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ORIGINAL PAPER

Temporal variability of the Buenos Aires, Argentina, urban heat island

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Abstract This paper describes the statistical characteristics and temporal variability of the urban heat island (UHI) intensity in Buenos Aires using 32-year surface meteorological data with 1-h time intervals. Seasonal analyses show that the UHI intensity is strongest during summer months and an "inverse" effect is found frequently during the afternoon hours of the same season. During winter, the UHI effect is in the minimal. The interannual trend and the seasonal variation of the UHI for the main synoptic hours for a longer record of 48 years are studied and associated to changes in meteorological factors as low-level circulation and cloud amount. Despite the population growth, it was found a negative trend in the nocturnal UHI intensity that could be explained by a decline of near clear-sky conditions, a negative trend in the calm frequencies and an increase in wind speed. Urban to rural temperature differences and rural temperatures are negatively correlated for diurnal and nocturnal hours both for annual and seasonal scales. This result is due to the lower interannual variability of urban temperatures in comparison to rural ones.

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1 Introduction

The acceleration of urban growth is a common feature in most of Latin American cities. Approximately half of the world's population currently lives in cities, and this value is expected to increase to 61% by 2030 (UNFPA 2009). Urbanization including residential, commercial, and industrial developments gives rise to one of the most dramatic human-induced change of an ecosystem: a natural environment, often containing transpiring vegetation and a permeable surface, is converted to a built landscape accompanied by the introduction of new surface materials (such as concrete, asphalt, etc.) coupled with the emission of heat, moisture, and pollutants change radiative, thermal, moisture, roughness, and emissions properties of the surface and the atmosphere above (Roth 2002). These modifications of urban surfaces cause the local air and surface temperatures to rise several degrees in comparison to the simultaneous temperatures of the surrounding less built-up suburban/rural areas. This phenomenon is known as the urban heat island (UHI) and is quantified by the temperature difference between the urban and suburban/rural environment (Oke 1973, 1987; Landsberg 1981; Arnfield 2003; Roth 2007). Among the negative impacts of the UHI is the risk of climatic and biophysical hazards in urban environments as heat stress and exposure to air pollutants (Rosenzweig et al. 2005). Oke (1973) concluded that even a city of 1,000 people could have an UHI effect, and the magnitudes of the UHI were linearly correlated with the logarithms of the population. More recently, Fujibe (2009) also demonstrated that urban warming was not only detectable at large cities but at slightly urbanized sites in Japan.

Many causes contribute to the formation of the UHI: blanketing effect of urban atmospheric pollution, high heat capacity, and conductivity of building and paving materials and altered urban energy balance terms leading to positive thermal anomalies (Oke 1982). The intensity of the UHI depends on many factors and exhibits large variability with the time of day and season. In general, late afternoon urban temperatures are higher than rural temperatures, but there are also data suggesting that many urban midafternoon air temperatures are cooler than surrounding rural areas (Karl et al. 1988; Bejarán and Camilloni 2003; Peterson 2003). Other factors that influence the UHI intensity and development are meteorological parameters as wind speed, cloud cover, and near-surface temperature lapse rate. The UHI intensifies under cloudless sky and light wind conditions because cloud amount and wind speed affect the insolation and ventilation, which are the most relevant variables to describe the radiative and turbulent exchanges that influence the atmospheric stability in an urban environment (e.g. Runnalls and Oke 2000; Morris et al. 2001; Mihalakakou et al. 2002; Alonso et al. 2007).

Several authors have demonstrated that the UHI intensifies as cities grow and their urbanization keeps on. The enhancement of the UHI in time has been documented, among others, for Madrid, Spain (Martínez et al. 1991); Tucson, Arizona, USA (Comrie 2000); Seoul, Korea (Kim and Baik 2002); and New York, USA (Gaffin et al. 2008). However, unlike what was observed in other world cities, a negative linear trend in Buenos Aires, Argentina, UHI intensity for 1959–1997 have been found considering the yearly mean urban–rural temperature difference despite the city growth (Camilloni and Barros 1997).

Prior studies of Buenos Aires urban climate found that during the daytime, the Buenos Aires UHI is more intense in July (austral winter) than in January and during the nighttime it is more intense in January (austral summer) than in July (Barros and Camilloni 1994; Figuerola and Mazzeo 1998). Nevertheless, none of them analyzed datasets with both a high temporal resolution and an extended period of time coverage. Hence, analyses of data collected over long observational periods are required to explain the temporal variability of the UHI magnitude and to evaluate the physical processes that influence it.

The goal of this paper is to assess the annual and seasonal statistical characteristics of the Buenos Aires UHI considering more than 30 years of hourly data. Particularly, the evolution of its intensity over time and trends are studied associated to changes in meteorological factors as wind speed and cloud amount. The paper is organized as follows: Section 2 describes the study area, dataset, and the methodology. Section 3 presents the Buenos Aires UHI climatology and Section 4 evaluates the decadal and interannual variability of the heat island effect. Section 5 explores the urban–rural temperature difference dependency on temperature and Section 6 shows the links between UHI intensity and meteorological factors. Section 7 presents the main conclusions.

2 Study area description and methods

Buenos Aires is located around 35° S along the western coast of the Río de la Plata estuary. The metropolitan area extends for 4,000 km^2, and its surface is featureless with only minor differences in height of less than 30 m. The city population comprises more than 13 million inhabitants transforming it into one of the world's mega cities (cities with more than ten million people). Its population grew steadily during the twentieth and the beginning of the twenty-first centuries, and from 1940 to 1960 the growth was accelerated by industrialization (Fig. 1).

The UHI effect in Buenos Aires is studied using hourly meteorological data from the urban station Buenos Aires Central Observatory (BACO; 34°35′ S, 58°26′ W), and from the international airport at Ezeiza (EZE, 34°49′ S, 58°32′ W), 30 km southwest of the downtown area (Fig. 2). The urban site selected for this study is within a park of 0.4 km^2 near the geographical center of the actual urban area. This meteorological station can be considered as representative of the urban meteorological conditions as the local effects of the station environment are negligible due to the small area of the park which is closely rounded by a built-up area. The airport monitoring station is located in an open environment with vegetated surface features similar to those found in natural landscapes. This pair of stations represents probably the best practical method to determine the Buenos Aires UHI. Although the urban growth could get closer to Ezeiza during the last

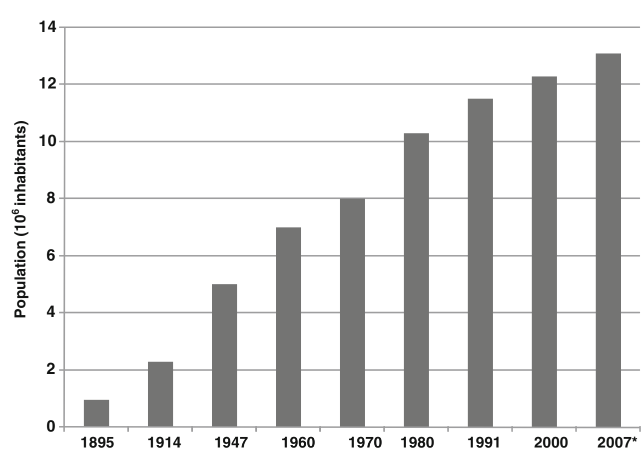


Fig. 1 Evolution of the Buenos Aires Metropolitan area population according to national census (*asterisk* estimation)

