this city (see Table 1). The CTN90pct time series for the cities of Rio de Janeiro and Porto Alegre reveals more homogeneous NHWD values (Figure 3(b)) through the full period, similarly to what was noticed for the CTX90pct index (Figure 3(a)). However, the CTN90pct index for Brasília (Figure 3(b)) presented a marked increase during the second half, in contrast to what was found for the CTX90pct index (Figure 3(a)). This behaviour was also identified for the cities of Manaus and São Paulo, which presented similar increasing trends for both indices. Regarding Recife the increase of the NHWD values over the second half of the period recorded with CTX90pct is not present in the CTN90pct index, showing once again a clear contrast between the NHWD historical time series evolution obtained when applying both indices. This can be interpreted as an indication of distinct max/min temperatures evolutions over the last decades in different regions of Brazil.

3.1.2. NHWD trends

The trend values were calculated for three distinct periods, the full period from 1961 to 2014, and the two shorter sub-periods 1961–1980 and 1981–2014. These two shorter sub-periods were chosen based on previous studies showing that several regions of the planet have recorded more pronounced temperature increase since the 1980s (IPCC, 2014). The choice of these sub-periods was also found to be suitable when analysing the NHWD time series in the previous section, where it is possible to identify an increase in the NHWD values, specially since the 1980s over some cities (Figure 3). Special attention is devoted to this sub-period after the 1980s, not only to investigate how intense the NHWD increase was in some cities, but also to understand the contribution of this sub-period for the trend over the entire 1961–2014 period.

3.1.2.1. Trends of indexes base on temperature for the entire 1961–2014 period: Figure 4 shows for both indices an increasing trend for the period 1961–2014 in NHWD values for all cities, except Porto Alegre, where a small negative trend was identified in the CTN90pct index. Most positive trends obtained for CTX90pct were found to be statistically significant at the 5% level, while those obtained for the CTN90pct index were only found to be statistically significant for Brasília and São Paulo. Particularly in what respects the CTX90pct index, most cities recorded positive and statistically significant NHWD trends, with the exception of Brasília and Rio de Janeiro. These results indicate a less pronounced and sustainable positive evolution regarding minimum temperatures over the period 1961–2014 when comparing to maximum temperatures. Manaus and Recife were the cities with the highest positive and statistically significant trends regarding the CTX90pct index. However, concerning the CTN90pct index, these two cities show positive trend values too but not statistically significant. Manaus was, from all cities and for the CTX90pct index, the one that recorded the highest positive trend presenting a value superior to 12 days per decade. Interestingly, although the corresponding results with the CTN90pct index present a very strong trend value, it is statistically non-significant due to the large NHWD variability over the considered period. The city of Recife presents contrasting results for the two indices, with the CTX90pct (CTN90pct) index recording a strong and significant (weak and non-significant) trend. São Paulo recorded for both indices positive and statistically significant trends with the highest values being observed for the CTX90pct index. Regarding Rio de Janeiro the trend values are similar and statistically non-significant for both indices. In what concerns the Brazilian capital (the city of

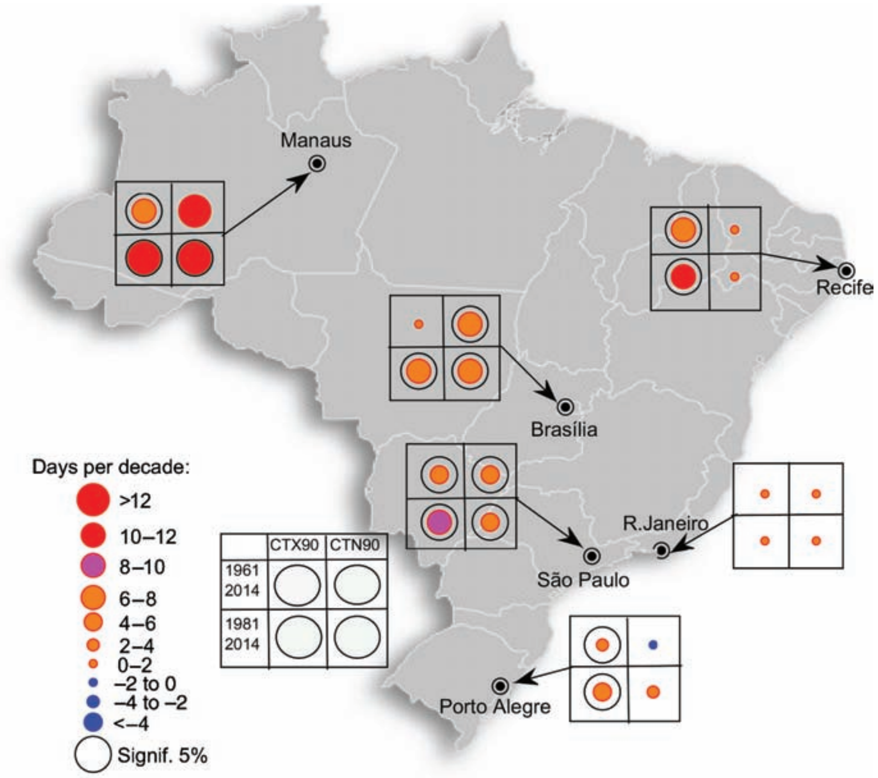

Figure 4. NHWD trend values regarding the sub-periods of 1961–2014 (top) and 1981–2014 (bottom) and for the CTX90pct index (left) and for the CTN90pct index (right) with respect to all the six cities analysed. [Colour figure can be viewed at wileyonlinelibrary.com].

Brasília), it is the only city with a reverse situation, i.e. the highest and statistically significant values were recorded with the CTN90pct while the CTX90pct index observed a much weaker trend. The identified trend in CTN90pct may be due to the occurrence of fewer cold front intrusions along the year over the Brazilian Center-West region.

