Revista Brasileira de Meteorologia, **v. 36, n. 2,** 305−316, 2021 rbmet.org.br
DOI: http://dx.doi.org/10.1590/0102-77863620119

Article

# Hotter, Longer and More Frequent Heatwaves: An Observational Study for the Brazilian City of Campinas, SP

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Received: 23 December 2020 - Accepted: 26 January 2021

## Abstract

Worldwide there is accumulated evidence of heatwave intensification due to climate change. Regional differences in the effects of heatwaves require local studies to implement public mitigation and adaptation strategies. This work analyzes and characterizes heatwaves' occurrence for the city of Campinas, Brazil, through an observational study from 1956 to 2018. The definition of heatwaves adopted requires that the maximum and minimum daily temperatures be above the daily limits derived from climate normal 1961-1990. The annual and seasonal metrics of the number, frequency, and heatwaves' duration showed significant and positive trends, except in winter. We found that the longest, the more intense, and the most frequent events occurred in the last 20 years and that a significant change in trend occurred at the beginning of the 1980s. Lastly, we performed an exploratory study of intra-urban variability, comparing heatwave metrics between two different weather stations that are 30 km apart in the city of Campinas. We found similar metrics patterns for the two weather stations, with more prolonged and more frequent heatwave events for the region's station with a higher rate of urban land occupation.

**Keywords** heatwave, climate change, climatology, trend, Brazil.

# Ondas de Calor mais Quentes, Duradouras e Frequentes: Um Estudo Observacional Para a Cidade Brasileira de Campinas, São Paulo

## Resumo

Em todo o mundo, existem evidências acumuladas da intensificação de ondas de calor devido às mudanças climáticas. As diferenças regionais nos efeitos das ondas de calor requerem estudos locais para a implementação de estratégias públicas de mitigação e adaptação. Este trabalho analisa e caracteriza a ocorrência de ondas de calor para a cidade de Campinas, Brasil, por meio de um estudo observacional de 1956 a 2018. A definição de ondas de calor adotada requer que as temperaturas máximas e mínimas diárias estejam acima dos limites diários derivados da normal climática 1961-1990. As métricas anuais e sazonais de número, frequência e duração de ondas de calor mostraram tendências significativas e positivas, exceto no inverno. Verificou-se que os eventos mais longos, mais intensos e mais frequentes ocorreram nos últimos 20 anos e que uma mudança significativa de tendência ocorreu no início da década de 1980. Por fim, realizou-se um estudo exploratório da variabilidade intra-urbana, comparando-se as métricas de duas estações meteorológicas distantes 30 km entre si, em Campinas. Foram encontrados padrões de métricas semelhantes para as duas estações meteorológicas, com eventos de ondas de calor mais prolongados e frequentes para a estação localizada na região com maior taxa de ocupação do solo.

**Palavras-chave** ondas de calor, mudança climática, climatologia, tendência, Brasil.

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## 1. Introduction

According to the Intergovernmental Panel on Climate Change report (Allen *et al.*, 2019), global warming is already approximately 1 °C above the average of 1850-1900 period. With an increase in temperature, more likely is the occurrence of heatwaves, which are projected to increase in duration, frequency and intensity due to climate change (Russo *et al.*, 2014; Argüeso *et al.*, 2016; Perkins-Kirkpatrick and Gibson, 2017; Feron *et al.*, 2019).

Heatwaves can have multiple implications, social, economic and ecological. One of the main consequences of extreme heat is in people's health, causing heat-related illness or even death. Numerous studies have shown higher mortality and morbidity risks for more intense and longer heatwaves (Brooke Anderson and Bell, 2011; Son *et al.*, 2016; Geirinhas *et al.*, 2018, 2019; Zhao *et al.*, 2019).

The impacts of heatwaves depend on regional characteristics. Some populations may be better adapted to heatwaves, while others may observe mortality risk changes even with small temperature variations (Brooke Anderson and Bell, 2011; Guo *et al.*, 2017). For this reason, it is critical to study heatwaves locally in order to assess their specific impacts in a region, enabling the definition of local mitigation and adaptation strategies.

In this paper, we performed an observational study of heatwaves for the city of Campinas, aiming to provide a basis for investigating their health burden. Campinas is a Brazilian municipality in São Paulo state, located in the country's southeast region. According to the last Brazilian census, Campinas has more than one million inhabitants and a population density of more than 1300 persons per square kilometer (IBGE, 2010). Campinas is the fourteenth most populous Brazilian city and the third most populous municipality in São Paulo state. Following the Köppen-Geiger climate classification, Campinas is classified as dry-winter humid subtropical Cwa climate (Beck *et al.*, 2018).

Previous works for Campinas have only covered temperature changes without focusing on heatwaves (Astolpho *et al.*, 2004; Vincent *et al.*, 2005; Blain *et al.*, 2009; Blain, 2010). The present work complements a few regional studies focused on Brazilian heatwaves (Bitencourt *et al.*, 2016; Geirinhas *et al.*, 2018; dos Reis *et al.*, 2019; Bitencourt, *et al.*, 2020).

## 2. Material and Methods

This section describes the characteristics of the dataset used in the present study (Section 2.1). Considering the multiple existing approaches to compute heatwaves, Section 2.2 describes the method we adopted to compute heatwaves and the metrics to describe them.

### 2.1. Data characterization

We used daily minimum (Tmin) and maximum temperatures (Tmax) in °C from two weather stations in Campinas. The weather station identified as IAC, is administered by the "Instituto Agronômico de Campinas" (Agronomic Institute of Campinas) and has records being collected since 1890. The weather station VCP is located at the Viracopos Airport and has records since 1983. For both weather stations, we considered the time series ended in 2018. In 1956, the IAC's the weather station was moved from a central region of Campinas to the outskirts of the city. While previous studies have shown no significant impact in the temperature trends recorded by the weather station after the move, we decided to consider only records of the new location, as specified by Fig. 1 and the second column of Table 1. VCP is located in the south region of the city as shown in Fig. 1. Both weather stations are approximately 30 km distant from each other. Along with the time series, the amount of missing data is 1.60% Tmax for IAC, and 2.20% for VCP (Tmax and Tmin). Missing values were not filled, and leap days were removed. Table 1 provides additional information about the datasets considered in the present study.