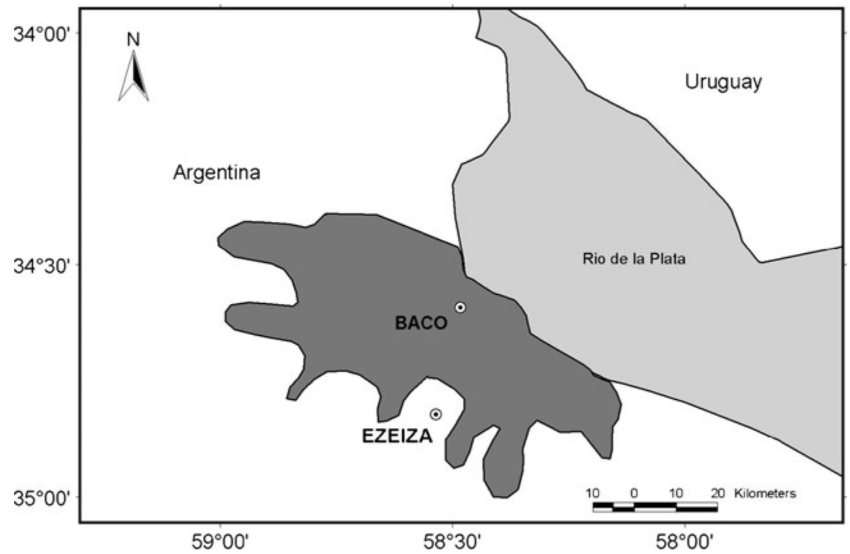


Fig. 2 Buenos Aires metropolitan area (*dark gray area*) and location of meteorological stations considered in this study: Buenos Aires Central Observatory (*BACO*) and Ezeiza

decades, the fact is that this has always been the most important international airport in the country with intense aircraft traffic. Severe land-use restrictions apply in the area for security reasons, and consequently the rural landscape around it did not change significantly during the period of the present study. Records at BACO started at the beginning of the twentieth century, but temperature data from the rural site are available only since 1959 for the main synoptic observation hours: 03, 09, 15, and 21 local time (LT). Since 1976, 24 hourly information is accessible and consequently a detailed climatology of the UHI was performed for 1976–2007. This is not a minor feature because studies that include hourly information of Buenos Aires city are unusual and generally referred only to a few years. Consequently, this study presents a more robust result, considering 32 years of 24 hourly data. Additionally, the temporal variability of the UHI for the main synoptic hours was studied for a longer period (1960–2007). Finally, the interannual variability of the Buenos Aires UHI effect was analyzed considering some meteorological factors as cloud cover and wind velocity. Annual and seasonal basis analyses were considered at all the stages of the study. The UHI intensity is calculated as the difference between the hourly mean urban (T_u) and rural (T_r) temperatures:

$$\mathrm{UHI} = T_u - T_r \tag{1}$$

3 Some aspects of the UHI climatology

Figure 3 presents the hourly variations (mean and standard deviation) in Buenos Aires UHI intensity. Due to the importance of solar power for this topic, it is necessary to indicate the difference between "local time" and "solar time". Solar time is based upon a 24-h clock and is longitude dependent. Solar noon (12.00) is the point when the sun is at its highest point in the sky. Solar time is associated with each specific location, so it is unpractical to use it nationally. Internationally, a Coordinated Universal Time (UTC) is defined. Zero (0) hours UTC is midnight in Greenwich England, which lies on the zero longitudinal meridian. Due to its geographical position, Argentina is situated at UTC 4, but officially the UTC 3 was adopted. In other words, the official hour is 1-h advanced with respect to the corresponding time-zone schedules. All references of "local time" in this work correspond to the official Argentine hour. The UHI exhibits a mean daily cycle with a maximum of 2.1°C at 02 LT and a minimum in the afternoon, between 14 LT and 15 LT of 0.1°C. However, hourly values can reach much more than 2.1°C. In fact, between 00 LT and 06 LT, more than the 10% of days show an urban/rural difference greater than 4°C (Fig. 4), considered

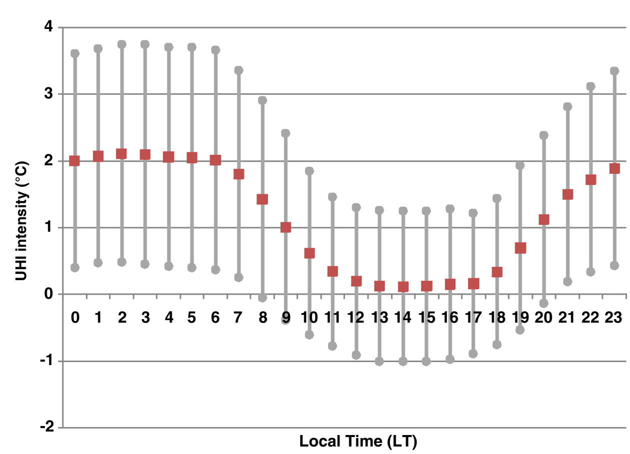


Fig. 3 Hourly variations of the heat island intensity. Mean (*squares*) and standard deviations (*bars*)

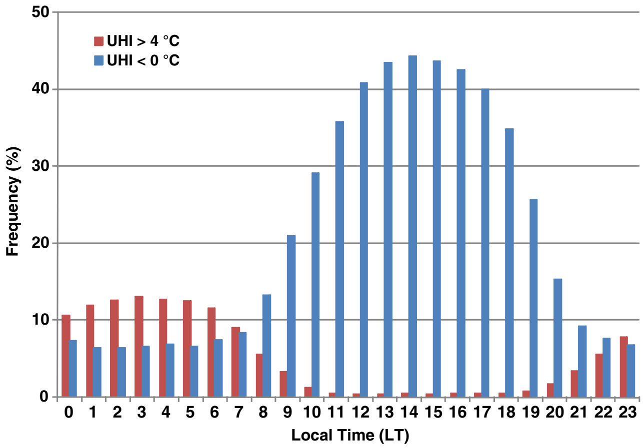


Fig. 4 Hourly frequency distribution of "inverse" (UHI<0°C) and extreme (UHI>4°C) heat islands

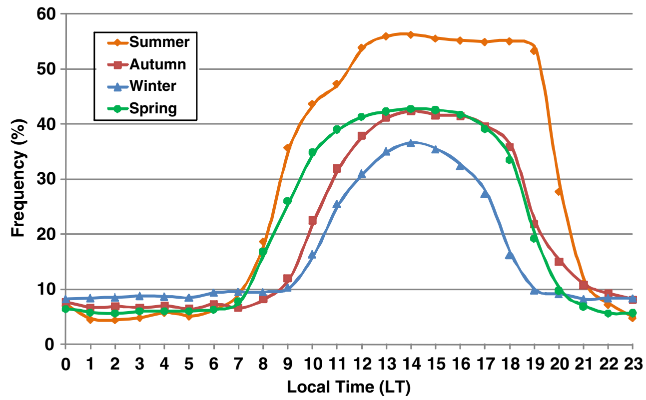


Fig. 6 Seasonal frequency distribution of "inverse" heat island (UHI<0°C)

as a reference value to describe an intense UHI event in Buenos Aires (Figuerola and Mazzeo 1998). By the other hand, negative values, i.e. "inverse heat islands" can be seen at all hours although this phenomenon occurs much more often during the afternoon (Fig. 4).