3.1.2.2. Trends of indexes based on temperature for the 1981–2014 sub-period: The second sub-period (1981–2014) shows a generalized NHWD increase for most investigated cities and for both indices (Figure 4). The trends recorded for the full period are generally leveraged by the exceptional positive trend values identified during the 1981–2014 sub-period. During the 1981–2014 sub-period, both indices show for all cities positive trend values and most of them are statistically significant at the 5% level. This situation contrasts with a rather different profile observed during the period of 1961–1980, without a single statistically significant positive trend and several negative ones (not shown). It is worth emphasizing that during this sub-period the city of Manaus showed the highest NHWD increase for both indices. The city of Recife showed also a large and statistically significant positive trend values regarding CTX90pct index (only surpassed by the value recorded for Manaus). This result for Recife is in agreement with previous studies that identified a gradual increase of extreme heat events, especially since the 1990s decade over the northeast Brazilian region (Moura, 2016). São Paulo recorded positive and statistically significant trend values although stronger for CTX90pct than the CTN90pct index, confirming a more pronounced NHWD increase based on maximum temperatures as shown in Figures 3(a) and (b). Rio de Janeiro was the city with the lowest NHWD trend variations between indices and between the sub-periods of 1961–1980 and 1981–2014, presenting positive but statistically non-significant trends.

3.2. Regional atmospheric circulation

In this section, we characterize the average regional atmospheric circulation patterns associated with the formation of summer (DJF) HW periods over some Brazilian cities as this is the season that can lead to more serious HW impacts (Bastos *et al.,* 2014; Son *et al.,* 2016). To this purpose anomaly fields of several meteorological variables are assessed through composites of summer HW events, which were obtained separately for each city. For the sake of simplicity and due to space limitation we will focus on the cities of Porto Alegre, São Paulo, and Manaus. These composites were defined as the arithmetic means calculated for a sub-sample of the main analysis period, which correspond to particular intense summer HW time periods identified separately for each city and following a methodology already described in Section 2. The anomaly values represented here correspond to HW summer composites which are significantly different from the corresponding summer climatology at the 5% level, computed with a two-tailed *t*-test. The summer climatology for two important variables (H500 and T850) can be observed in Figure 5.

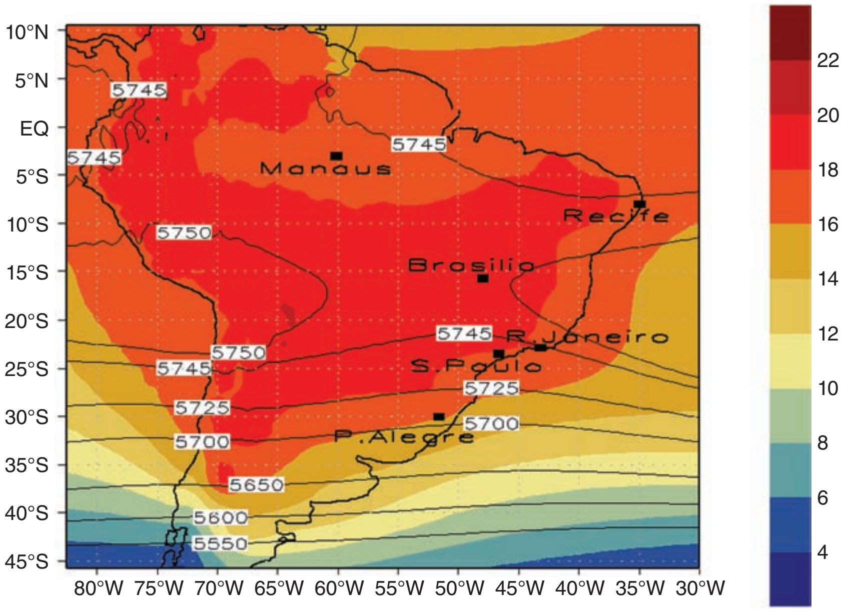

Figure 5. Air temperature at 850 hPa (shaded, °C) and 500 hPa geopotential height (contour gpm) summer climatological field (1979–2014). [Colour figure can be viewed at wileyonlinelibrary.com].

3.2.1. In altitude (H500; T850)

For the cities of Porto Alegre and São Paulo, the atmospheric upper-level flow pattern associated with summer HW events is very similar (Figures 6(b) and (d)). In fact, for both cities, the H500 anomaly field presents a well-marked concentric positive anomaly, but also an intense 850 hPa positive temperature (T850) anomaly which is slightly offset to the west with respect to the H500 anomaly. The T850 fields are known for being both adequate representatives of the low troposphere state and relatively insensitive to some of the problems that affect reanalysis variables near the surface (García-Herrera *et al.,* 2005; Trigo *et al.,* 2005). In this respect, such intense positive T850 anomalies are the trademark of an exceptional low tropospheric heating. Regarding these two cities, we observe that this conspicuous maximum H500 positive anomaly is (for both cities) centred eastward the city of Porto Alegre, throughout all southern Brazilian coast (Figures 6(b) and (d)). It is also worth noting that the composite relative to the city of Porto Alegre presents the highest anomalies for both H500 and T850.

These near circular H500 and T850 positive anomalous patterns are clear signatures of the presence, during summer HW events for both cities, of a quasi-stationary anticyclonic circulation system which can be of the Anticyclonic Ridge type or even a full blocking pattern (Trigo *et al.,* 2004; Sousa *et al.,* 2017). The presence of these persistent anticyclonic patterns which were also recorded for the cities of Brasília and Rio de Janeiro (not shown) provide the ideal meteorological setting both in altitude and at the surface for the development of high air temperature levels (Sousa *et al.,* 2017).

For the city of Manaus, and considering its equatorial location, the characteristics of the HW anomalies in altitude are considerably different. Over the equatorial regions, the atmospheric state is mainly conditioned by the ITCZ positioning and irregular displacements, which tend to modulate the intensity of tropical convective activity (Tedeschi *et al.,* 2016). The ITCZ system is characterized for being a very well defined east–west oriented nebulous cover band associated with low-pressure values, the low-level convergence of the trade winds over the equatorial oceans and with high levels of convective precipitation and humidity (Garreaud *et al.,* 2009). Thus, in altitude, the atmospheric signature of an ITCZ weakening over the equatorial region is usually associated with the presence of positive H500 anomalies, although much less pronounced than the corresponding anomalies for the south Brazilian cities (Figure 6(f)). These anomalies represent conditions of clear sky, subsidence, and absence of cloud cover, allowing a more pronounced low tropospheric heating. In fact, the positive H500 anomaly fields for the city of Manaus over the Amazon region are indicative of a weakening of the ITCZ during summer HW events (Figure 6(f)).

