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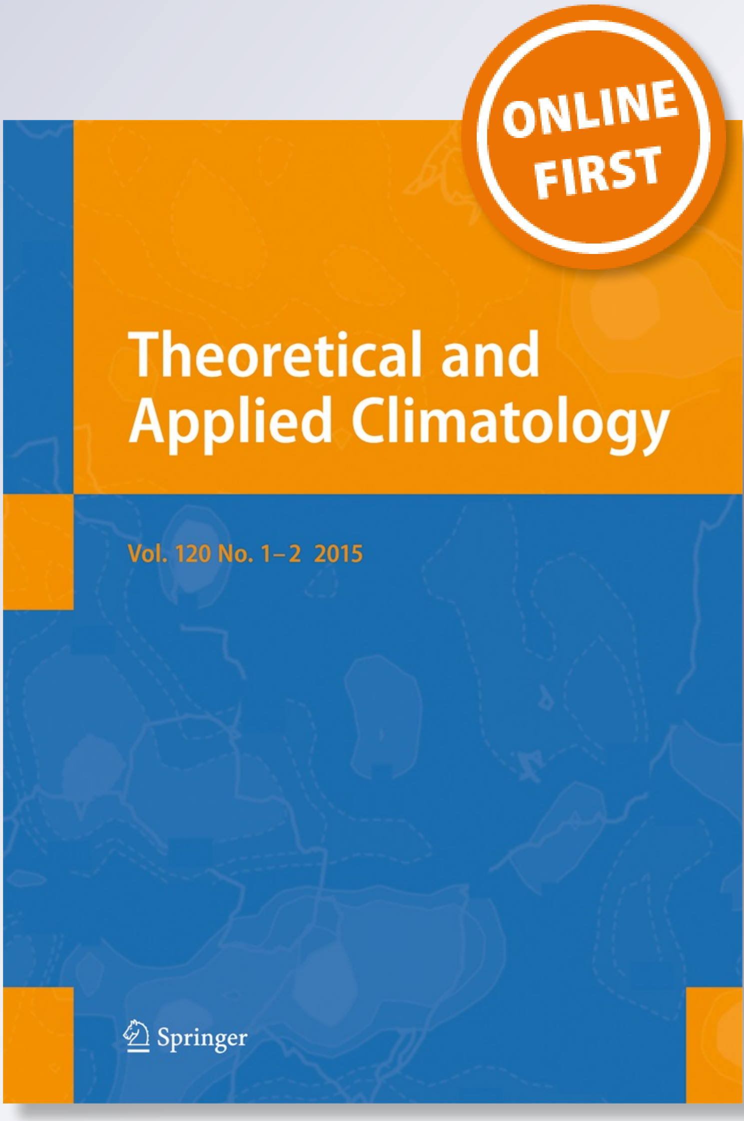

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ORIGINAL PAPER

Long-term variability of heat waves in Argentina and recurrence probability of the severe 2008 heat wave in Buenos Aires

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Abstract Heat waves are one of the main concerns related to the impacts of climate change, because their frequency and severity are projected to increase in a future climate. The objectives of this work are to study the long-term variability of heat waves over Argentina and to estimate recurrence probability of the most severe 2008 heat wave in Buenos Aires. We used three definitions of heat waves that were based on (1) daily maximum temperature above the 90th percentile (MaxTHW), (2) daily minimum temperature above the 90th percentile (MinTHW) and (3) both maximum and minimum temperatures above the corresponding 90th percentiles (EHW). The minimum length of a heat wave was 3 days, and the analysis was performed over the October–March period. Decadal values in Buenos Aires experienced clear increases in heat waves according to MinTHW and EHW, with the highest frequency for both in the 2001–2010 decade, but at other stations, combinations of different trends and decadal variability resulted in some cases in a decrease of extreme heat waves. In the north-western part of the country, a strong positive change in the last decade was found, mainly due to the increment in the persistence of MinTHW but also accompanied by increases in MaxTHW. In general, other stations show a clear positive trend in MinTHW and decadal variability in MaxTHW, with the largest EHW cases in the last decade. We also estimated recurrence probability of the longest and most severe heat wave in Buenos Aires (over 1909–2010, according to intensity measured by the cumulative excess of maximum daily temperature above the 90th percentile) that occurred from 3 to 14 November 2008, by means of simulations with a stochastic first-order autoregressive model. The recurrence probability of such long and severe heat wave is small in the present climate but it is likely to increase substantially in the near future even under a moderate warming trend.

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1 Introduction

Impacts from recent climate-related extremes, such as heat waves, reveal significant vulnerability and exposure of some ecosystems and human society to current climate variability (Field et al. 2013). These impacts include enhanced morbidity and mortality (Robine et al. 2008; Barriopedro et al. 2011), crop failures, forest fires, stress for livestock and wildlife, spreading of pests and increased energy demand for cooling (De Bono et al. 2004; Beniston et al. 2007).

On the global scale, there is only a medium confidence that the length and frequency of warm spells, including heat waves, have increased since the middle of the twentieth century (Hartmann et al. 2013). This uncertainty was mostly caused by the lack of data and studies over South America and Africa. However, models project near-term increases in the duration, intensity and spatial extent of heat waves and warm spells over most land regions (Kirtman et al. 2013).