Some seasonal differences in the hourly Buenos Aires UHI intensity can be appreciated when summer (Dec–Jan–Feb), autumn (Mar–Apr–May), winter (Jun–Jul–Aug), and spring (Sep–Oct–Nov) are considered (Fig. 5). The amplitude of the daily cycle is greatest during summer with the largest UHI intensities during the night hours and an average inverse UHI between 12 and 19 LT. The nocturnal UHI effect is minimal in winter although during the day it reaches the maximum intensities in comparison with the rest of the seasons. Autumn and spring present an intermediate behavior most of the time.

The inverse UHI is evaluated analyzing frequencies with negative UHI intensities. Although the annual climatology presented in Fig. 4 shows a frequency of more than 40% of days of this effect during the daytime hours, the seasonal analysis shows noticeable differences particularly between summer and winter (Fig. 6). More than 50% of summer days show this inverse effect between 12 and 19 LT with an abrupt decrease in its occurrence few hours later (for example, 11% at 21 LT). During winter, the maximum frequency is 36.5% at 14 LT while spring and autumn present an intermediate behavior.

4 Temporal variability of the Buenos Aires UHI

4.1 Decadal variability

A decadal analysis of the daily cycle of the UHI intensity evidences some changes with time. Considering the 1976–1985, 1986–1995, and 1996–2005 periods, a progressive decrease in the UHI intensity can be observed during nighttime when the maximum effect occurs. During the day, when the UHI effect is lower, an increase of the intensity is observed but only for the last decade (Fig. 7). The decadal analysis on seasonal basis show a decrease in the UHI intensities at nocturnal hours with time at all seasons (Fig. 8). In the afternoon, when the UHI effect is less noticeable, an increase of the intensity is observed.