3.2.2. At surface (Tmax; Tmin; HRsup; Prec; RadS; RadT; SLP; u10; v10)

3.2.2.1. São Paulo: Figure 7(a) shows positive maximum temperature (Tmax) anomalies over most Southeast Brazil region (particularly over São Paulo and Minas Gerais states). This core sector shows maximum values of 4 °C recorded westward of the metropolitan region of São Paulo. Figure 7(b) also shows positive minimum temperature (Tmin) but located further south indicating a clear dipole structure between the maximum Tmax and Tmin positive anomalies. The very high Tmax values recorded for the region of São Paulo and Minas Gerais during summer HW events over São Paulo match well spatially with positive solar radiation (RadS) anomalies and negative thermal radiation (RadT) anomalies in this region

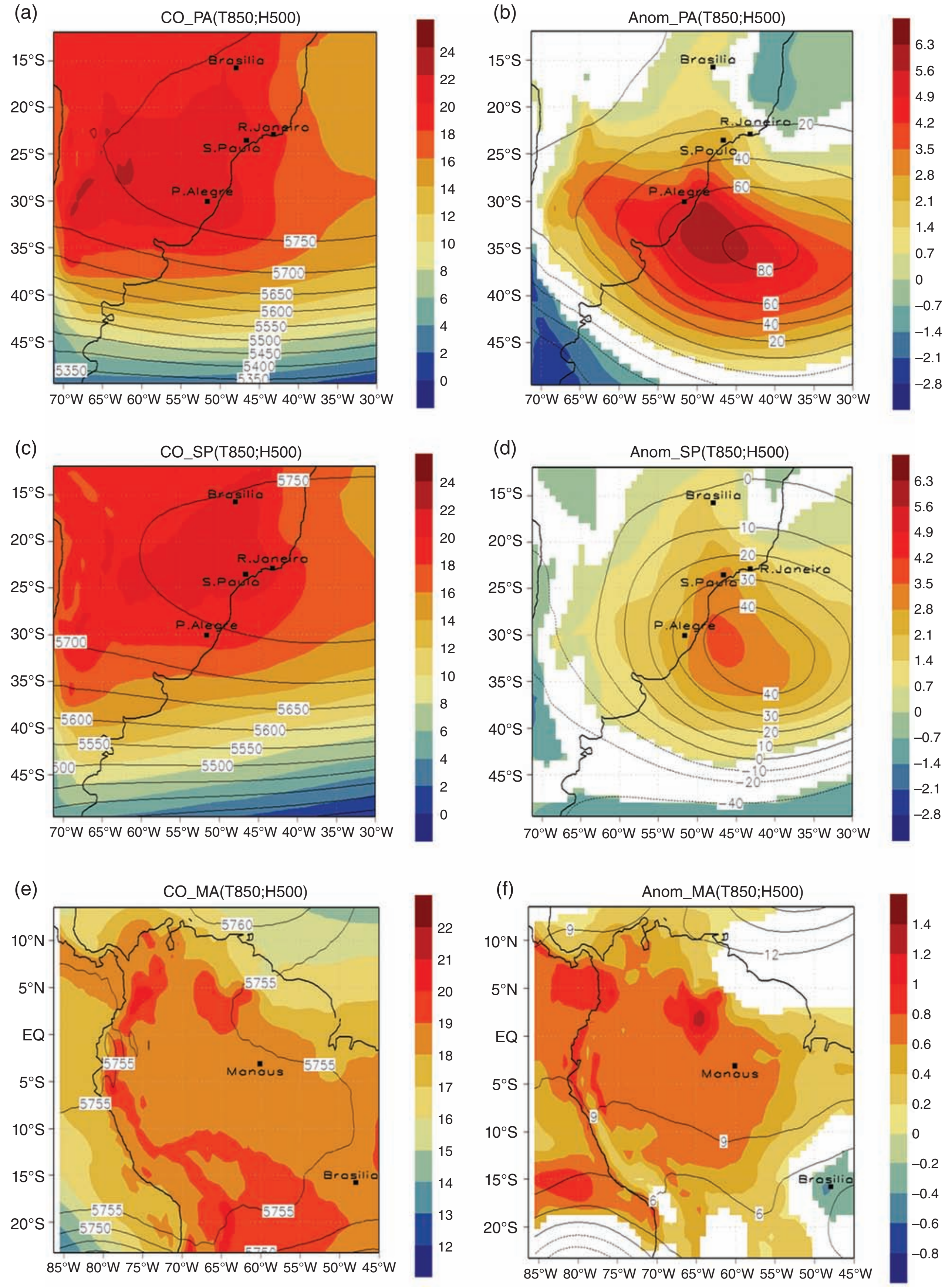

Figure 6. Air temperature at 850 hPa (shaded, °C) and 500 hPa geopotential height (contour, gpm) intense summer HW events composite for P. Alegre (a), S. Paulo (c) and Manaus (e), and averaged anomaly fields for Porto Alegre (b), S. Paulo (d) and Manaus (f). [Colour figure can be viewed at wileyonlinelibrary.com].

(Figures 7(e) and (f)), indicating therefore the occurrence of clear sky conditions that induce high levels of solar radiation incidence and low levels of thermal radiation retention near the surface. When such radiative imbalance is observed over a considerable number of days and dry atmospheric and soil conditions are observed simultaneously, Tmax values are enhanced amplifying the daily thermal amplitude, establishing positive feedback mechanisms between the atmosphere itself and between the soil and the atmosphere (Fischer *et al.,* 2007). In fact, when analysing precipitation (Prec) and relative humidity (HRsup) anomalies during summer HW events over São Paulo, it is evident that exceptionally low levels of these meteorological parameters were recorded throughout this geographical area of São Paulo and Minas Gerais (Figures 7(c) and (d)). This situation probably promoted low levels of soil moisture that together with high levels of solar radiation incidence at surface changed the sensible and thermal heat fluxes enhancing Tmax.