### 2.2. Heatwave identification methodology

Different authors adopt distinct methods to compute heatwaves. Although there are no optimal and universal criteria for measuring these events, a common aspect is that a heatwave is considered a period of consecutive days in which a determined threshold is exceeded (Perkins, 2015). The strategy adopted for threshold definition varies among the existing studies. The simplest method defines a fixed threshold that is region-dependent and focuses on the analysis of extreme maximum temperature values. This approach presents problems, for example, to detect heatwaves during the winter since relevant deviations of typical winter Tmax values can still be below a fixed threshold (Robinson, 2001; Perkins and Alexander, 2013; Horton *et al.*, 2016).

An alternative approach to fixed thresholds consists of considering maximum temperature distribution percentiles, taking into account its climatic variability (Rusticucci *et al.,* 2016). To improve this methodology, besides the percentile-based thresholds, a moving window centered on each calendar-day is used to calculate the percentiles, usually a 15-day window (Fischer and Schär, 2010; Perkins *et al.* 2012; Geirinhas *et al.*, 2018; Feron *et al.*, 2019; Bitencourt *et al.*, 2020). This approach is advantageous because it analyzes the extreme values considering a normal distribution for each period of the year, allowing the computation of heatwaves in any season.

Besides, some studies consider only the maximum temperature (Fischer and Schär, 2010; Perkins-Kirkpatrick and Gibson, 2017; Feron *et al.*, 2019; Bitencourt *et al.*,

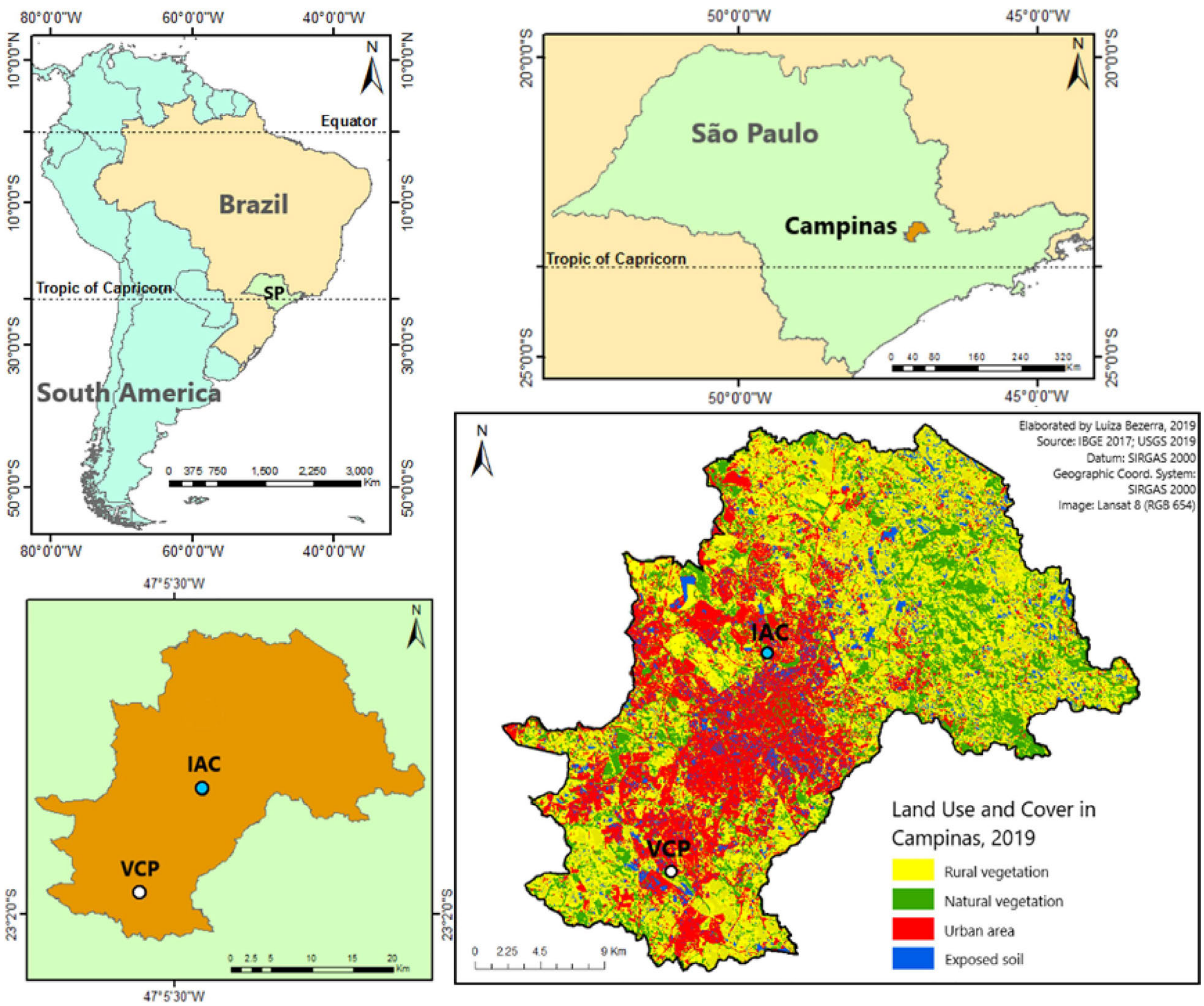


**Figure 1** - Map showing the location of Campinas city and the weather stations considered for this study: IAC (Agronomic Institute of Campinas) in blue and VCP (Viracopos Airport) in white, including a map of land use and cover in Campinas (2019) showing rural vegetation (yellow), natural vegetation (green), urban area (red) and exposed soil (blue).