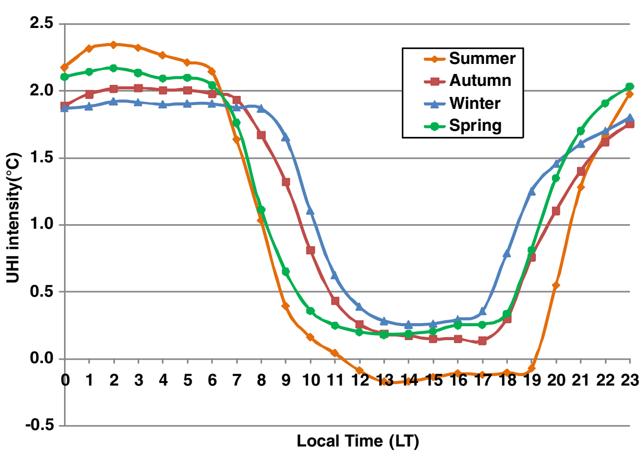


Fig. 5 Seasonal diurnal variation of the UHI

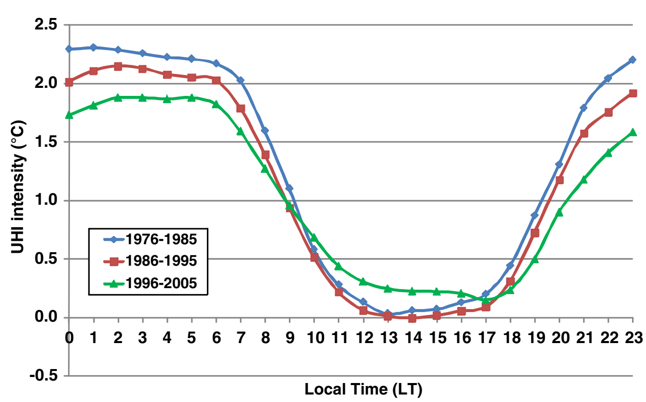


Fig. 7 Decadal variability of the daily cycle of the UHI

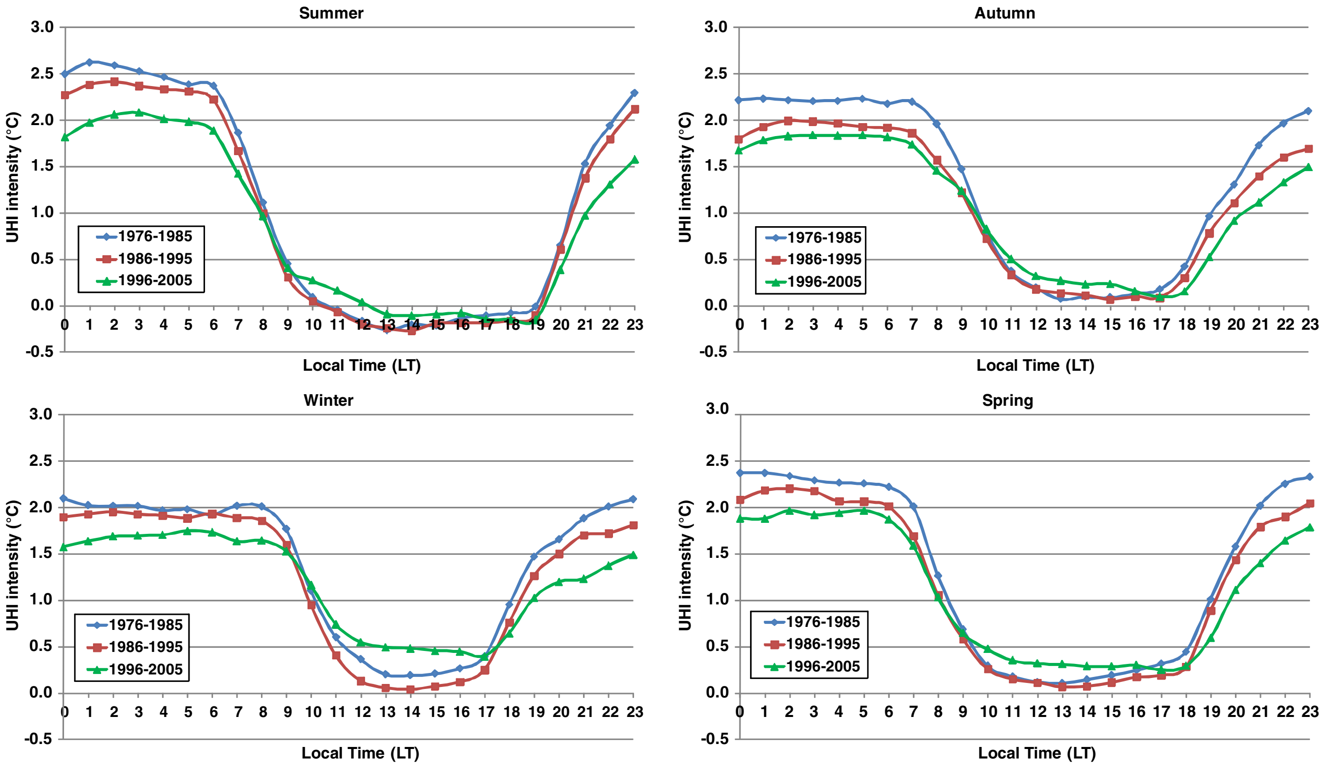


Fig. 8 Decadal variability of the seasonal mean daily cycle of the UHI

Figure 9 shows the frequency of days with UHI of >4°C for the three decades mentioned above. Two aspects are clearly reflected in all periods: (1) the UHI reaches its maximum intensity during the night and (2) diurnal extreme UHI intensities are very rare (less than 1% between 11 and 19 LT). The decadal analysis also shows that extreme UHI events appear to be less frequent with time. In fact, the number of intense UHI registered in the first decade (1976–1985) decreased to half or even less in the last decade (1996–2005) at many nocturnal hours. The frequency of inverse UHIs (the city cooler than the rural surrounding) shows that the last period (1996–2005) exhibits the lowest values during the daytime (10 to 16 LT) and the highest during the rest of the time (Fig. 10).

4.2 Interannual variability

The interannual variability of the UHI intensity is studied considering the main synoptic hours (03, 09, 15, and 21 LT) for 1960–2007. The annual means are presented in Fig. 11. They show the largest intensities at the nocturnal hours (03 and 21 LT) and the "inverse" effect with minimum mean intensities as low as −0.3°C during the afternoon (15 LT)

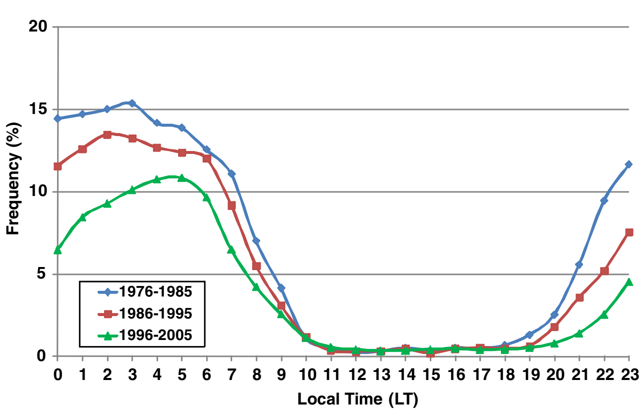


Fig. 9 Decadal distribution of frequencies of UHI>4°C

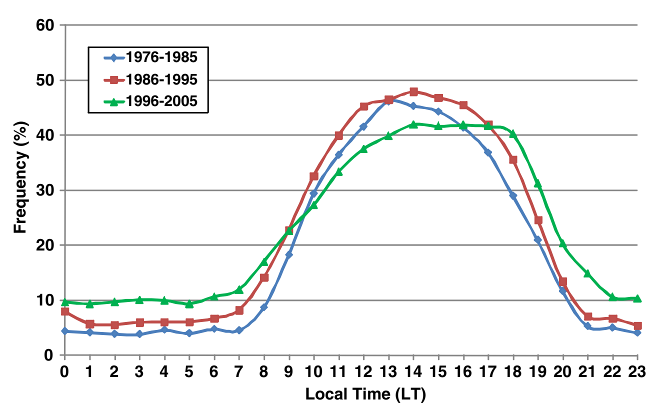


Fig. 10 Decadal distribution of frequencies of UHI<0°C

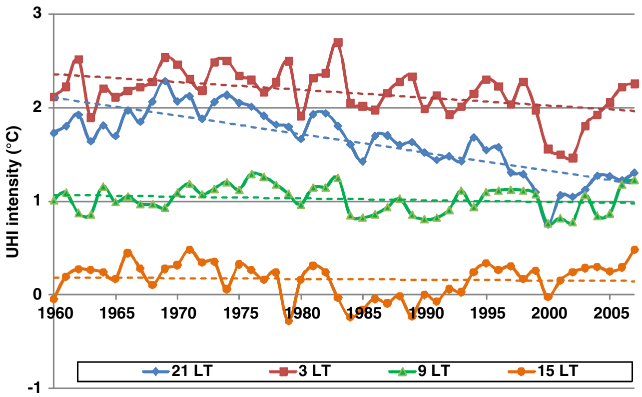


Fig. 11 Temporal variability of the annual mean UHI for the main synoptic hours. Linear trends are indicated as *dashed lines*

for some years. Although the annual mean "inverse" heat islands are small, 1% of the hourly mean values range between −6°C and −2.5°C with an extreme value of −8.9°C on 20th December 1983. Statistically significant negative linear trends at the 90% confidence level (Hoel 1971) for the nocturnal hours of −0.19°C/decade (21 LT) and −0.08°C/decade (03 LT) are found. An attenuation of the urban warming is observed although the Buenos Aires Metropolitan Area population had a persistent increase since the beginning of the twentieth century (Fig. 1). However, it might be suspected that these negative trends could be a consequence of the urban growth and the expansion of built-up areas that could affect the observations at the rural site as they get closer to it. Nevertheless, as pointed in Section 2, it seems this is not the case for Ezeiza due to the land-use restrictions in the area. Besides, Lowry (1977) indicated that in the surface boundary layer, the thermal effect of the city has a limited area of extent, and during the evening and night when the urban heat island frequently reaches its maximum intensity, the urban thermal plume quickly rises above the rural boundary layer. Consequently, although in some occasions the urban plume could reach the rural site, its impact on rural observations is probably negligible most of the time. The negative trends in the annual mean nocturnal UHI intensity indicate that population growth might not be the only aspect that must be taken into account for quantifying the Buenos Aires UHI effect as it is not a single function of population.

The seasonal analysis presented in Fig. 12 shows the largest UHI intensities at nocturnal hours in all seasons, with statistically significant negative trends at 21 LT for