Focusing on South America, Cerne and Vera (2011) showed that the majority of heat waves defined over a single

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station in Argentina are related to the progression of the South Atlantic convergence zone, which is regarded as an elongated convective band typically originating in the Amazon basin and protruding into the southeastern subtropical Atlantic Ocean (Carvalho et al. 2004). This large-scale synoptic pattern determines the warm meridional flow that drives high temperatures over the eastern subtropical coast of South America (e.g. Alessandro and de Garín 2003). A meridional transport of air masses over South America is the most intense over the entire Southern Hemisphere, mainly due to the presence of the mountain ridge of Andes (Rusticucci 2012).

The study of the occurrence of heat waves needs an extended quality-controlled data base containing daily data. Over Argentina, there have been studies related to the variability of extreme temperatures, but the spells were analysed during short periods because of incomplete data or their limited availability (Rusticucci and Vargas 1995, 2001). More recently and over a larger area, Alexander et al. (2006) considered one parameter related to warm spells, the Warm Spell Duration Index (WSDI). It is defined as the annual count of days with at least 6 consecutive days when maximum temperature exceeds the 90th percentile. This definition takes into account warm spells over the whole year, without consideration of the season, and it is restrictive about the number of missing data. The results over Argentina in the 1951–2003 period showed no significant linear trends, and these trends were both positive and negative over different regions. In an update of that paper, Donat et al. (2013) present HadEX2, which extended the number of stations and the period up to 1901–2010, and found the same sign and spatial inconsistency of the trends.

Without considering several days-long spells (only the number of days above or below some threshold individually), the number of warm nights (minimum temperature above the 90th percentile) has been increasing and the number of cold nights (minimum temperature below the 10th percentile) and days (maximum temperature below the 10th percentile) has been decreasing over Argentina, as well as over most land regions. However, the frequencies of warm days (maximum temperature above the 90th percentile) have been decreasing in some regions over Argentina (Rusticucci and Barrucand 2004; Alexander et al. 2006; Donat et al. 2013).

A definition of heat waves varies over literature but it is mainly related to the number of consecutive days that exceed a defined threshold. A relation between extreme temperature occurrence and their impacts on human health could provide useful thresholds for delimiting heat waves. As enhanced mortality in summer is related to temperature excesses of both minimum and maximum temperatures, so, we used these limits to define a heat wave. The analysis of this relationship is also useful for an installation of an operative alert system through the National Weather Service of Argentina (www.smn.gov.ar) that could contribute to the population preparedness in order to avoid health impacts.

The first main objective of this work is to study the long-term variability in the occurrence of heat waves over Argentina, with focus on the warm period of the year and considering different heat wave definitions. The second main aim is to estimate recurrence probability of the most severe and longest heat wave in Buenos Aires by simulations with a stochastic time series model. These simulations were performed for the present climate as well as under several climate change scenarios.

The paper is structured as follows: a description of data, definition of a heat wave and information about stochastic time series model are given in Sect. 2. Results concerning long-term variability of heat waves over Argentina are shown in Sect. 3. Estimates of recurrence probability of the most severe and longest heat wave in Buenos Aires are presented in Sect. 4. Finally, discussion and conclusions follow in Sect. 5.

2 Data and methodology

2.1 Data

The data were obtained from 58 stations located over Argentina north of 40° S (Fig. 1). This is the most populated region, and it is prone to severe heat waves. We utilized all available stations with long-term daily maximum and minimum temperature series (with less than 2 % of missing data). Originally, the data were provided by the Argentine National Weather Service and their quality was analysed through the European project CLARIS LPB, generating the open data base CLARIS LPB (Penalba et al. 2014). Table 1 shows all stations used for the analysis of long-term variability of heat waves, including their station ID, name, geographical coordinates and elevation. In this article, the term Buenos Aires represents the Autonomous City of Buenos Aires (Ciudad Autónoma de Buenos Aires).

2.2 Heat wave definition

Considering the impacts of heat waves on mortality in Buenos Aires, the extreme cases of excess mortality over the warm season (October–March) of the year are related to the occurrence of minimum temperature (MinT) above 20 °C (where the curve changes its curvature) and maximum temperature (MaxT) above 32 °C (Fig. 2). These values correspond to the mean daily 90th percentile calculated over the warm season (October–March) of the year in the 1961–1990 period. Therefore, the 90th percentiles of both MinT and MaxT were taken to define a heat wave for the warm season of the year. To specify the minimum number of consecutive days that define a heat wave, their persistence was analysed.

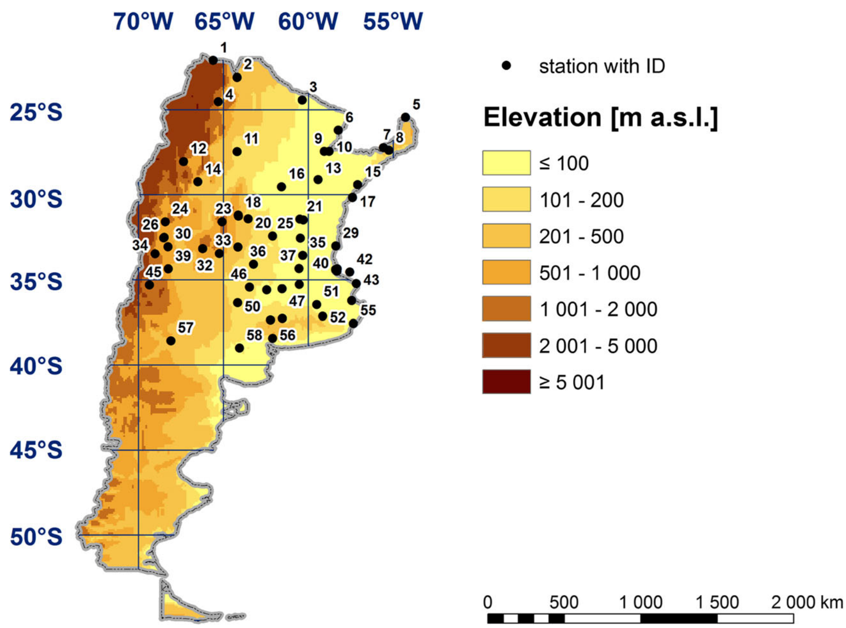

Fig. 1 Locations of stations and the elevation model (ETOPO5) over the continental parts of Argentina