**Table 1** - Characterization of datasets used in the study.

| Weather station ID | Elevation, latitude, longitude | Period of study | N (raw number of samples) |
|---|---|---|---|
| IAC | 669 m, 22°52' S, 47°04' W | 1956-2018 | 23011 |
| VCP | 657 m, 23°00' S, 47°08' W | 1983-2018 | 13149 |

2020), while other studies involve both maximum and minimum temperatures (Perkins and Alexander, 2013; Rusticucci *et al.*, 2016; Geirinhas *et al.*, 2018; Shiva *et al.*, 2019). The latter can be considered a more rigid definition of heatwave since it considers that a heatwave day must simultaneously exceed Tmax and Tmin thresholds.

In this study, we adopted the heatwave definition of Geirinhas *et al.* (2018), which defines a heatwave as a period of three or more consecutive days characterized by daily Tmax above the 90th Tmax percentile (CTX90pct) and daily Tmin above 90th Tmin percentile (CTN90pct). Percentiles are computed for each day of the year based on the climatological normal (1961-1990) with a 15-day window (centered on the day in question). A public software library has been developed to implement this methodology, and all the performed analyses are publicly available (Oliveira *et al.*, 2020a, b,c).

### 2.3. Heatwave metrics

We adopted four metrics to assess local heatwaves characteristics (number, duration, frequency, and intensity) for each weather station over the years and the seasons. Those indices, also adopted in other studies (Fischer and Schär, 2010; Perkins and Alexander, 2013; Cowan *et al.*, 2014; Feron *et al.*, 2019), are described as:

- Heatwave number (HWN): number of heatwave events per year/season;
- Heatwave duration (HWD): duration in days of the longest heatwave event per year/season;
- Heatwave frequency (HWF): number of days in a year/season under a heatwave, adopting the same definition as Feron *et al*. (2019);
- Heatwave amplitude (HWA): Tmax anomaly (in °C) against CTX90pct of the hottest day of each HW during a year/season. The HWA definition was adapted for this study and, here, it is considered a metric of heatwave intensity, according to Perkins and Alexander (2013).

Once percentiles and heatwave occurrences are computed, these metrics are evaluated for every year and season of the datasets (Oliveira *et al.*, 2020a,b,c), and trend analysis is performed, as described in Section 2.4. For yearly metrics, the calendar year (January to December) was adopted. For seasonal metrics, the calendar starts in December of the previous year until November of the considered year.

Finally, to assess the number of coincident heatwave days and metrics similarities, a comparison was performed between the weather stations, according to the period of VCP weather station (1983-2018).

### 2.4. Trend analysis

Mann-Kendall test (Mann, 1945) was used to test the existence of a significant trend (significance level of p-value $< 0.05$) in number (HWN), duration (HWD), and frequency of heatwaves (HWF) in Campinas. Mann-Kendal trend test (MK test) is a non-parametric test that is appropriate for non-normal distributions. The null hypothesis ($H_0$) for the MK test is that there is no monotonic trend in the series. The alternative hypothesis ($H_a$) is that a trend exists, and can be positive, negative, or non-null.

Also, data autocorrelation metric was obtained, and a modified version of the MK test was applied to account for serial correlation (Yue *et al.*, 2002; Blain, 2014; Hussain and Mahmud, 2019). The Trend Free Pre-Whitening method (TFPW) removes the trend from the time series in its first step, and then it eliminates a serial correlation component (lag-one autoregressive - AR(1)) before applying the trend test (Yue *et al.,* 2002). Previous studies (Yue *et al.*, 2002; Yue and Wang, 2002; Blain, 2014) demonstrated that if there is a positive serial correlation in the data, the probability of detecting a 'false' trend increases (probability of rejecting $H_0$).

We also employed the Pettitt test (Pettitt, 1979), a homogeneity test to detect change points along with the data series. The null hypothesis is that the series is homogeneous over time. The alternative hypothesis is that there is a time when a change occurs.

## 3. Results and Discussion

### 3.1. Annual metrics for IAC weather station

The metrics HWN, HWD and HWF for the IAC weather station, from 1956 to 2018 are shown in Figs. 2-4 respectively. For all three metrics, the graphs show higher values in the last 30 years that were not observed at the beginning of the time series. Along with the time series,