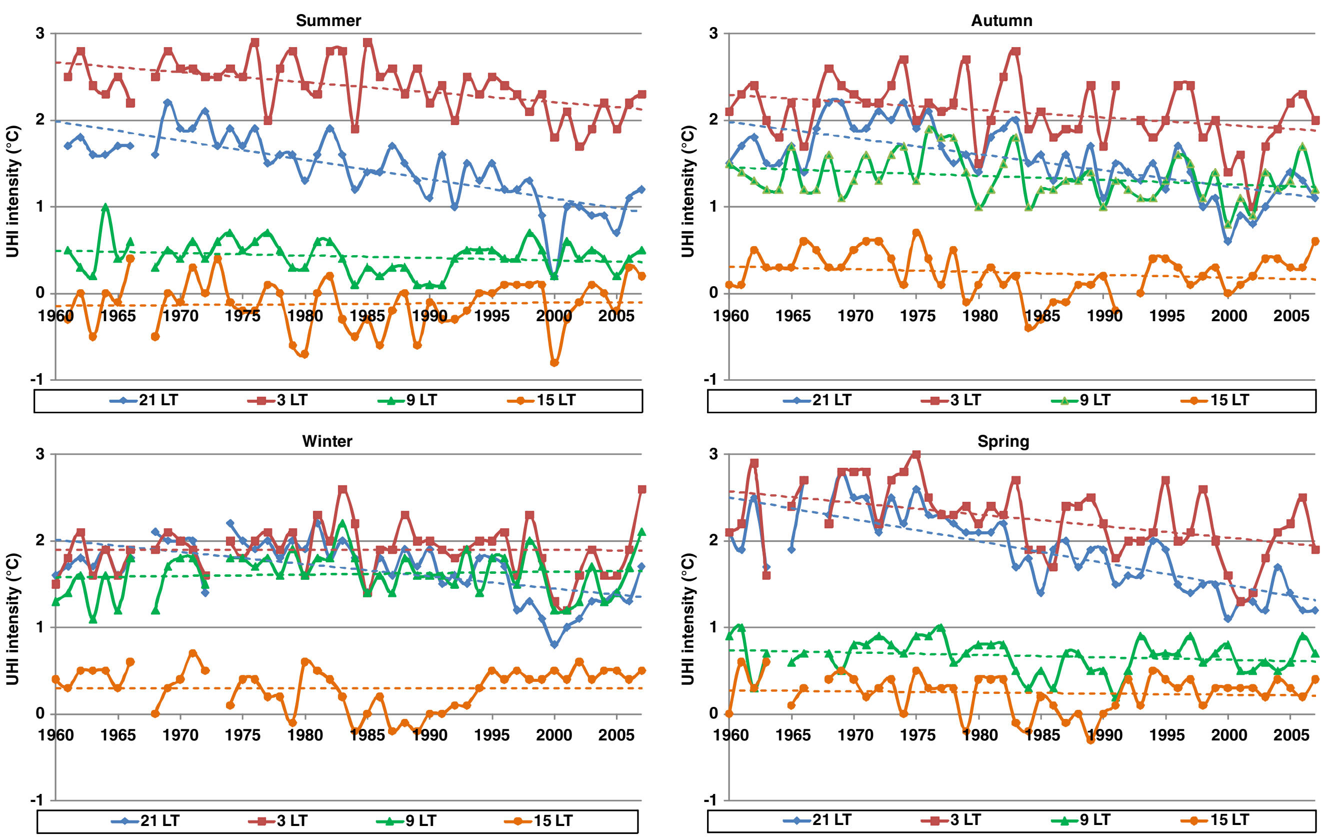


Fig. 12 Temporal variability of the seasonal UHI for the main synoptic hours. Linear trends are indicated as *dashed lines*

summer, autumn, and spring of −0.22°C/decade, −0.18°C/decade, and −0.25°C/decade, respectively. Diurnal UHI intensities are lower, although during autumn and winter the early morning (09 LT) and nocturnal UHI have almost the same magnitude. The diurnal UHI shows no significant trend at any season. In the afternoon, the "inverse" UHI effect is particularly evident during summer, when it is more frequent and shows the largest intensities.

5 Seasonal urban–rural temperature difference dependency on temperature

Camilloni and Barros (1997) showed that for many USA, Argentine, and Australian cities, yearly mean urban to rural temperature differences and rural temperature are negatively correlated. This correlation is not a mathematical artifact but a result of lower interannual variability of urban temperatures in comparison to rural ones. In this section, we explore if this inverse relation holds for Buenos Aires urban–rural temperature difference for diurnal and nocturnal hours both for the annual and seasonal scales.

Figure 13 shows the annual mean temperature differences between BACO and EZE for the main synoptic hours as a function of rural temperatures. Nocturnal differences show the largest significant negative linear trends with explained variances of 55% (21 LT) and 51% (03 LT).

Table 1 summarizes linear trends and correlation coefficients for the seasonal analysis. For all seasons and main synoptic hours, linear trends are negative and most of them are statistically significant. Only the diurnal values (09 and 15 LT) for spring and the early afternoon (15 LT) for autumn and winter are not significant. In order to explore if these linear trends are related to lower interannual variability of the urban temperature compared with the rural one, the standard deviations of BACO (σ_u) and EZE (σ_r) temperatures for different seasons and the main synoptic hours are also presented in Table 1.

The linear correlation coefficient ($R_{\mathrm{UHI},\,r}$) between UHI and T_r can be expressed as:

$$R_{\mathrm{UHI},r} = \left(\sigma_u / \sigma_{\mathrm{UHI}}\right)\left(R_{u,r} - \sigma_r / \sigma_u\right) \quad (2)$$

where σ_{UHI} is the standard deviation of the urban to rural temperature difference and $R_{u,\,r}$ is the linear correlation