In Buenos Aires, the analysis of persistence of days with MaxT above 32 °C and simultaneously MinT above 20 °C in the warm season (October to March) during the 1959–2010 period showed that 77 % of the spells lasted 1 or 2 days, and the longest one persisted for 12 consecutive days. Based on this distribution, and because the objective was to analyse more persistent events, a heat wave was defined when temperature was above the threshold (the seasonally varying 90th percentile) for at least 3 consecutive days. The station-specific 90th percentiles of MinT and MaxT calculated over 1961–1990 were used to define and analyse heat waves over the complete data base (period 1961–2010). Using this limited 1961–1990 period allows updating the list of heat waves without recalculating the percentiles and provides a better comparison with other studies.

We use three different definitions of heat waves: spells of 3 or more consecutive days with (1) MinT above the daily 90th percentile of MinT (heat waves based on MinT: MinTHW), (2) MaxT above the daily 90th percentile of MaxT (heat waves based on MaxT: MaxTHW) and (3) the joint occurrence of MinT and MaxT above their 90th percentiles. These latter will be called extreme heat waves (EHW), due to the severity of the definition. In these three types of heat waves, we analyse long-term variability and decadal occurrence of the number of days in heat waves, the persistence and the intensity.

We considered the warm half of the year from October to March, in order to capture early and late heat wave occurrences, too. These cases, although not necessarily associated with extreme absolute temperatures, could have huge impacts on society as well. For example, Campetella and Rusticucci (1998) presented synoptic conditions during a strong heat wave in the last days of summer (end of March) with a pronounced impact on society, as schools in Buenos Aires were temporarily closed.

2.3 Stochastic time series model for daily temperatures

In order to estimate recurrence probability associated with the 2008 heat wave in Buenos Aires, we make use of long artificial time series of MaxT simulated by a first-order autoregressive model (AR(1)). The AR(1) model provides characteristics of heat waves and temperature threshold exceedances that are generally in good agreement with observations (e.g. Mearns et al. 1984; Macchiato et al. 1993; Colombo et al. 1999; Kyselý 2010). Several variants of the AR(1) model exist; herein, we apply a model in which the seasonal cycle of MaxT is considered as a deterministic part and only deviations from this cycle are simulated as a stochastic component (Macchiato et al. 1993; Kyselý and Kim 2009; Kyselý 2010).

For the present climate experiment, parameters of the model (mean, variance and the first-order autocorrelation coefficient) are estimated from MaxT data in Buenos Aires over 1961–2009; 100,000-year-long artificial time series of MaxT are then generated with the AR(1) model, from which recurrence probability of events analogous to (or exceeding) the 2008 heat wave is estimated. In a similar way, experiments for a climate warmer by 1, 2, and 4 °C are carried out. Over Argentina, values of 2 to 3 °C correspond to the projected 75th percentile of the distribution from the ensemble of CMIP5 models, for the RCP 4.5 scenario and the end of the twenty-first century (IPCC 2013), so the range from 1 to 4 °C covers low- to high-climate change scenarios for Argentina and the late twenty-first century.

Table 1 Stations utilized

Station ID	Name	Latitude (° S)	Longitude (° W)	Altitude (m)
1	La Quiaca Observatorio	22.10	65.60	3459
2	Oran Aero	23.09	64.19	357
3	Las Lomitas	24.42	60.35	130
4	Salta Aero	24.51	65.29	1221
5	Iguazu Aero	25.44	54.28	270
6	Formosa Aero	26.20	58.23	64
7	Posadas Aero	27.22	55.58	125
8	Cerro Azul INTA	27.39	55.26	270
9	Resistencia Aero	27.45	59.05	52
10	Corrientes Aero	27.45	58.77	60
11	Santiago del Estero Aero	27.46	64.18	199
12	Tinogasta	28.04	67.34	1201
13	Reconquista Aero	29.11	59.42	53
14	La Rioja Aero	29.23	66.49	429
15	Paso de los Libres Aero	29.41	57.09	70
16	Ceres Aero	29.53	61.57	88
17	Monte Caseros Aero	30.16	57.39	54
18	Cordoba Aero	31.19	64.13	474
19	Cordoba Observatorio	31.24	64.11	425
20	Pilar Obs.	31.40	63.53	338
21	Sauce Viejo Aero	31.42	60.49	18
22	Parana Aero	31.47	60.29	78
23	Villa Dolores Aero	31.57	65.08	569
24	San Juan Aero	31.57	68.42	62
25	Marcos Juarez Aero	32.42	62.09	114
26	Mendoza Aero	32.5	68.47	704
27	Mendoza Observatorio	32.53	68.51	827
28	Rosario Aero	32.55	60.47	25
29	Gualeguaychu Aero	33.00	58.37	21
30	San Martin (MZA)	33.05	68.25	653
31	Rio Cuarto Aero	33.07	64.14	421
32	San Luis Aero	33.16	66.21	713
33	Villa Reynolds Aero	33.44	65.23	486
34	San Carlos (MZA)	33.46	69.02	940
35	Pergamino INTA	33.56	60.33	65
36	Laboulaye Aero	34.08	63.22	137
37	Junin Aero	34.33	60.55	81
38	Buenos Aires	34.35	58.29	25
39	San Rafael Aero	34.35	68.24	748
40	Castelar INTA	34.40	58.39	22
41	Ezeiza Aero	34.49	58.32	20
42	La Plata Aero	34.54	57.56	4
43	Punta Indio B.A.	35.22	57.17	22
44	Nueve de Julio	35.27	60.53	76
45	Malargue Aero	35.30	69.35	1425
46	General Pico Aero	35.42	63.45	145
47	Pehuajo Aero	35.52	61.54	87
48	Trenque Lauquen	35.58	62.44	95
49	Dolores Aero	36.21	57.44	9