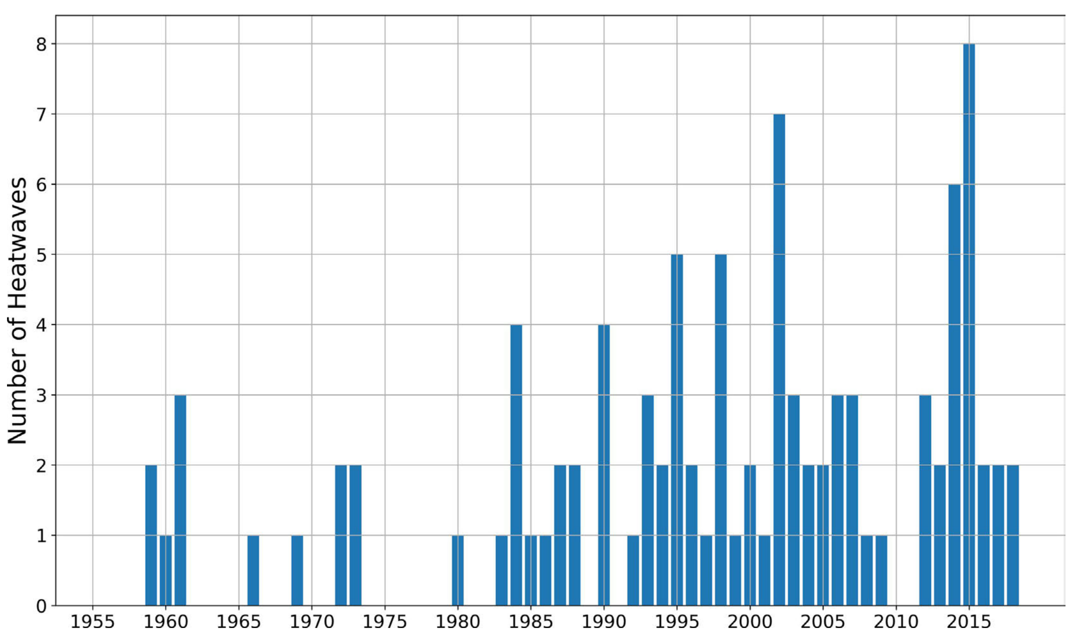


**Figure 2** - Annual number of heatwaves (HWN) for IAC weather station in the period of 1956-2018.

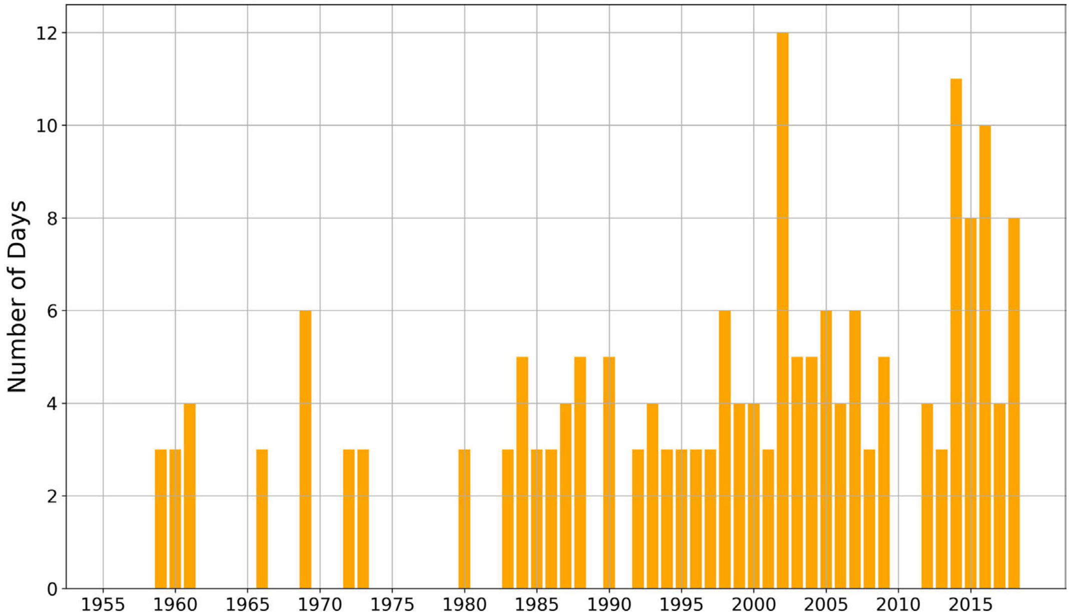


**Figure 3** - Longest duration of heatwaves in days per year (HWD) for IAC weather station in the period of 1956-2018.

there are 99 heatwaves in total, resulting in 389 days of heatwave events. In Fig. 2, the number of heatwaves (HWN) per year shows to be increasing. The years 2002, 2014, and 2015 present a higher number of events, with 2015 presenting the maximum number of eight heatwaves. In Fig. 3, we observe that the longest heatwave duration (HWD) increases mostly after 2000. The heatwaves with higher duration occurred in 2002, 2014, and 2016, being 2002 with the longest heatwave of 12 days. In Fig. 4, the heatwave frequency (HWF) also shows an increase since 1980. The years of 2002, 2014, and 2015 present more days under heatwave condition. In 2002, Campinas experienced more than one month under heatwave condition (37 days over the year).

This increasing pattern observed in Figs. 2-4 is confirmed by Table 2, which summarizes the metrics' descriptive statistics, divided into three sub-periods of 21 years. In Table 2, we can note that there is at least a double-fold increase in all metrics comparing one sub-period to the other. HWF metric is the one with a higher

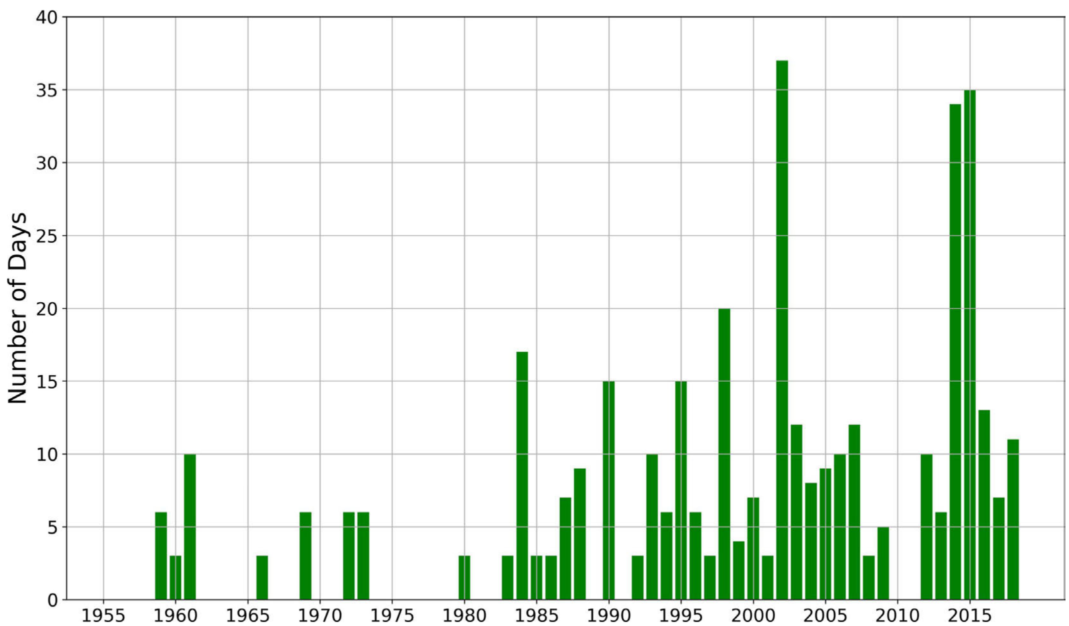


**Figure 4** - Annual number of heatwaves days (HWF) for IAC weather station in the period of 1956-2018.

**Table 2** - Yearly metrics values and statistical measures (average, standard deviation) for IAC weather station in the period of 1956-2018 including sub-periods of 21 years.