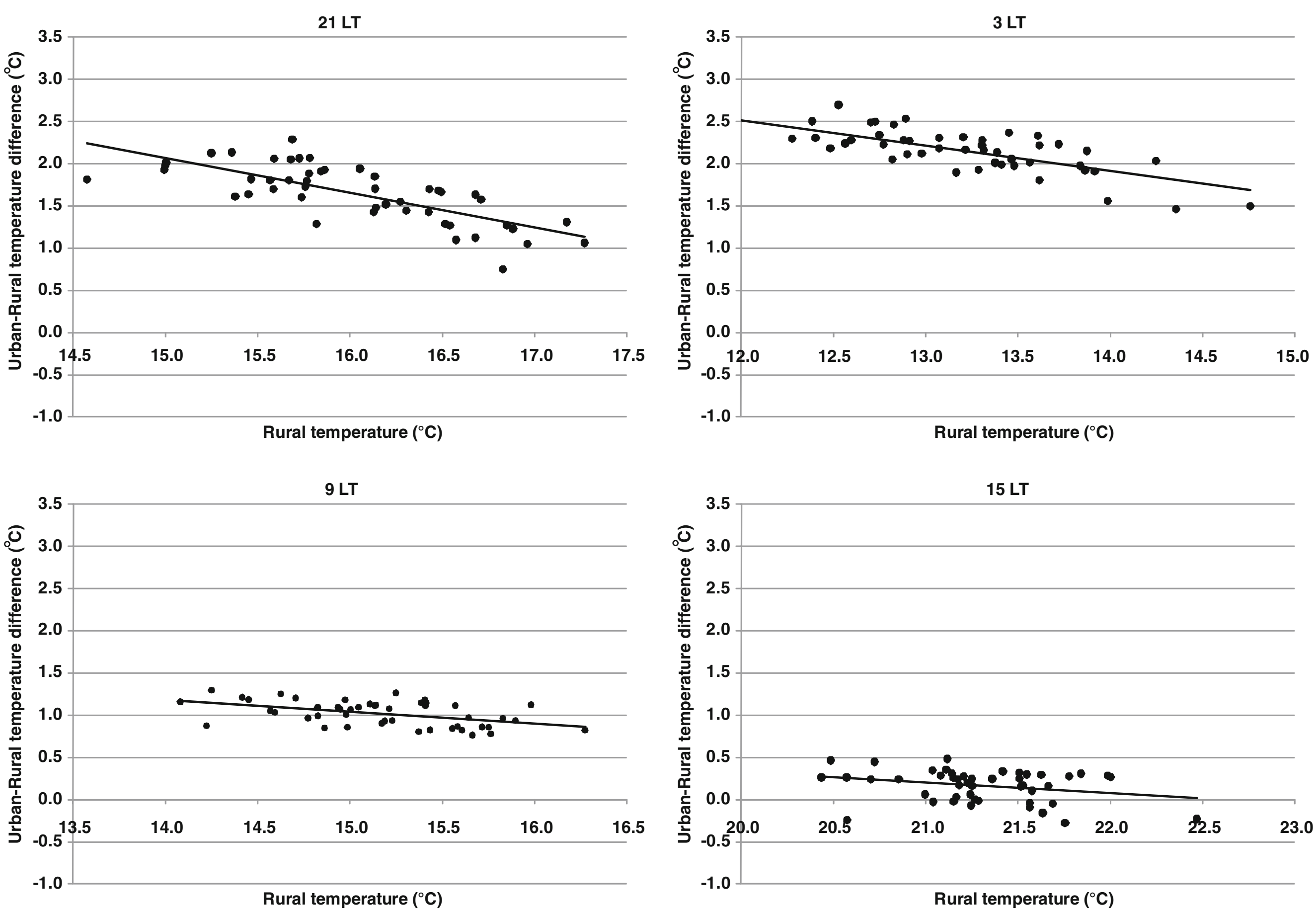


Fig. 13 Urban–rural temperature differences as a function of rural temperature for the main synoptic hours

Table 1 Linear trends between the UHI intensity and T_r for all seasons and main synoptic observation hours

	Summer				Autumn				Winter				Spring			
	21LT	03LT	09LT	15LT	21LT	03LT	09LT	15LT	21LT	03LT	09LT	15LT	21LT	03LT	09LT	15LT
Trend	−0.26	−0.16	−0.12	−0.18	−0.22	−0.20	−0.16	−0.09	−0.20	−0.20	−0.15	−0.10	−0.35	−0.35	−0.08	−0.08
R	−0.59	−0.47	−0.49	−0.62	−0.49	−0.55	−0.59	−0.28	−0.58	−0.70	−0.61	−0.31	−0.70	−0.71	−0.27	−0.27
$R_{u,\ r}$	0.90	0.95	0.97	0.97	0.90	0.94	0.97	0.94	0.94	0.97	0.97	0.94	0.87	0.89	0.96	0.95
σ_u	0.73	0.81	0.70	0.86	0.80	0.91	0.88	0.72	0.85	0.92	0.95	0.77	0.61	0.62	0.61	0.66
σ_r	0.89	0.90	0.78	1.01	0.91	1.05	1.01	0.74	0.96	1.08	1.05	0.76	0.87	0.87	0.66	0.71
σ_r/σ_u	1.22	1.11	1.11	1.17	1.14	1.15	1.15	1.03	1.13	1.17	1.11	0.99	1.43	1.40	1.08	1.08

R is the linear correlation coefficient between UHI and T_r, $R_{u,\ r}$ is the linear correlation coefficient between T_u and T_r and σ_u and σ_r are the standard deviations of T_u and T_r, respectively

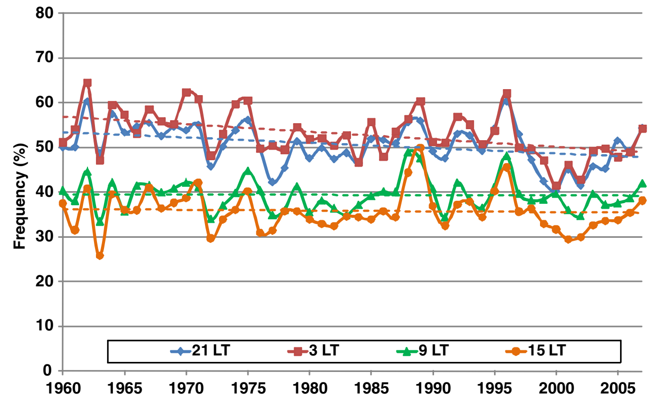


Fig. 14 Temporal variability of the annual frequency of days with low cloud amount at the urban station for the main synoptic hours. Linear trends are indicated as *dashed lines*

coefficient between the urban and rural temperatures. Appendix includes the formalization of Eq. 2. The sign of $R_{\mathrm{UHI},\ r}$ depends on the difference ($R_{u,\ r}-\sigma_r/\sigma_u$). In all cases except for winter at 15 LT, σ_u is lower than σ_r leading to negative values of $R_{\mathrm{UHI},\ r}$ (Table 1). In the following section, a physical explanation for the observed UHI changes is analyzed and associated to modifications in meteorological factors as cloud cover and wind that could influence the temporal variability of the Buenos Aires UHI intensity.

6 UHI intensity and meteorological factors

6.1 Cloud cover

Cloudiness condition is one of the meteorological parameters that influence the UHI intensity. Initially mentioned by Sundborg (1950) who showed that cloudiness is negatively correlated with the UHI, different studies all over the world show that UHI intensity decrease with increasing cloud cover (Kidder and Essenwanger 1995; Eliasson 1996; Figuerola and Mazzeo 1998; Morris et al. 2001). In this work, the annual and seasonal temporal variability of days with near clear-sky conditions are investigated in

Table 2 Linear trends of the seasonal frequency of days with low cloud amount (0–2 octas) for the main synoptic hours

	21 LT	3 LT	9 LT	15 LT
Summer	*−0.145*	*−0.222*	0.031	0.027
Autumn	*−0.176*	*−0.178*	−0.093	−0.122
Winter	−0.070	−0.114	0.088	−0.005
Spring	−0.085	*−0.168*	−0.047	0.030

Statistically significant values at the 95% confidence level are set in italics (Hoel 1971)

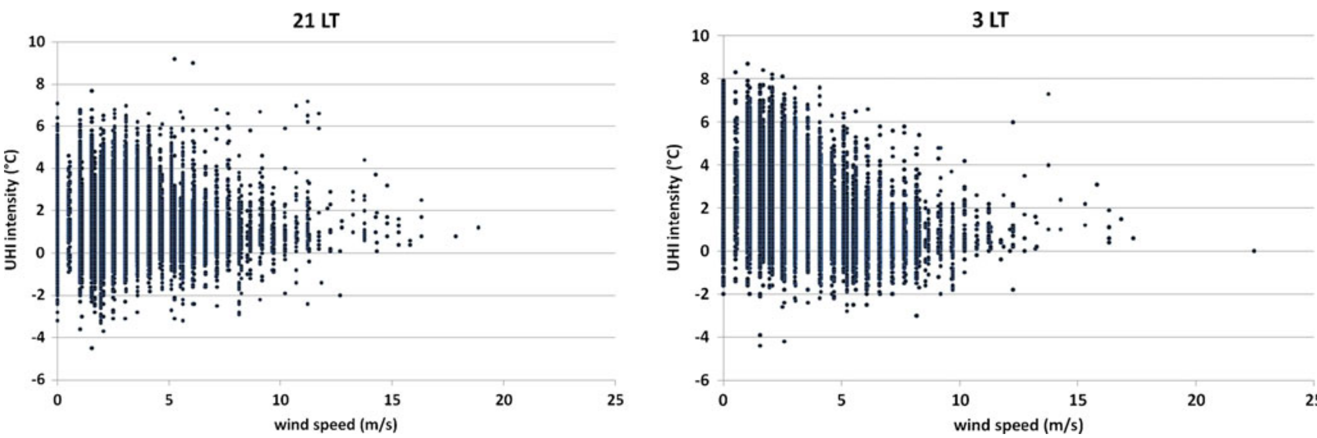


Fig. 15 Scatterplots of the association between nocturnal UHI intensities (21 LT and 3 LT) and rural wind speeds

order to evaluate its influence on the Buenos Aires UHI magnitude.

