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Urban heat island in the metropolitan area of São Paulo and the influence of warm and dry air masses during summer

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1. Introduction

The Metropolitan Region of Sao Paulo (MRSP) is a very large and complex conurbation of 39 cities, including the city of Sao Paulo (Fig. 1). It has almost 20 million inhabitants and 7 million vehicles. Its climate presents a wet summer from December to February and a dry winter from June to August. The predominant circulation is a northeasterly flow, caused by a semipermanent high pressure feature, the South Atlantic High, however this large-scale feature is often changed by the passage of cold fronts. The sea breeze circulation also penetrates in the MRSP, usually during the afternoon and early night, increasing the wind velocity and changing its direction to SE. Topography, that may cause mountain-valley flows when the wind intensity is weak, along with the buildings, influence the circulation in the MRSP (Oliveira et al., 2003).

The Urban Heat Island (UHI) is defined as the thermal gradient between an urbanized area and its non-urban surroundings. Even though simple in definition, it is a complex phenomenon to characterize through an observational study (Arnfield, 2003). In Sao Paulo, past works indicated that the UHI has maximum intensity at night, caused by anthropogenic sources and the release of energy storage into the urban canopy, a similar behavior to those in middle latitude locations (Monteiro, 1986; Freitas et al., 2007). However, Ferreira et al. (2011) investigated the difference between the mean temperature of stations located inside the city and the mean temperature of stations at rural areas southeast from the city, during 2004, and observed a daytime maximum intensity for the UHI (from 1400 LT to 1600 LT) and minimum during morning hours. The UHI minimum intensity varied from 0.94 °C in November (0300 LT) to -0.26 °C in June (0900 LT), and the maximum from 2.6 °C in July (1600 LT) to 5.5 °C in September (1500 LT). They also found a correlation between the solar radiation and the UHI intensity, indicating that the latter is determined by the seasonal variation of the daily values of the solar radiation, since the local radiometric characteristics of the surface and the atmosphere causes an increase on energy input in the urban area. Also, the diurnal evolution of the anthropogenic heat (AH) calculated for the city of Sao Paulo indicates larger values during the day, reaching a maximum of 20 W m^{-2}. Vehicular sources are responsible for 50 % of the AH maximum, stationary sources contribute with 41 %, and human metabolism represents 9 % of the total. The AH in Sao Paulo corresponds to approximately 11 % of the surface net radiation annual value (Ferreira et al., 2010), as the stored energy flux corresponds to 50 % of the all-wave net radiation during the day and 27 % at night (Ferreira et al., 2013). However, even inside the urban area of the MRSP, great differences are present: different levels of urbanization, parks, preserved vegetated areas, water bodies, commercial, industrial, and residential areas, etc, and, therefore, the UHI is still not completely characterized, as well as its interaction with other meteorological processes.

During the austral summer of 2014 (December/2013, January, and February/2014), the southeast part of Brazil was under the influence of a hot and dry air mass (GREC, 2015). This phenomenon produced positive anomalous temperature values, negative anomalous precipitation values, and a suitable case study to verify the influence of this air mass in the UHI at Sao Paulo. Therefore, this work aims to better understand the UHI in the MRSP and its interaction with the warm and dry air mass of the summer of 2014.

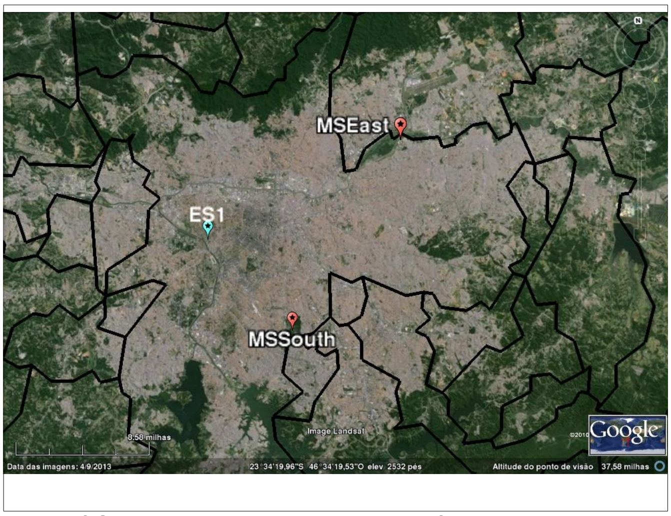

Figure 1: Metropolitan Region of Sao Paulo and the location of the urban environmental station (ES1) and the 2 suburban meteorological stations (MSEast and MSSouth). Black lines are the boundaries of the municipalities and the larger area, comprising the three stations, is Sao Paulo city (23° 32' 51''S and 46° 38' 10''W).