From an atmospheric circulation point of view, such clear sky conditions and associated negative precipitation and relative humidity anomalies are characteristic of quasi-stationary anticyclonic circulation patterns, as confirmed when analysing the H500 and T850 anomalies (Figure 6(d)). At the surface, this atmospheric configuration is also visible in the SLP anomaly field (Figure 7), which shows a similar well defined concentric configuration of positive values centred westward the southeast Brazilian coast. Additionally, this SLP anomaly field is consistent with the genesis of an anticyclonic wind configuration recorded when analysing the 10 m zonal (u10) and meridional (v10) wind anomalies (Figure 7). This near-surface wind pattern is responsible for a strong warm advection of air masses formed over the Minas Gerais state southward towards southern Brazil, Uruguay and eastern of Argentina.

3.2.2.2. Porto Alegre: The situation recorded for Porto Alegre is qualitatively similar to what was described previously for the city of São Paulo, including the presence of a quasi-stationary anticyclonic pattern inducing strong positive H500 and T850 circular anomalies over the Atlantic Ocean, to the east of south Brazil (Figure 6(b)). This atmospheric circulation pattern favours clear sky conditions and absence of cloud cover inducing high levels of solar radiation, which are easily identified when analysing the exceptional high (low) levels of solar (thermal) radiation balance at surface recorded between Rio de Janeiro and Porto Alegre (Figure 8(e)). Figures 8(c) and (d) show low levels of HRsup and Prec which combined with high levels of solar radiation incidence contributed with the formation of warm and dry air masses over this region. However, these anomalous cores of HRsup, PRec, RadS, and RadT do not show such a perfect spatial match with the positive Tmax anomalies identified near Porto Alegre as previously noticed for the case of São Paulo. Thus, for Porto Alegre, contrary to São Paulo, the high anomaly values of air temperature recorded cannot be explained solely based on radiative balance terms. The exceptional high Tmax values recorded during summer HW events for the region of Porto Alegre reached 5 °C above the summer climatology for a large swath of the coastal area (Figure 8(a)), and were probably induced by the high levels of solar radiation incidence together with a strong advection of warm and dry air masses formed over the state of Minas Gerais. As shown by the wind anomaly fields, these air masses can be advected southward by the anticyclonic circulation, further heating areas closed to Porto Alegre. This anticyclonic wind configuration is associated with the exceptional positive and concentric SLP anomaly located westward the state of São Paulo and Rio de Janeiro which are a clear signature at the surface of the quasi-stationary anticyclonic pattern identified in altitude by the H500 and T850 anomaly field (Figure 6(b)). These fields recorded for Porto Alegre are similar to those found by Cerne and Vera (2011) for the end of the summer HW events in central Argentina, where positive temperature anomalies, also supported by these same radiative balance and strong advection processes, are developed in Uruguay and southern Brazil.

3.2.2.3. Manaus: Historically hot and dry periods over the city of Manaus are known for being strongly conditioned by the ITCZ positioning which may, under specific oceanic/atmospheric conditions, move out from its predominant location (Tedeschi *et al.,* 2016; Tedeschi and Collins, 2016). When northward ITCZ displacements occur, the meteorological conditions over the equatorial region where Manaus is located tend to be more stable with less precipitation and reduced values of cloud cover and relative humidity. This meteorological context results in near-surface latent and sensible heat flux changes over this region. Particularly during dry spells, the increase in sensible heat flux is a major factor for generating hot and dry periods (Figueroa *et al.,* 1995). Figure 9(a) shows positive Tmax anomalies of the order of 3–3.5 °C throughout the entire Amazon region (Figure 9(a)), encompassing the city of Manaus. Similarly to what was identified for the cities of São Paulo and Porto Alegre, there is also a closed spatial match between the positive Tmax anomaly nucleus and the positive (negative) anomaly nucleus of RadS (Prec, RadT, and HRsup). Regarding HRsup (Figure 9(c)), the spatial distribution of values relatively to Tmax is almost identical indicating that a deficit of heat removal from the atmosphere for energy changes by latent heat fluxes was likely one of the major factors responsible for the Tmax enhancing recorded. This HRsup and Prec deficit suggests a reduction in atmospheric convective activity, which is compatible with the RadS and RadT anomalies (Figures 9(e) and (f)) that indicate high levels of solar radiation incidence and low levels of thermal radiation retention at the surface. Thus the positive Tmax anomaly nucleus recorded over the Amazon region, and specially northward the city of Manaus (Figure 9(a)), is consistent with an ITCZ northward displacement and consequently convective activity weakening over this area, resulting in both below normal atmospheric humidity and soil conditions, leading to enhanced sensible heat fluxes and increased temperatures values.