| | | 1956-1976 | 1977-1997 | 1998-2018 | Total 1956-2018 |
|---|---|---|---|---|---|
| Heatwave Number (HWN) | Metric value | 12 | 30 | 56 | 98 |
| | Average/Year | 0.57 | 1.43 | 2.67 | 1.56 |
| | Standard Deviation | 0.93 | 1.5 | 2.15 | 1.80 |
| Heatwave Duration (HWD) | Metric value | 25 | 50 | 111 | 186 |
| | Average/Year | 1.19 | 2.38 | 5.29 | 2.95 |
| | Standard Deviation | 1.83 | 1.86 | 3.13 | 2.89 |
| Heatwave Frequency (HWF) | Metric value | 40 | 103 | 246 | 389 |
| | Average/Year | 1.90 | 4.90 | 11.71 | 6.17 |
| | Standard Deviation | 3.05 | 5.43 | 10.92 | 8.25 |

increase in respect to the beginning of the data series (over 6-fold) while the others increase between 4-5 fold. Geirinhas *et al.* (2018) also found an increase in the number of heatwaves and the number of heatwave days for the city of São Paulo and other main cities of Brazil. The intensification of heatwaves for the city of Campinas can be associated with the increasing trend of minimum temperatures, as reported in Blain *et al.* (2009).

From the highlighted years, 2002, 2014, 2015, and 2016 events can be associated with the warmer phase of El Niño-Southern Oscillation (Melo *et al.*, 2014, 2016), though 2002 heatwaves can be correlated with a moderate El Niño (INPE; IRI, 2002). The reduction or absence of events in 1999, 2000, 2010, and 2011 coincide with La Niña (INPE; NOAA; Melo *et al.* 2010, 2011).

### 3.2. Trend analysis

Statistical significance values for original MK and TFPW tests, along with Sen's slope (Sen, 1968) - trend magnitude estimator - are presented in Table 3. Our findings show significant and positive trends for all three metrics (HWN, HWD, HWF) using both tests. These results are aligned with Brazilian and South America studies, which identify an increase in number, duration, and frequency of heatwaves (Bitencourt *et al.*, 2016; Ceccherini *et al.*, 2016; Rusticucci *et al.*, 2016; Geirinhas *et al.*, 2018).

Although there is a serial correlation in our data, we observed that it does not significantly change the MK test results. Our outcome is in agreement with Yue and Wang (2002), which state that when there is a considerable number of samples ($n > 70$) and a big trend ($slope > 0.005$), the serial correlation has no significant effect on the MK test results.

Pettitt test results (Table 3) indicate that, for this weather station, there is a change point occurring at the beginning of the 1980s for all metrics, confirming the increasing tendency we observed in Section 3.1. This observation is consistent with Geirinhas *et al.* (2018), which finds a significant and positive trend in the number of heatwave days since 1980 for major cities in Brazil (São Paulo, Manaus, and Recife).

### 3.3. Seasonal metrics

Seasonal metrics were assessed in order to identify if any season would present intensification of the heatwave phenomenon. The metrics HWN, HWD, and HWF for the IAC weather station from 1956 to 2018 are shown in Figs. 5-7, respectively.

Regarding the number of heatwaves (HWN), the maximum number of heatwaves per season is four, which occurs in summer (2014 and 2015) and autumn (2002) (Fig. 5). In 2002, four out of seven heatwaves occurred in autumn. For 2014 and 2015, heatwaves mostly occurred in summer (4 out of 6, 8 for each year, respectively). For the winter season, it is evident that the number of winter heatwaves increased and started to be more frequent after 1980.

About the duration of heatwaves (Fig. 6), the longest summer event occurred in 2014 with 11 days. In spring,

**Table 3** - Mann-Kendall and Pettitt tests results for yearly heatwave metrics: number (HWN), duration (HWD) and frequency (HWF).

| | Original MK | | TFPW MK | | | Pettitt test | | |
|---|---|---|---|---|---|---|---|---|
| Yearly Metrics | slope | p-value | trend | slope | p-value | trend | p-value | change point |
| HWN | 0.036 | 1.33E-05 | positive | 0.035 | 4.26E-06 | positive | 5.13E-05 | 1983 |
| HWD | 0.083 | 5.36E-07 | positive | 0.085 | 2.00E-07 | positive | 3.61E-05 | 1982 |
| HWF | 0.143 | 2.64E-06 | positive | 0.135 | 2.58E-06 | positive | 2.45E-05 | 1983 |