Table 1 (continued)

Station ID	Name	Latitude (° S)	Longitude (° W)	Altitude (m)
50	Santa Rosa Aero	36.34	64.16	191
51	Azul Aero I	36.45	59.50	132
52	Tandil Aero	37.14	59.15	175
53	Coronel Suarez Aero	37.26	61.53	233
54	Pigue Aero	37.36	62.23	304
55	Mar del Plata Aero	37.56	57.35	21
56	Bahia Blanca Aero	38.44	62.10	83
57	Neuquen Aero	38.57	68.08	271
58	Rio Colorado	39.01	64.05	79

3 Long-term variability of heat waves in Argentina north of 40° S

Since the number of heat waves is small each year, we aggregated the number of days during heat waves (heat wave days) in decades, in order to analyse temporal changes in their occurrence. The first decade starts in the October 1960–March 1961 warm season.

The mean numbers of heat wave days per decade during the warm season for the whole 1961–2010 period, considering the three definitions MinTHW, MaxTHW and EHW, are shown in Fig. 3. As an example, the city of Buenos Aires experienced, on average, 8 heat wave days per year for MinTHW, 6.5 heat wave days per year for MaxTHW and, if we consider MinT and MaxT simultaneously above their 90th percentiles, 2.5 heat wave days per year for the EHW definition. The most persistent extreme warm temperatures occurred over the north and north-eastern part of Argentina, for all three heat wave definitions.

Figure 4 shows the geographical distribution of the number of heat wave days for each decade. There is great variability among regions, but in general, the decade 2001–2010 was typical for the highest number of heat wave days according to all definitions. Although the occurrence of heat wave days by the MaxTHW definition decreased in some regions by the end of the twentieth century, the occurrence of MinTHW increased, and when combining both limits, EHW also showed the largest number of occurrences in the last decade, surpassing the 1981–1990 warm decade.

Decadal frequency of heat waves (according to MinTHW, MaxTHW and EHW) at four typical stations is shown in Fig. 5. Decadal values in Buenos Aires experienced clear increases in heat waves according to MinTHW and EHW, with the highest frequency for both in the 2001–2010 decade, while a less pronounced increase in heat waves according to MaxTHW. The combination of different trends and decadal variability at other stations resulted in some cases in the decrease of the extreme heat waves (EHW), as shown in Córdoba (central Argentina). In the central-western part of the country, Mendoza shows an increment in the last decade, particularly for MinTHW. In the north-western part of the country, La Quiaca presents a huge increment in the last decade in EHW, mainly due to the increment in the persistence of MinTHW but also accompanied by increases in MaxTHW. Due to the sharp increase in the number of heat waves in the north-western region of Argentina (La Quiaca, Tinogasta), we checked again the data quality. The comparison with hourly data at other nearby stations in the 1991–2010 period confirmed the observed change in the last decade.

In general, most other stations over the analysed region show a clear positive trend in MinTHW, and decadal variability in MaxTHW, with the largest EHW cases in the last decade.

In order to analyse the variability of more frequent shorter heat waves, we separate the heat waves into two main groups according to their length, 3 to 5 days and longer. The

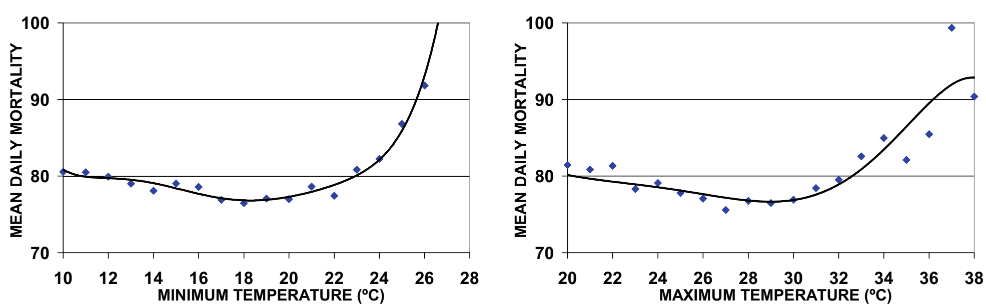

Fig. 2 Minimum and maximum daily temperature vs. mean daily mortality in Buenos Aires (2001–2012) warm season