Figure 14 shows the annual frequency of days with low cloud amount (0 to 2 octas). While the nocturnal hours (21 LT and 3 LT) exhibit a negative trend the diurnal values do not show any significant change. These results suggest that the negative trend in the nocturnal UHI presented in Fig. 11 could be related to a modification in the nocturnal radiative exchanges due to an increase in cloud amount that leads to a reduction of the urban effect during nighttime. Clouds that absorb and re-emit infrared radiation downward affect the pattern of nocturnal terrestrial longwave radiation: the nocturnal infrared radiation obtained from the clouds is available for absorption by the surface and partially offsets the surface radiative loss. This absorption may, in turn, slow the nocturnal radiative cooling and decrease the differences in the observed temperatures between urban and rural areas.

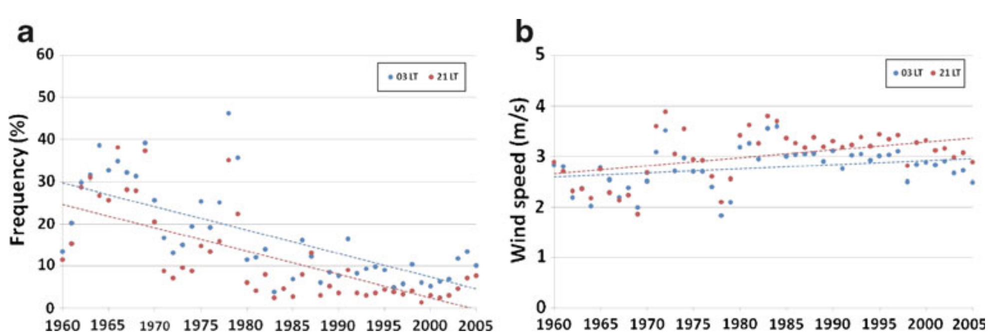
The seasonal analysis of the near clear-sky conditions frequency presents different characteristics among seasons. During summer and winter, nocturnal and diurnal conditions have opposite behavior. Negative trends are observed at nocturnal hours and slight positive trends during daytime. Autumn and spring exhibit negative trends at all studied hours, except in the early afternoon (15 LT) in spring (Table 2).

Consequently, both annual and seasonal analyses indicate that changes in cloud cover could partially explain the reduction of the nocturnal Buenos Aires UHI. As the UHI development and intensity is favored by clear-sky conditions, the decrease in the frequency of this condition during 1960–2007 could be related with the attenuation of the nocturnal urban warming excess. Causes of the observed nocturnal cloud changes are not analyzed in this study and further work is necessary to explore the possible mechanisms involved.

6.2 Wind speed

The strength of the regional airflow affects the UHI development and magnitude. Higher urban–rural temperature differences tend to be associated with conditions of calm to low wind speed while high wind speed prevents the development of UHIs. Moreover, Oke and Hannell (1970) and Oke (1976) defined a "limiting wind speed" at which the intensity of the UHI intensity becomes null. Wind speeds of 6 or 7 m/s are reference values of this critical limit found for cities as Seoul (Korea) and Salamanca (Spain) (Kim and Baik 2002; Alonso et al. 2007). Figure 15 shows the spread of the nocturnal UHI intensities and their association with rural wind speeds between 1960 and 2007. As expected, the linear correlation

Fig. 16 Interannual variability of **a** relative frequency of calm conditions (in %) and **b** wind speed (in m/s) in Buenos Aires during nighttime. Linear trends are indicated as *dashed lines*



coefficients between both variables are negative (−0.13 at 21 LT and −0.40 at 3 LT) and the limiting wind speed for the Buenos Aires UHI appears to be above 10 m/s, larger than in other world cities although it seems a reasonable value according to the city size (Oke 1987).

Calm frequencies have decreased particularly during nighttime when the UHI effect is more evident (Fig. 16a). Although annual calm frequencies exhibit an important interannual variability, the observed negative linear trends are in agreement with the reduction of the UHI intensity. Seasonal analysis shows that the decrease in nocturnal calm frequencies is common to all seasons (Figure not shown). Accompanying the decline in the occurrence of calm conditions positive trends in the wind speed are also found (Fig. 16b).

6.3 Combined influence of cloud cover and low-level circulation

The most frequent long term mean wind directions (two thirds of cases) in Buenos Aires correspond to the first (NE) and second (SE) quadrants with a percentage of calm periods over the year of 15%. Table 3 presents the nocturnal Buenos Aires UHI intensity for the most frequent wind directions and for overcast (6 to 8 octas) and near clear-sky conditions (0 to 2 octas) and the relative frequency of both cloudiness cases. As expected, the highest mean UHI values are reached for near clear-sky conditions that almost double the intensities under the overcast ones. Regarding wind direction, the maximum is found when the wind is from the E and the lowest values are recorded when the wind is coming from the N. Both SE and S directions are associated to more frequent nocturnal overcast conditions than to clear skies and the opposite occurs with the N and NE directions. For the eastern winds, both cloudiness extremes considered have almost the same frequency.

Different studies (Camilloni 1999; Simionato et al. 2005; Di Luca et al. 2006) showed changes in the low-level regional circulation associated to a southward shift of the South Atlantic high with an enhancement of the northeasterly winds in Buenos Aires and La Plata River since 1960. This result could also partially explain the negative Buenos Aires' UHI trend as the city could be more frequently affected by the river and it can be speculated that the rural station could be affected by the urban plume due to its relative position 30 km southwest of the downtown area. However, Figuerola and Mazzeo (1998) showed that when these conditions of NE wind direction at both stations (BACO and EZE) are simultaneous, a cool urban island (UHI<0°C) is frequently observed. Additionally, changes in the frequencies of the E and SE directions could also contribute to explain the observed negative trend in the nocturnal annual mean urban bias effect. Figure 17 presents the decadal variability of both wind directions frequencies at the urban station. Except for the last incomplete decade, there is a tendency for a reduction in the frequency of the E winds associated to the largest UHI (Table 3). There is also a rise in the occurrence of the SE direction that presents almost twice the frequency of overcast skies than clear ones (Table 3) increasing the unfavorable conditions for the development of the urban heat island.