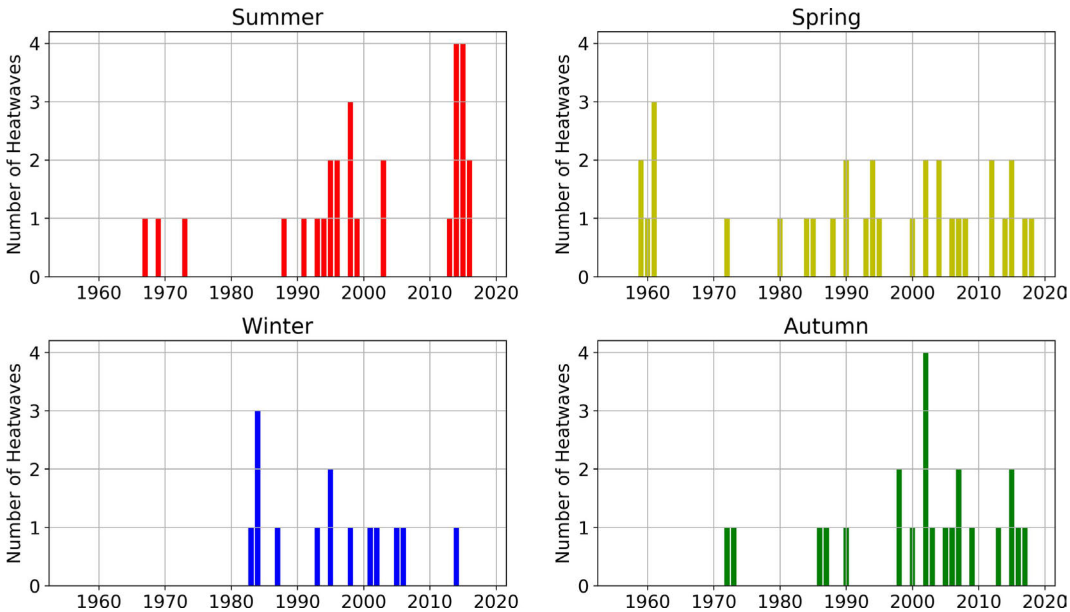


**Figure 5** - Seasonal number of heatwaves (HWN) for IAC weather station in the period of 1956-2018.

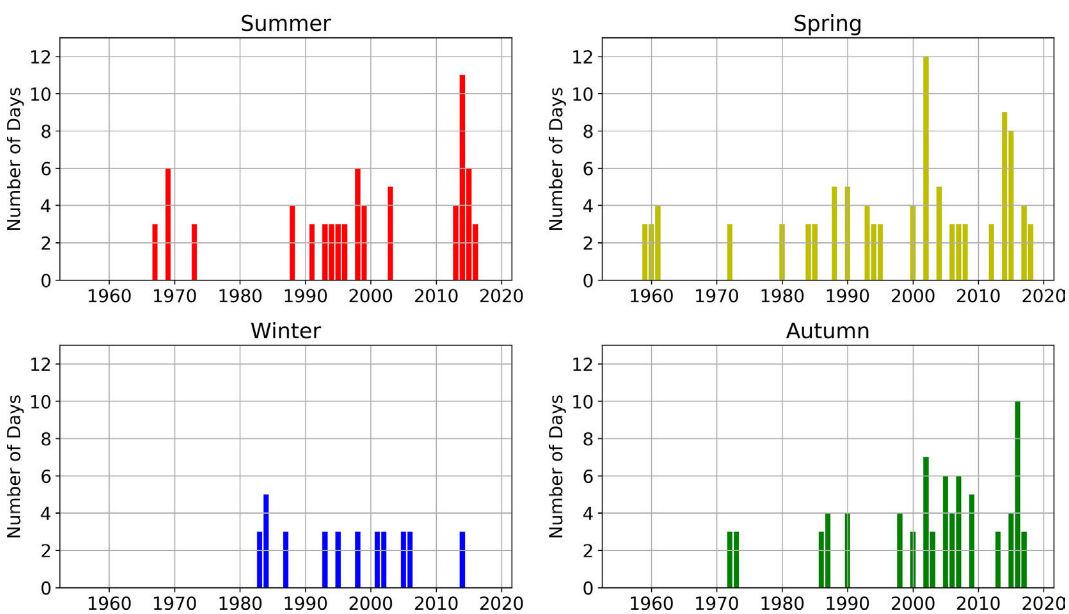


**Figure 6** - Longest duration of heatwaves in days/season (HWD) for IAC weather station in the period of 1956-2018.

the years with the longer heatwaves are 2002 (12 days), 2014 (9 days) and 2015 (8 days). The longest autumn heatwave occurred in 2016 (10 days), followed by 2002 (7 days). In winter, the only year with a heatwave duration higher than 3 days is 1984 (5 days).

Regarding the sum of heatwave days (Fig. 7), the highest number of days with heatwaves occurred in summer 2014, 21 of 33 days with heatwaves in total for this year. In 2015, 18 days were summer heatwaves and 11 days were autumn heatwaves, which means 29 days out of 36 heatwave days occurred in these seasons. For 2002, 34 heatwave days occurred in autumn (19 days) and spring (15 days), considering a total of 37 heatwave days in this year. In winter, 1984 has the highest sum of 14 heatwave days out of 17.

Some studies attempt to assess the link between temperature extremes and severe droughts. In the southern hemisphere, the extreme events are normally associated with the atmospheric blocking and the intense solar radiation available in the spring and summer (Rodrigues and Woollings, 2017). They contribute to heat the air (sensitive heat) by raising the temperature. The years 2014 and 2015

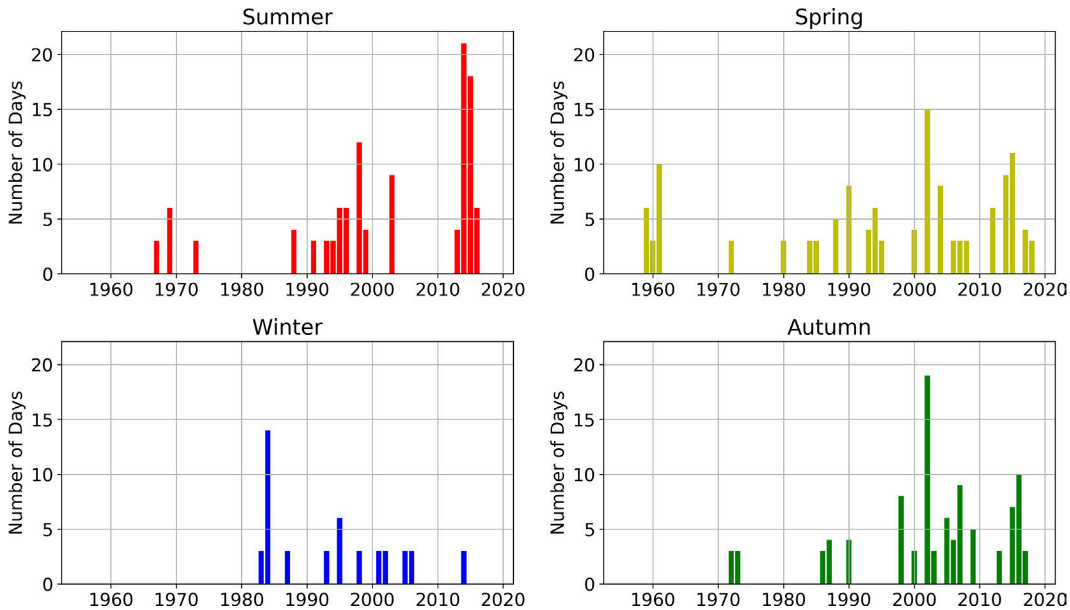


**Figure 7** - Seasonal number of heatwaves days (HWF) for IAC weather station in the period of 1956-2018.

were anomalously dry, especially in the summer (Coelho *et al.*, 2016; Nobre *et al.*, 2016). In the spring of 2002 and 2016, the rainy season was delayed. Pereira *et al*. (2017) show a trend of delay in the beginning of the São Paulo state's rainy season.