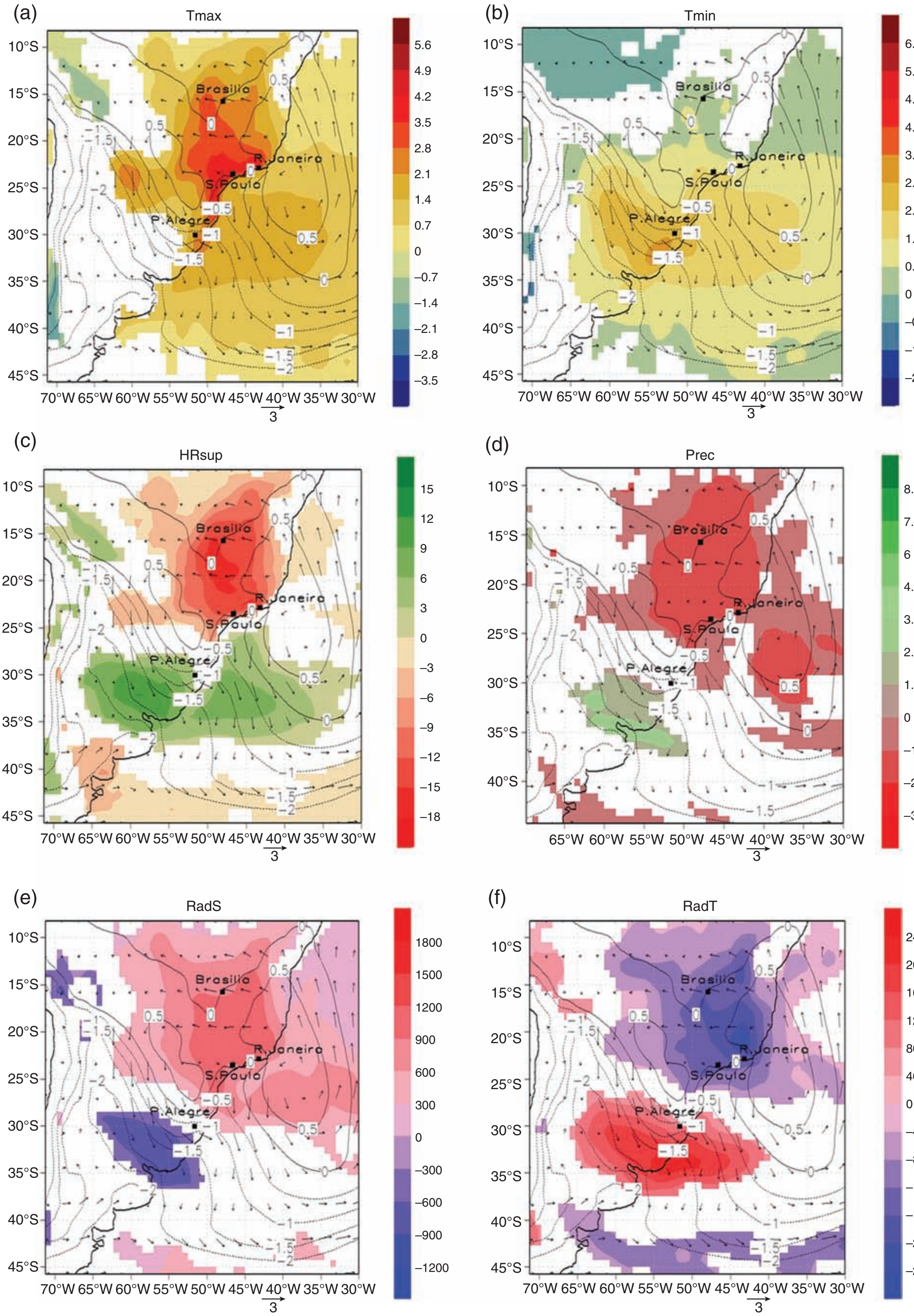

Figure 7. Averaged anomaly fields regarding the city of São Paulo and for intense summer HW events of SLP (contour, hPa), wind 10 m height (vector, m s^{-1})) and of (a) Tmax (shaded, °C), (b) Tmin (shaded, °C), (c) HRsup (shaded, %), (d) Prec (shaded, mm), (e) RadS (shaded, W m^{-2}), (f) RadT (shaded, W m^{-2}). [Colour figure can be viewed at wileyonlinelibrary.com].