Table 3 Nocturnal UHI intensity (in °C) for two extreme cloud cover conditions and the most frequent wind directions in Buenos Aires

	Overcast (6–8 octas)	Clear sky (0–2 octas)
N	1.0 (3.3)	1.9 (8.3)
NE	1.7 (4.6)	3.2 (9.7)
E	2.0 (4.4)	3.8 (4.8)
SE	1.8 (4.7)	3.5 (2.5)
S	1.5 (7.3)	3.0 (5.9)

In brackets is indicated the relative frequency (in %) of each cloud cover condition

7 Summary and conclusions

Buenos Aires, Argentina, is one of the most populated cities in South America. In this work, the UHI effect is analyzed considering 32 years of hourly data at both annual and seasonal scales. The largest intensities are found for the nocturnal UHI during summer months and an "inverse" effect (the city cooler than the rural surrounding) is found frequently during the afternoon hours of the same season. During winter, the amplitude of the daily cycle of the UHI is minimum.

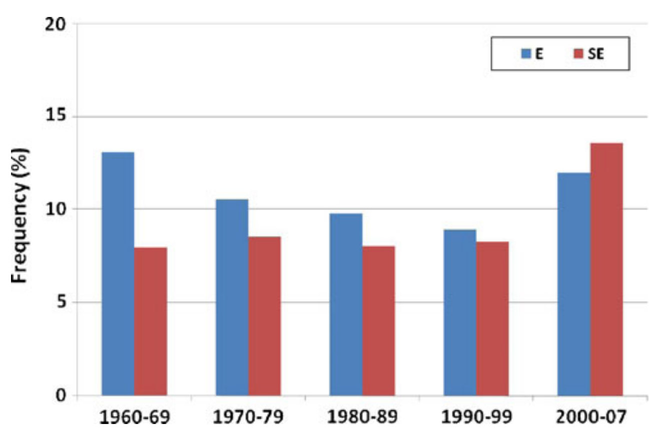


Fig. 17 Decadal relative frequency (in %) of E and SE wind directions in Buenos Aires during nighttime

Although the Buenos Aires Metropolitan Area population had a persistent increase since the beginning of the twentieth century, the nocturnal UHI effect has been decreasing since 1960. Both the decadal and the interannual variability analyses show a reduction of the nocturnal UHI intensity for all seasons. Not only it is found a negative trend in the nocturnal mean UHI magnitude but also in the occurrence of extreme values (UHI>4°C). Low-level circulation and the amount of cloud cover trends have been used to explore if the modification in the conditions of insolation and ventilation could physically explain the observed UHI effect changes. Cloud cover data show a decline of near clear-sky conditions during nighttime that was accompanied by a negative trend in the calm frequencies and an increase in the wind speed. Both changes are physically consistent with the reduction in the UHI intensity.

Urban to rural temperature differences and rural temperatures are negatively correlated for diurnal and nocturnal hours both for annual and seasonal scales. This result is due to the lower interannual variability of urban temperatures in comparison to rural ones and it can be speculated that the inverse relation between UHI magnitude and rural temperatures could also be related to an easier vertical dissipation of heat caused by a greater frequency of unstable atmospheric conditions.

The historical negative trend of Buenos Aires UHI strength and its dependency on rural temperature demonstrates that population growth is not the only aspect that must be consider in quantifying the urban excess warming. In summary, we show that the temporal variability of the UHI could be at least partially explained by changes in radiative and dynamical processes.

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Appendix

The linear correlation coefficient ($R_{\mathrm{UHI},\ r}$) between the yearly mean urban to rural temperature differences (UHI) and rural (r) temperature for N years can be expressed as

$$R_{\mathrm{UHI},r} = \frac{\sigma_{\mathrm{UHI},r}}{\sigma_{\mathrm{UHI}}\sigma_r} \tag{3}$$

where $\sigma_{\mathrm{UHI},\ r}$ is the covariance between UHI and r, and σ_{UHI} and σ_r are the corresponding standard deviations. Considering that UHI is calculated as the difference between the annual mean urban (u) and rural (r) temperatures and $\overline{u}$ and $\overline{r}$ are the means of u_i and r_i with $i=1,\ldots\ldots N$, Eq. 3 becomes

$$R_{\mathrm{UHI},r} = \frac{1}{N}\frac{\sum_{i=1}^{N}\left[(u_i - r_i) - \overline{(u-r)}\right](r_i - \overline{r})}{\sigma_{\mathrm{UHI}}\sigma_r} \tag{4}$$

so

$$R_{\mathrm{UHI},r} = \frac{1}{N}\frac{\sum_{i=1}^{N}[(u_i - r_i) - (\overline{u} - \overline{r})](r_i - \overline{r})}{\sigma_{\mathrm{UHI}}\sigma_r} \tag{5}$$

and

$$R_{\mathrm{UHI},r} = \frac{1}{N}\frac{\sum_{i=1}^{N}[(u_i - \overline{u}) - (r_i - \overline{r})](r_i - \overline{r})}{\sigma_{\mathrm{UHI}}\sigma_r} \tag{6}$$

$$R_{\mathrm{UHI},r} = \frac{1}{N\sigma_{\mathrm{UHI}}\sigma_r}\left[\sum_{i=1}^{N}(u_i - \overline{u})(r_i - \overline{r}) - \sum_{i=1}^{N}(r_i - \overline{r})^2\right] \tag{7}$$

Multiplying and dividing by σ_u

$$R_{\mathrm{UHI},r} = \frac{1}{N\sigma_{\mathrm{UHI}}\sigma_r}\frac{\sigma_u}{\sigma_u}\left[\sum_{i=1}^{N}(u_i - \overline{u})(r_i - \overline{r}) - \sum_{i=1}^{N}(r_i - \overline{r})^2\right] \tag{8}$$

$$R_{\mathrm{UHI},r} = \frac{\sigma_u}{\sigma_{\mathrm{UHI}}}\left[\frac{1}{N}\frac{\sum_{i=1}^{N}(u_i - \overline{u})(r_i - \overline{r})}{\sigma_u\sigma_r} - \frac{1}{N}\frac{\sum_{i=1}^{N}(r_i - \overline{r})^2}{\sigma_u\sigma_r}\right] \tag{9}$$

The linear correlation coefficient ($R_{u,\ r}$) between the yearly mean urban and rural temperatures for N years can be expressed is

$$R_{u,r} = \frac{1}{N}\frac{\sum_{i=1}^{N}(u_i - \overline{u})(r_i - \overline{r})}{\sigma_u\sigma_r} \tag{10}$$

Thus, Eq. 9 becomes

$$R_{\mathrm{UHI},r} = \frac{\sigma_u}{\sigma_{\mathrm{UHI}}}\left[R_{u,r} - \frac{{\sigma_r}^2}{\sigma_u\sigma_r}\right] \tag{11}$$

Resulting in

$$R_{\mathrm{UHI},r} = \frac{\sigma_u}{\sigma_{\mathrm{UHI}}}\left[R_{u,r} - \frac{\sigma_r}{\sigma_u}\right] \tag{12}$$

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