Metrics values are summarized in Table 4, divided into sub-periods of 21 years. When comparing 1977-1997 to 1998-2018, the number of heatwave events (HWN) in the latest period doubled for summer and increased sixfold for autumn. In spring, there was a constant increase for the three sub-periods.

The duration of heatwaves (HWD) in 1998-2018 increased more than five times for autumn and doubled for summer and spring compared to the previous period. Regarding the sum of heatwave days (HWF) per season, the number of heatwave days increased sevenfold for autumn, threefold for summer, and twice for spring.

For all the three metrics, autumn had the most considerable change. Winter is an exception among the seasons. It has no heatwaves in the first sub-period, with an increase in all metrics from 1977-1997 and then a decrease for the next sub-period.

For summer, spring and autumn, there is an upward trend for all the three metrics, considering the original Mann Kendall test (MK test), while no trend was detected for the winter season (Table 4).

According to these heatwave metrics (Figs. 5-7, Table 4), we can observe that except for winter season, the highest number, more prolonged and frequent events occur in the past 20 years, even more pronounced in the past decade for summer. Despite methodological differences to identify heatwaves, our findings are partially aligned with the conclusions of Bitencourt *et al.* (2016), which found out that most heatwaves in Brazil occur in spring and summer, although in our studies, autumn has an equally relevant number of events. Bitencourt et al. (2016) define a heatwave according to Tmax, first selecting events with 3 or more consecutive days with Tmax above the mean Tmax added to 1-standard deviation (events exceeding the 3rd quartile were considered heatwaves). In contrast, Reis et al. (2019) consider a heatwave as a period of 6 or more consecutive days with Tmax above the daily 90th percentile. Their study observed more frequent heatwaves in winter and spring.

The heatwave amplitude (HWA) was evaluated separately, and Table 5 shows the incidence of seasonal heatwaves according to Tmax anomaly ranges against CTX90pct. In summer, there is a higher increase of heatwaves with an amplitude between 2-4 °C in the sub-period of 1998-2018. Among autumn heatwaves, there is an increase of heatwaves with 0-2 °C above CTX90pct, also in this last period. In winter, the amplitude of events is concentrated between 0-2 °C. Spring has a higher number of events with 2 to 4 °C amplitude, with more constant occurrences when comparing the sub-periods. We highlight that the daily percentile thresholds vary according to the seasons. Although summer and spring have higher thresholds, they also have higher amplitudes, presenting amplitudes above 4 °C, with a maximum amplitude of 5.3 °C occurring in spring. Most of the seasonal heatwaves have an amplitude between 0 °C and 2 °C (63 out of 98) above their CTX90pct.

### 3.4. Comparing IAC and VCP heatwave patterns

To investigate the presence of intra-urban variabilities, we conducted an exploratory analysis of heat-

**Table 4** - Seasonal metrics values for IAC weather station in the period of 1956-2018 including sub-periods of 21 years.

| | | Summer | Autumn | Winter | Spring |
|---|---|---|---|---|---|
| Heatwave Number (HWN) | 1956-1976 | 3 | 2 | 0 | 7 |
| | 1977-1997 | 8 | 3 | 8 | 10 |
| | 1998-2018 | 17 | 18 | 6 | 15 |
| | Total 1956-2018 | 28 | 23 | 14 | 32 |
| | MK test (trend, p-value) | positive, 0.014 | positive, 0.0006 | no trend, 0.06 | positive, 0.03 |
| Heatwave Duration (HWD) | 1956-1976 | 12 | 6 | 0 | 13 |
| | 1977-1997 | 19 | 11 | 17 | 29 |
| | 1998-2018 | 39 | 58 | 18 | 57 |
| | Total 1956-2018 | 70 | 75 | 35 | 99 |
| | MK test (trend, p-value) | positive, 0.022 | positive, 0.0003 | no trend, 0.05 | positive, 0.01 |
| Heatwave Frequency (HWF) | 1956-1976 | 12 | 6 | 0 | 22 |
| | 1977-1997 | 25 | 11 | 29 | 35 |
| | 1998-2018 | 74 | 80 | 18 | 69 |
| | Total 1956-2018 | 111 | 97 | 47 | 126 |
| | MK test (trend, p-value) | positive, 0.013 | positive, 0.0003 | no trend, 0.06 | positive, 0.02 |

**Table 5** - Tmax anomaly (against CTX90pct) occurrences for IAC weather station in the period of 1956-2018 including sub-periods of 21 years.

| | | Number of Tmax anomalies in the temperature range | | |
|---|---|---|---|---|
| | | [0-2] °C | ]2-4] °C | Over 4°C |
| Summer | 1956-1976 | 2 | 1 | 0 |
| | 1977-1997 | 7 | 1 | 0 |
| | 1998-2018 | 9 | 7 | 1 |
| | Total | 18 | 9 | 1 |
| Autumn | 1956-1976 | 2 | 0 | 0 |
| | 1977-1997 | 3 | 0 | 0 |
| | 1998-2018 | 16 | 2 | 0 |
| | Total | 21 | 2 | 0 |
| Winter | 1956-1976 | 0 | 0 | 0 |
| | 1977-1997 | 7 | 1 | 0 |
| | 1998-2018 | 5 | 1 | 0 |
| | Total | 12 | 2 | 0 |
| Spring | 1956-1976 | 1 | 6 | 0 |
| | 1977-1997 | 4 | 5 | 1 |
| | 1998-2018 | 7 | 7 | 1 |
| | Total | 12 | 18 | 2 |

waves for a different weather station in Campinas, located in the Viracopos airport (VCP), 30 km apart from the IAC weather station. VCP samples are restricted to the 1983-2018 period, which imposes a difficulty in estimating the VCP climate normal 1961-1990. Our approach to the problem consisted of performing a linear regression between VCP (target) and IAC (predictor) temperatures Tmax and Tmin, using the parallel data available for 1983-2018. From the resulting model, we used 1961-1990 IAC data to predict the VCP climate normal, and we finally computed the HWN, HWD, and HWF metrics for the VCP database for the period 1983-2018.