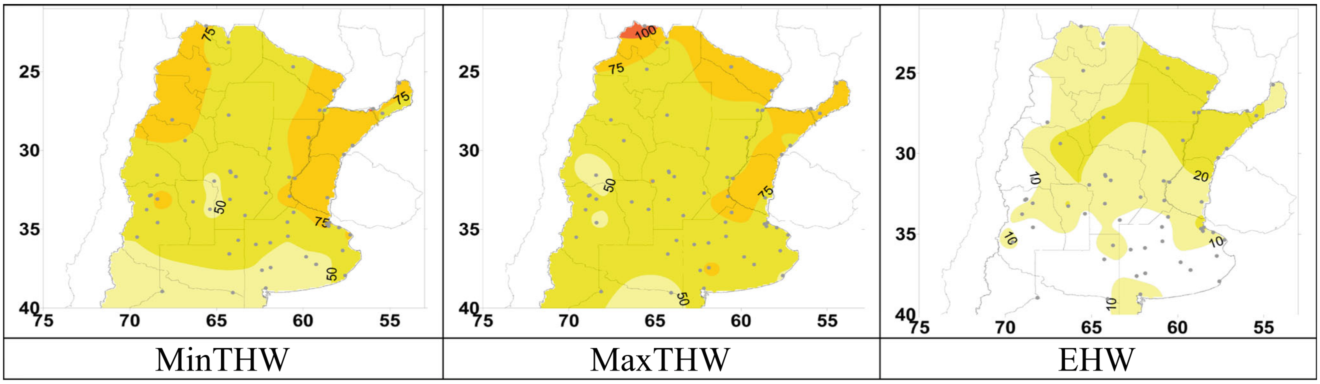

Fig. 3 Mean number of days in heat waves per decade, considering MinTHW, MaxTHW and EHW (warm season)

difference in the number of short heat waves between the last (2001–2010) and the first (1961–1970) decades shows an increase in most of the country, for all three definitions (Fig. 6). All stations present significant increasing trends for MinTHW (not shown).

Considering only these short heat waves, the north-western part of the country experienced from 10 to 30 more heat wave days for MinTHW in the last decade compared to the first decade, which is a substantial increase. All over the country, up to 5 more heat wave days for EHW occurred, with more than 10 heat wave days in the north-western region. The zero increment of heat wave days over central Argentina (according to MaxTHW) was related to the warm 1961–1970 decade in this region, as shown in Fig. 4. A similar pattern but with generally insignificant linear trends was found for long heat waves.

To summarize this variability, all heat waves and stations are analysed together. The time series of the number of heat waves shows positive significant trend in all definitions, mainly driven by the short heat waves (Fig. 7).

Beside the duration, we considered the intensity of heat waves, measured by the sum of degrees C above the 90th percentile (cumulative excess of temperature). For comparison, the degree days were computed for each event, as the ratio between the intensity and length in each event. The degree days were accumulated for decades, and the differences in degrees C between two decades (2001–2010, 1961–1970) were computed. The short heat waves had the largest differences. A strong warming can be seen mainly over the northwest in MinTHW, while less warming or cooling in other regions (not shown).

4 Recurrence probability of the extreme heat wave of November 2008 in Buenos Aires

Since Buenos Aires is the location with the longest and most complete temperature record in Argentina, and also the area where most of the country's total population lives, we focused on the most severe heat wave in Buenos Aires in more detail.

Over the whole period of available data (1909–2010), the November 2008 heat wave was the longest and most extreme one, mainly considering MaxT. It lasted for 12 days (from 3 to 14 November) and was associated with the cumulative MaxT excess above the 90th percentile of 32.6 °C. The heat wave was rather exceptional as to its length and the cumulative MaxT excess compared to other heat waves in Buenos Aires, as the second most severe heat wave since 1909 (March 1952) had the cumulative MaxT excess of only 26 °C and lasted 11 days. This November 2008 heat wave was also exceptional in MinT and EHW, compared to the March 1952 heat wave, which lasted 11 days, the cumulative excess was 54 vs 16 °C in EHW and 22 vs 4 °C in MinT. Its spatial extent, considering persistence, covers a region in central-eastern Argentina (Fig. 8).

Its recurrence probability was estimated from simulations of time series of MaxT by a first-order autoregressive (AR(1)) model (see Sect. 2.3). We generated 100,000-year-long series for the present climate (with parameters of the AR(1) model estimated over 1961–2009) in the first step and analogous series for a climate warmer by 1, 2 and 4 °C, to represent possible climate change scenarios for the late twenty-first century.

We focused on three heat wave characteristics that define severity of the 2008 heat wave:

1. Cumulative MaxT excess above the 90th percentile ≥ 32.6 °C,
2. Length ≥ 12 days,
3. Both conditions 1 and 2 met.

Table 2 shows that the recurrence probability of a heat wave similar or exceeding the November 2008 heat wave in Buenos Aires is small in the present climate. The return periods are estimated in the order of several hundreds to several thousands years, depending on the chosen characteristic. However, even a moderate warming substantially increases probability of such event: in a climate warmer by +1 °C, the return periods decline by an order of magnitude, and in a climate warmer by +4 °C, such heat waves are likely to occur regularly (once every 1–3 years).