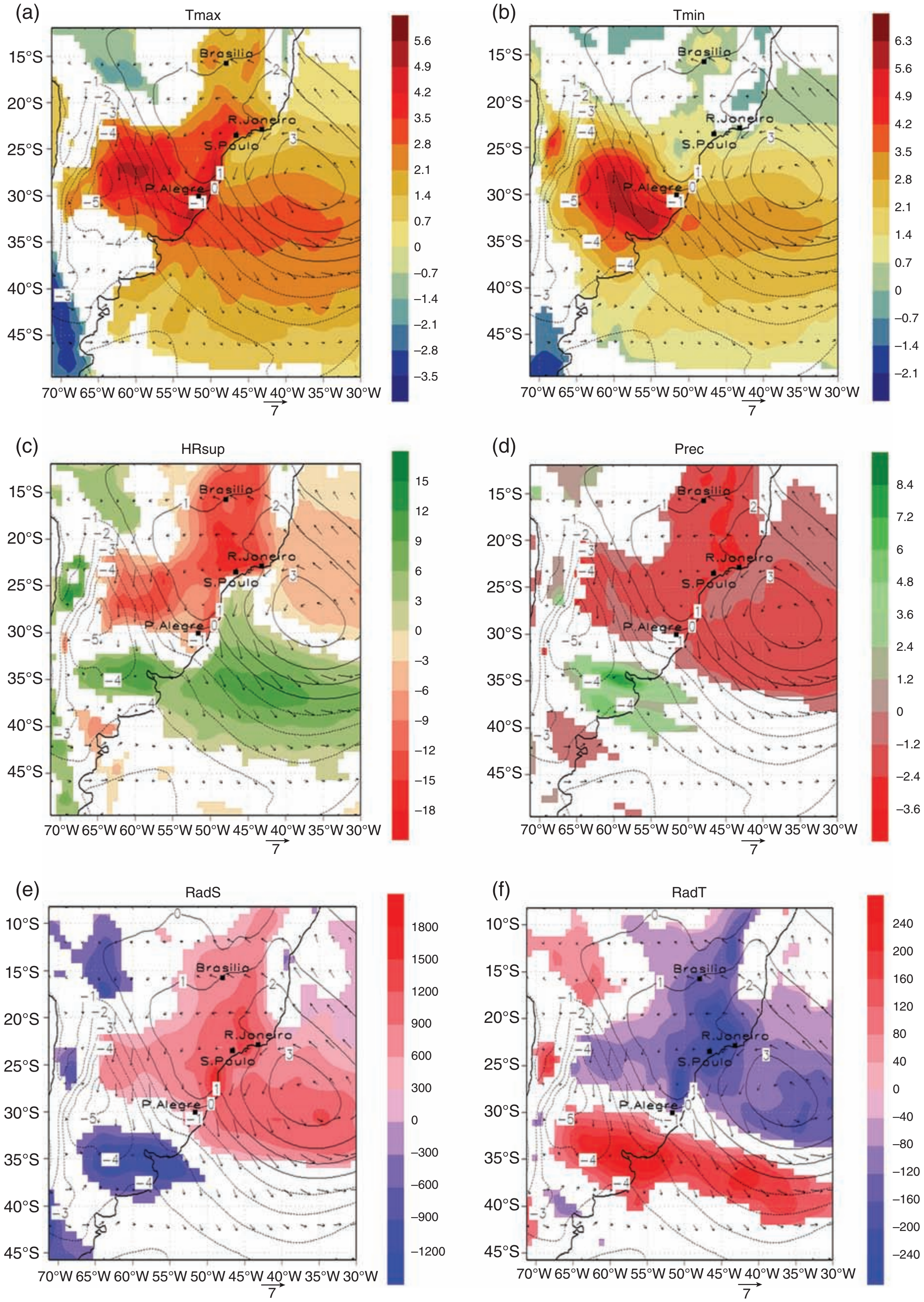

Figure 8. Averaged anomaly fields regarding the city of Porto Alegre and for intense summer HW events of SLP (contour, hPa), wind 10 m height (vector, m s^{-1}) and of (a) Tmax (shaded, °C), (b) Tmin (shaded, °C), (c) HRsup (shaded, %), (d) Prec (shaded, mm), (e) RadS (shaded, W m^{-2}), (f) RadT (shaded, W m^{-2}). [Colour figure can be viewed at wileyonlinelibrary.com].

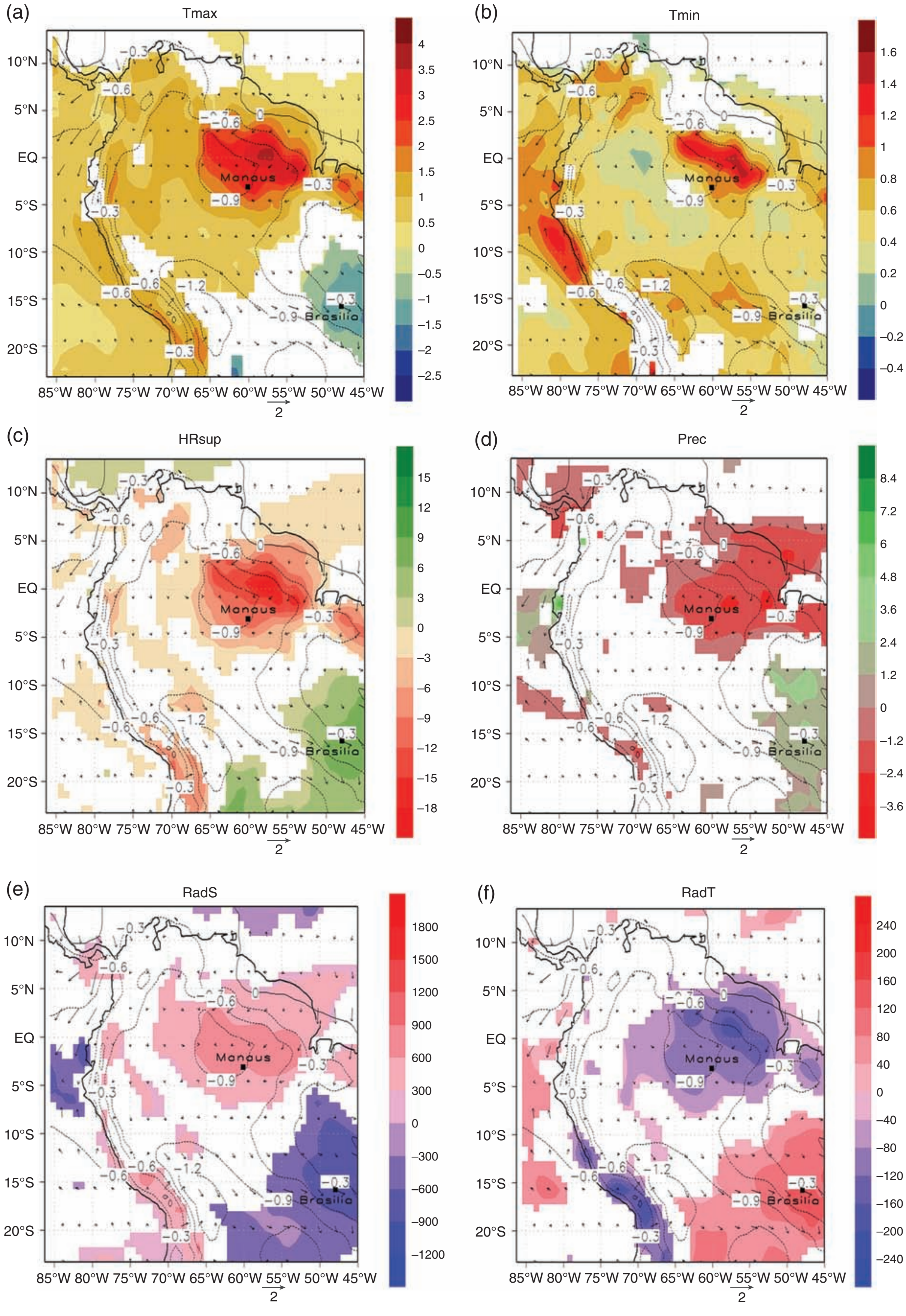

Figure 9. Averaged anomaly fields regarding the city of Manaus and for intense summer HW events of SLP (contour, hPa), wind 10 m height (vector, m s^{-1}) and of (a) Tmax (shaded, °C), (b) Tmin (shaded, °C), (c) HRsup (shaded, %), (d) Prec (shaded, mm), (e) RadS (shaded, W m^{-2}), (f) RadT (shaded, W m^{-2}). [Colour figure can be viewed at wileyonlinelibrary.com].