We found that the VCP metrics outnumbers IAC in the number of heatwaves, duration of events, and the sum of heatwave days, even if their metrics present similar patterns (Fig. 8 highlights the 2014-2015 spring-summer transition period). VCP registered 596 heatwaves in the period, while IAC registered only 346 heatwave days, with 230 coincident days. Such a difference was also observed in works that show intra-urban thermal variability, and it is explained, for example, by the different levels of urbanization in different regions (Rosenthal et al., 2014; Gomes et al., 2019; Lapola et al., 2019). Analogously, IAC weather station is located in an area with higher vegetation cover and population density of 1187,20 inhabitants per km$^2$ (Campinas, 2010), while VCP station is in a region with a higher level of urbanization (Fig. 1), population density of 2458,24 inhabitants per km$^2$ (Campinas, 2010), and a higher percentage of exposed soil (23.89% against 5.59% from IAC) according to Bezerra and Avila (2017).

## 4. Conclusions

This paper has investigated yearly and seasonal occurrences of heatwaves for the city of Campinas from 1956 to 2018. The adopted trigger to detect heatwaves requires that both maximum and minimum daily temperatures are above a 90th percentile threshold during three or more consecutive days, characterizing an extreme event condition. This observational study found that heatwaves are increasing in number, duration and frequency in the

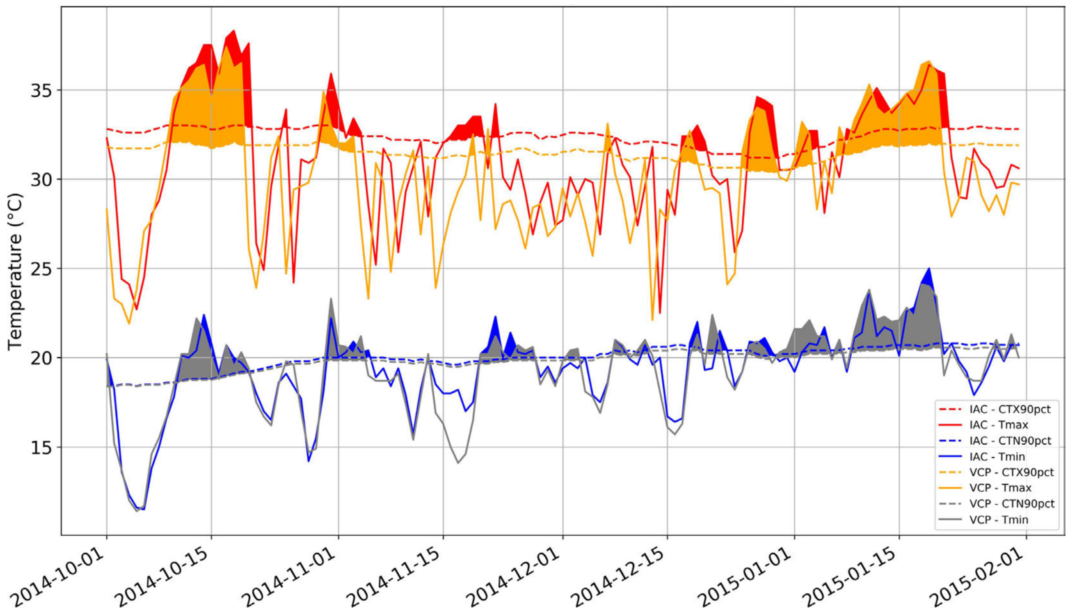


**Figure 8** - Weather stations comparison: the graphs show Tmax (red) and Tmin (blue) times series for IAC, Tmax (orange) and Tmin (gray) for VCP weather station in the 2014-2015 spring-summer transition period (October, 2014 - January, 2015). The dashed lines represent the daily 90th percentile threshold for Tmax (CTX90pct) and Tmin (CTN90pct). Painted regions represent temperatures that are above the thresholds. We observe that while IAC and VCP present similar heatwave patterns for the most extreme events, VCP has more days under heatwaves than IAC.

city of Campinas. Particularly, our regional analysis points out a significant shift in trend starting in the 1980s decade. Most intense, frequent, and prolonged events occur in the last 20 years of the data series agreeing with global warming tendency.

Those results demonstrate the urgency in elaborating adequate public policies to prevent and minimize the consequences of heatwave events. Also, the comparison of heatwave metrics between two weather stations located in different areas of the city revealed the importance of considering intra-urban variability when assessing heatwave impacts (Rosenthal *et al*., 2014).

With the methodology adopted in this work, we can contribute to further research on evaluating heatwaves' effects. To better understand the impact of land occupation and regional characteristics on heatwave metrics, future work includes advancing the comparison between weather stations from different regions of Campinas. Also, we plan to study future scenarios of heatwaves in Campinas and the impacts of extreme heat on health, considering data provided by the ETA model (Lyra *et al*., 2018).

## Acknowledgments

We thank the Airspace Control Institute (ICEA - Instituto de Controle do Espaço Aéreo) and the Agronomic Institute of Campinas (IAC - Instituto Agronômico de Campinas) for providing the data which made this study possible. In specific, we thank Dr. Gabriel Blain for his technical support.

This work belongs to the project 'Human health and adaptation to climate change in Brazil: a data science approach' funded by FAPESP (São Paulo Research Foundation) 17/20013-0, scholarships 19/08306-8 and 18/20034-0.

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