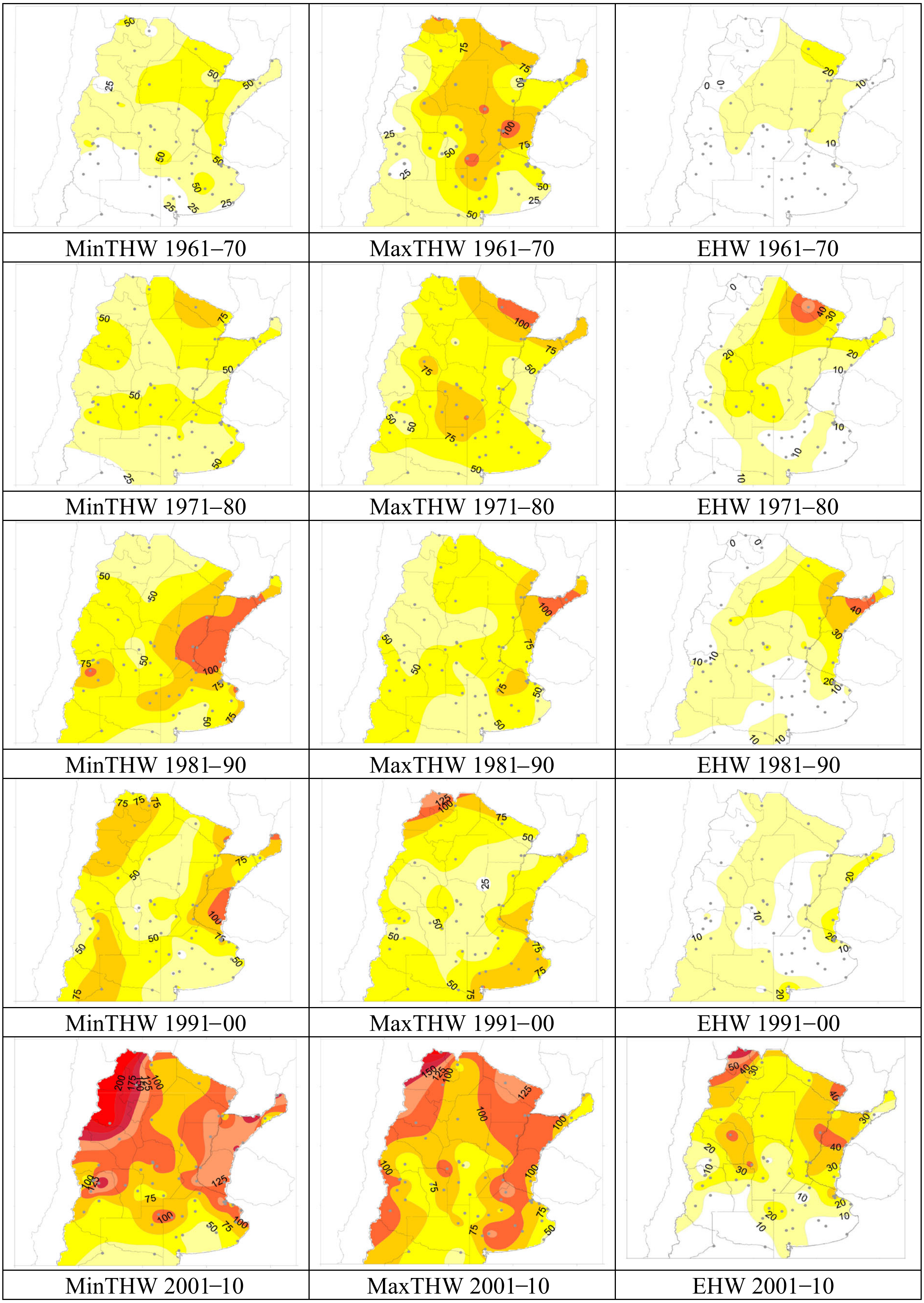

Fig. 4 Number of days in heat waves per decade, considering MinTHW, MaxTHW and EHW (warm season)