4. Discussion

From a climatic point of view, results show a clear contrast over the NHWD values recorded for the different Brazilian cities and in some cases even for the same city between the two investigated indices. Disparities on NHWD values were identified for all statistical aspects here analysed namely the NHWD mean, the NHWD standard deviation values and also the trend values for the total analysis period (1961–2014) and for the sub-period (1981–2014). Despite all disparities, cities like São Paulo, Manaus, Recife, and Brasília showed a clear statistically significant NHWD positive trend since the 1980s decade which is in agreement with recent studies. Soares *et al.* (2017) show that the near-surface temperature has been increasing over much of South America during the period of 1975–2004, suggesting a particularly strong warming over central Brazil which can not be explained by natural climate variability alone. In particular, Ceccherini *et al.* (2016) and Bitencourt *et al.* (2016) highlighted the increase in intensity and in the frequency of HWs in South America and in Brazil since 2000, associated with a faster increasing in maximum temperature compared to the minimum temperature. The northeast Brazilian region has been recording since 1974, an increase of the number and intensity of positive thermal anomalies (Moura, 2016). Almeida *et al.* (2017) recorded for the Amazon region and for the period 1980–2014, very significant positive trend values for both maximum and minimum temperatures, which is in agreement with our results that show for both indices a strong positive and significant NHWD trend for the city of Manaus and for the sub-period 1981–2014. We recognize that urban heat islands and deforestation/land use may have an important role for the development of HWs here investigated and therefore enhance the impacts of extreme climate events. Recent studies indicate that this region has experienced both effects (urbanization and land use and cover change) in the last four decades (de Souza *et al.,* 2016; Ometto *et al.,* 2016). The exceptional high NHWD values recorded since the beginning of 21st century and especially for the years of 2005 and 2010 regarding the city of Manaus are representative of the abnormally hot and dry periods that have been observed in this region. The extreme 2005 and 2010 Amazon droughts events resulted in part from the warming of the Tropical North Atlantic SST and of the co-occurrence of an El Niño in the particular case of 2010 (Marengo and Espinoza, 2016; Panisset *et al.,* 2017).

Concerning the regional atmospheric circulation of summer HW episodes for the cities of Manaus, São Paulo and Porto Alegre, it is clear that in all cases the HW genesis is closely related to a very well defined radiative energy transfer pattern. This configuration is defined by exceptionally high values of solar radiative incidence at the surface, which is associated with dry meteorological conditions represented here by negative precipitation and relative humidity anomalies. This relationship between the summer HW episodes and such radiative and dry meteorological scenario is supported on the almost perfect spatial match between the Tmax, Prec, HRsup, RadS, and RadT anomalies, also found in other studies which notice that during the hot and dry Amazon years of 2005 and 2010 the solar radiation levels at surface and the land surface temperature values were above normal (Panisset *et al.,* 2017).

Due to the different geographical localizations, the high-level atmospheric circulation patterns responsible for these specific radiative and dry meteorological scenarios are not the same for the three cities here investigated: Manaus, São Paulo, and Porto Alegre. The city of Manaus is situated within the north and equatorial Brazilian region, where the atmospheric configuration is influenced by the Tropical Atlantic Ocean and tends to experience wet meteorological conditions in association with active ITCZ episodes, favouring convective activity over this region. Throughout the seasonal cycle, ITCZ presents very well defined migration mechanisms responsible for the observed climatic conditions, namely in what concerns water vapour transport and precipitation levels over the equatorial and central South America. This migration constancy led some authors to describe the north and central South America climate as making part of the monsoon type (Jones and Carvalho, 2002; Vera *et al.,* 2006). The weakening of the convective activity and the decrease of the water vapour content over northern South America, which is connected to the development of above normal dry and hot conditions at the surface, is the result of exceptional intense northward ITCZ displacements (Tedeschi *et al.,* 2016; Tedeschi and Collins, 2016). Northward ITCZ displacements are related to SST anomalies over the North Tropical Atlantic Ocean (Zeng *et al.,* 2008) and to ENSO, that tend to influence the normal wind pattern, the levels of temperature and atmospheric convective activity throughout this region (Grimm, 2003; Andreoli *et al.,* 2017).

Based on the anomaly fields description this work helped to establish a relationship between summer HW events in Manaus and above the normal clear sky and dry conditions, likely promoted by ITCZ northward displacements associated with meridional SST gradients over the Tropical North Atlantic Ocean. This relationship was documented in previous studies through negative correlation between the abnormal SST values and Amazonian precipitation and river flow levels (Aragão *et al.,* 2007; Marengo *et al.,* 2008; Coelho *et al.,* 2012; Panisset *et al.,* 2017).

Regarding the cities of São Paulo and Porto Alegre, the quasi-stationary anticyclonic atmospheric circulation pattern that provided the ideal radiative and dry meteorological conditions for the development of summer HW events, was likely promoted by a westward migration of the South Atlantic Subtropical High System. During the summer, the 500 hPa flow pattern, which guides the baroclinic waves (cold fronts on the surface), moves to higher latitudes, allowing the Subtropical High to prevail in the Southern Atlantic close to the continent. This move towards SW hinders the passage of frontal systems that usually affect the south, southeast and central-west regions of Brazil. Under these conditions, subsidence prevails promoting decreased atmospheric humidity, reduced cloudiness (i.e. clear sky conditions prevail) and high levels of solar radiation incidence at the surface (Sousa *et al.,* 2017). This radiative and dry meteorological pattern was identified for both São Paulo and Porto Alegre HW conditions, which presented a considerable spatial match between Tmax, RadS, RadT, Prec, HRsup anomalies. Those results are in agreement with previous studies which shows the influence of the South Atlantic Convergence Zone (SACZ) on HWs occurrences over subtropical South America (Cerne *et al.,* 2007; Cerne and Vera, 2011; Hannart *et al.,* 2015). Over the southeast Brazilian region where the city of São Paulo is located, the presence of this anticyclone pattern is associated with a reduced in the number of SACZ episodes. The SACZ, similarly to the ITCZ, is characterized by a well-defined northwest-southeast oriented nebulous cover band associated with high levels of precipitation and humidity and to wet meteorological conditions. During austral summer the SACZ is essential for defining precipitation variability over the central west and southeast regions of Brazil. Eventual reduction of SACZ episodes over these regions in association with westward migration of the South Atlantic Subtropical High, which in turn can be related to SST anomalies over the South Atlantic Ocean, can lead to abnormally warm and dry conditions in these regions (Otto *et al.,* 2015; Coelho *et al.,* 2016).