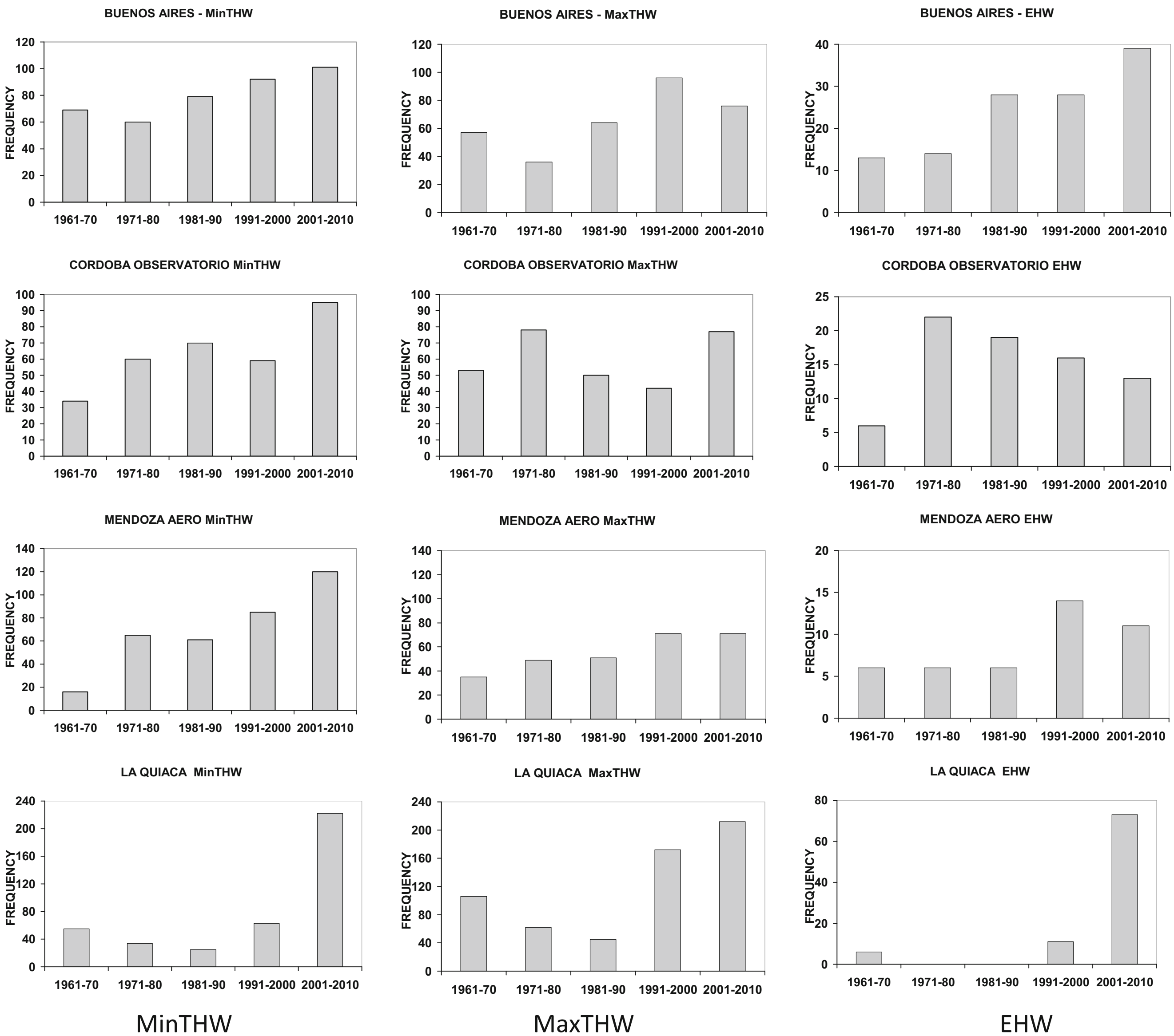

Fig. 5 Number of days in heat waves for MinTHW, MaxTHW and EHW over decades from 1961–70 to 2001–10 at stations Buenos Aires, Córdoba Observatorio, Mendoza Aero and La Quiaca (from *top* to *bottom*)

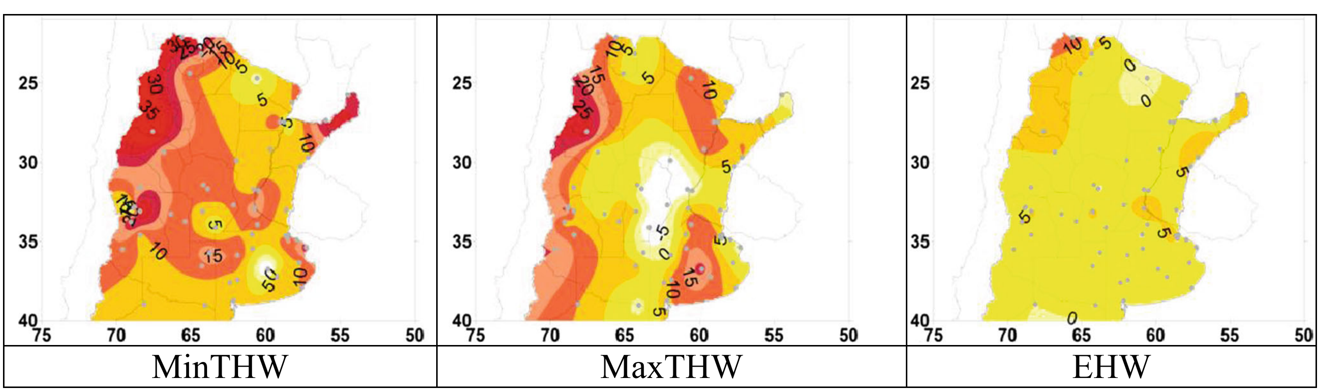

Fig. 6 Differences in the number of short (3 to 5 days) heat waves between 2001–10 and 1961–70, considering MinTHW, MaxTHW and EHW

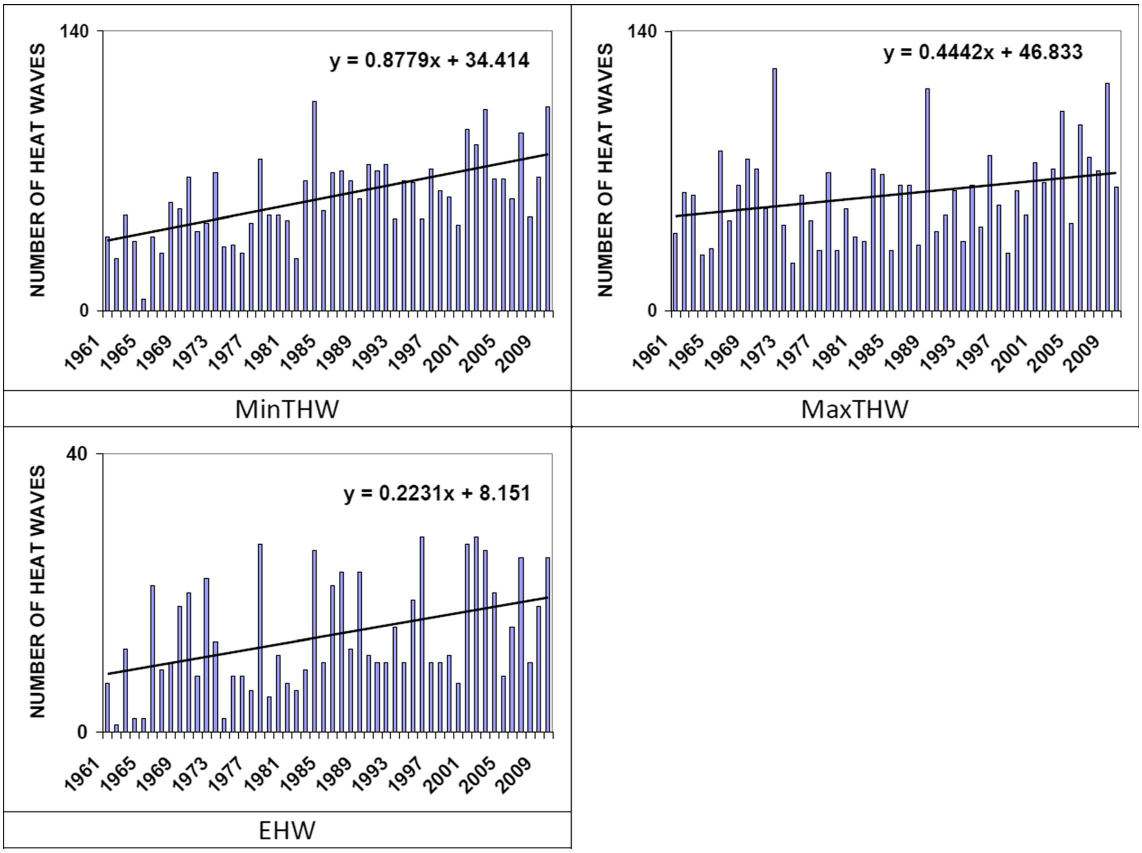

Fig. 7 Time series of the number of heat waves, all lengths and stations over Argentina (1961–2010). Linear trend is fitted to the data

5 Discussion and concluding remarks

The frequency of heat waves has been increasing in Argentina for all examined definitions over the 1961–2010 period. This finding brought more evidence for the IPCC statement that there is a worldwide increment of heat waves, since Hartmann et al. (2013) noted that the medium confidence is caused by a lack of studies, among others, over South America.

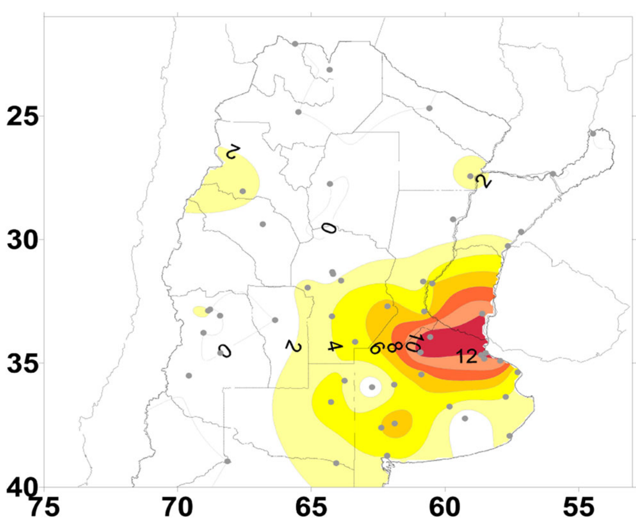

Fig. 8 Number of days during the 2008 November heat wave, considering MaxTHW

Generally, we found pronounced decadal variability, but the largest number of heat waves was observed in the last 2001–2010 decade, surpassing the warm 1981–1990 decade. The relatively cold 1991–2000 decade might be related to a lower activity of the South Atlantic Convergence Zone compared to the previous decade, as shown in Carvalho et al. (2004). However, Cerne and Vera (2011) demonstrated that heat waves over central Argentina occur even when the activity of the South Atlantic convergence zone is suppressed.

Focusing on individual stations, decadal values in Buenos Aires experienced increases in MinTHW and EHW, while the combination of different trends and decadal variability resulted in some cases (e.g. Córdoba and Las Lomitas) in the reduction of extreme heat waves in the last decade. The stations over the north-western part of the country (La Quiaca, Orán, Salta and Tinogasta) showed a strong positive change in the last decade, mainly due to increased persistence of MinTHW, but also accompanied by increases in MaxTHW.

In general, other stations showed a clear positive trend in heat waves in the light of MinTHW, and decadal variability in MaxTHW, with the most severe cases in the last decade when the simultaneous combination of MaxT and MinT excesses was most frequent. There was a particularly strong increase

Table 2 Return periods of the 2008 heat wave in Buenos Aires, estimated with the AR(1) model for the present climate and three climate change scenarios

Return period [in years] of a heat wave with	Present climate (1961–2010)	+1 °C warming	+2 °C warming	+4 °C warming
1. Cumulative MaxT excess above the 90th percentile (TS) ≥ 32.6 °C	610	95	18	1.3
2. Length ≥ 12 days	3700	380	55	3
3) TS ≥ 32.6 °C and length ≥ 12 days	6250	670	80	3.5

in the intensity and number of heat waves of short lengths (3 to 5 days) in all three heat wave definitions.

Recurrence probability of the longest and most severe heat wave in Buenos Aires (over 1909–2010, according to intensity measured by cumulative excess of MaxT above the 90th percentile) that occurred in 2008 was estimated by simulations with a stochastic first-order autoregressive model that reproduces structure of the time series of daily temperatures. The results show that the recurrence probability of such long and severe heat wave is small in the present climate, but it is likely to increase substantially in the near future even under a moderate warming trend: by a factor of 6–10 with only a 1 °C warming, by a factor of ~30–70 with a 2 °C warming and by a factor of ~500–1000 with a 4 °C warming. These results should be taken into account also in the design of adaptation and mitigation measures to protect society against adverse effects of extreme events in a changing climate.

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