Porto Alegre is situated further south from all the other cities considered in an extratropical region. The climate over this Brazilian region is also strongly determined by the South Atlantic High positioning. Under high-pressure conditions, clouds are absent and consequently high levels of solar radiation incidence are received at the surface. Thus, in similarity with São Paulo, a westward migration of the Atlantic Subtropical high helps to explain the persistent anticyclonic circulation pattern identified for summer HW events over Porto Alegre associated with abnormally dry conditions and increased solar radiation incidence at the surface that lead to the development of exceptionally high temperatures. This configuration was also responsible for a strongly southward advection of hot and dry air masses from the region of Minas Gerais.

The establishment of this persistent anticyclonic circulation pattern centred over the southwest South Atlantic Ocean to the east of the southeast Brazilian regions can also be linked to strengthening the final part of the South American Low-Level Jet (SALLJ). The SALLJ, the SACZ, and the ITCZ are all part of South America Monsoon System. The SALLJ is a low-level atmospheric jet located over the eastern border of the Andes mountain range, between the latitudes of 20–40°S. During the summer this low-level jet is induced by the tropical North Atlantic trade winds which suffer a southeast deflection promoted by the Andes mountain range (Marengo *et al.,* 2004). Thus SALLJ is responsible for transporting large amounts of moisture from the Amazon basin to south and Southeast Brazilian regions (Gimeno *et al.,* 2016) and therefore predominantly dry and warm periods over these Brazilian regions are commonly associated with the SALLJ weakening (Liebmann *et al.,* 2004). The wind anomalies of Figure 8 show, particularly between 25 and 30°S, an enhanced southward flow, suggesting a strengthened LLJAS induced by the anticyclonic circulation. Such a strengthened SALLJ contributes with an anomalous transport of water vapour southward, resulting in positive RadT (Figure 8(f)) and HRsup (Figure 8(c)) anomalies.

5. Conclusions

The overwhelming majority of future climate scenarios point out for an increase of extreme climate events like HWs, partially due to the anthropogenic component (Fischer and Knutti, 2015; Ouzeau *et al.,* 2016). It is, therefore, necessary to describe and understand more accurately the bridge between these extreme events and several impacts that may result from them for the human activity. This reveals to be even more important in regions such as South America and especially Brazil where, despite the investment over the last years in investigating the relation of HWs with public health and with certain economic sectors, there is a clear gap of studies analysing the topic from a purely atmospheric and climatic perspective. The wide range of HWs impacts across many different sectors implies that in most cases their definitions are broad and ambiguous. Taking into account all these aspects, this study presents an objective climatic HW characterization for six Brazilian cities over the most recent decades, based on two indices to define HWs.

It is interesting to notice some distinction in results when assessing the evolution of HW events throughout Brazil according to the use of the definition being based on the maximum or minimum temperature. Corroborating previous works, this study also identified positive and statistically significant HW frequency trends over the 1981–2014 period for all investigated cities but particularly strong for the cities of São Paulo, Recife and Manaus. Besides regional warming induced by climate change, the positive identified trends are also related to urban heat island and deforestation use effects. Furthermore, the ENSO phenomenon and sea breeze circulation may also play an important role in enhancing and/or weakening regional temperature conditions. Using reanalysis fields in respect to several meteorological variables it was also possible to establish the bridge between the summer HW events and the main regional atmospheric systems acting over South America. The radiative balance at the surface has been found to be the main and fundamental factor responsible for the development of summer HWs in Manaus, São Paulo, and Porto Alegre. The excessive solar radiative flux and associated lack of soil moisture imply changes in the near-surface latent and sensible heat fluxes namely an increase in sensible heat flux that represents a major factor for triggering an HW event.

The methodology adopted in this study is very relevant as, to the best of our knowledge, there has never been a comprehensive assessment of HWs for Brazil, evaluating various regions and including an extensive atmospheric regional circulation component. This approach provides robust climatic and meteorological support for future studies seeking to understand the associated HWs impacts. Possible improvements of the current analysis should be addressed in future studies, for instance, considering the intensity and persistence of HW events.

This work can also be used for diagnosing general circulation models control runs and evaluating future climatic scenarios. With this in mind, it is fundamental to invest in this type of analysis for both additional Brazilian regions and meteorological variables driving efforts to improve the meteorological station data network in order to use other HW definitions and meteorological variables that can complement this type of approaches.

Despite the characterization of HW events and associated climate anomalies in atmospheric parameters, impacts remain to be investigated in the region. Several studies applied to Brazil established a relationship between the occurrence of periods marked by high temperatures (often accompanied by high air pollution levels) and an increase in deaths related to cardiovascular/cerebrovascular accidents and respiratory diseases (Gouveia *et al.,* 2003; Hajat *et al.,* 2005; Bell *et al.,* 2008). From an economic point of view, some studies show that the occurrence of exceptionally high temperatures in Brazil can be related to shortages in agriculture and animal production (Gusso *et al.,* 2003; McKechnie and Wolf, 2010; Olesen *et al.,* 2011) and increases in energy consumption due to air conditioning demand. All these socio-economic impacts are particularly relevant in vast countries like Brazil that present a wide range of ecoregions, a large and diverse population and with several economic sectors heavily weather dependent (e.g. agriculture, animal production, natural resources, and energy production). Based on climatic change scenarios, it is projected that at the end of the 21st century some counties located in northern Brazil are likely to be particularly affected by high rates of temperature increase, and taking into account the low wealth levels *per capita* in this region, it is envisaged that a fraction of the poorest population will suffer serious health and economic damages (Costa *et al.,* 2015).

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