2. Methodology

This work used the temperature records of one station of the Environmental Agency of the state of Sao Paulo (CETESB) and 2 automatic meteorological stations in different parts of the MRSP, described in Table 1 and presented in Fig. 1. The meteorological stations are located at suburban, peripheral areas of the city of Sao Paulo, east (MSEast) and south (MSSouth) from the center of the city. Unfortunately, there are no meteorological or environmental stations north and west from the city center. The environmental (ES1) station is the only station at the center of the city that present recording series long enough to compare to the suburban stations. The temperature differences between the suburban and urban stations hourly averages were calculated, a spectral analysis was performed to assess the most significant periods of variation of these differences, and a diurnal cycle was produced. The influence of sea-breeze is investigated on a case study during August 6th 2013. Finally, the influence of the anomalous meteorological conditions of the austral summer of 2014 on the UHI in the MRSP is analyzed, comparing the averages of the temperature differences, during the day and at night, for December, January and February of the past years to the same months for the 2013/2014 summer.

Station	Type	Location (lat/lon)	Period recorded	Characteristic	Frequency
ES1	Environmental	-23.561067° S / -46.701649° W	Jan/2004 to Dec/2014	URBAN	Hourly averages
MSEast	Meteorological	-23.480523° S/ -46.499796° W	Jan/2004 to Dec/2004	SUBURBAN	Hourly averages
MSSouth	Meteorological	-23.650727° S / -46.621959° W	Jul/2009 to Aug/2014	SUBURBAN	Hourly averages

Table 1: Characterization of the observational stations.

3. Results

3.1 Spectral analysis and diurnal cycle

Hourly temperature differences were calculated between the urban station (ES1) and the suburban stations (MSEast and MSSouth), creating two time series. There were only a few gaps in each series, that were filled by each month average value for each hour of the day. A periodogram was performed for each series and the 4 most significant periods were shown (Fig. 2). Both series presented a strong signal on the 24 hours and 12 hours periods, not showing much influence of seasonal variations. The result suggests that the most important periods in the UHI temporal evolution are diurnal and semi diurnal. Therefore, the average temperature difference for each hour of the day was calculated using the complete series of each suburban station and Fig. 3 presents the resulting diurnal evolution of the UHI.

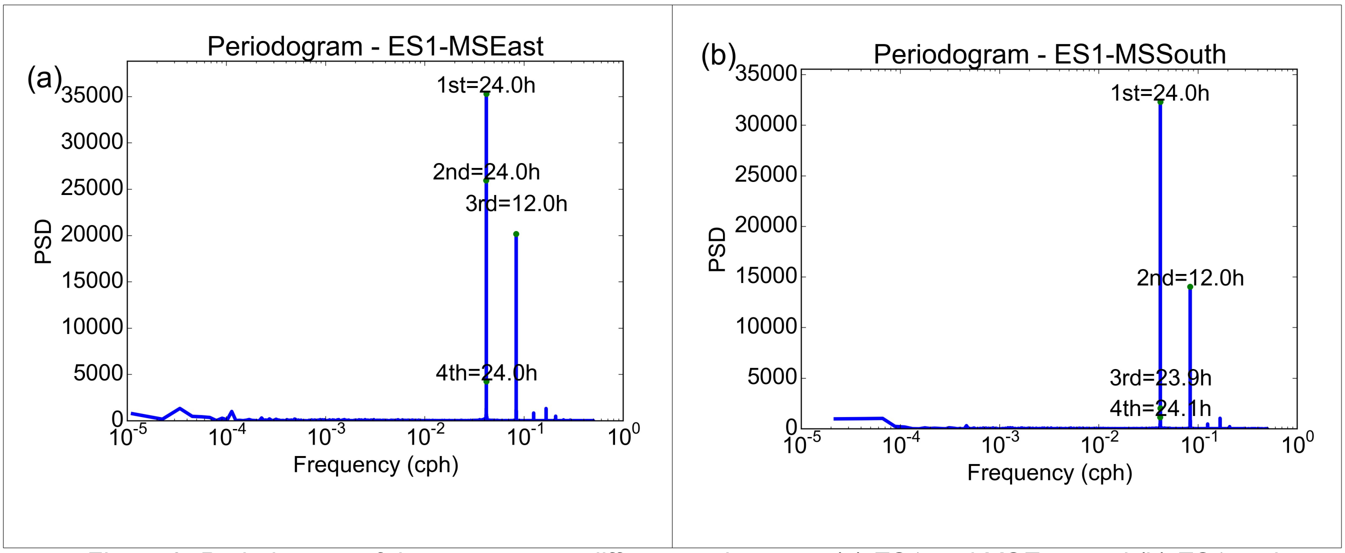

Figure 2: Periodogram of the temperature differences between (a) ES1 and MSEast and (b) ES1 and MSSouth.

The diurnal evolution of the temperature differences between urban and suburban stations (Fig. 3) indicate a morning Urban Cool Island, with a maximum intensity at 0900 LT. The intensity decreases from 0900 LT to 1200 LT and then the situation changes, indicating Urban Heat Island, that increases its intensity, peaking at 1700 LT. These results are in agreement with previous work (Ferreira et al., 2013). The maximum UHI intensity may have the influence of the sea breeze, that occurs in the MRSP approximately 50% of the days of the year. At night, the UHI is consistently present, which leads to a greater average of its intensity (around 1 °C).

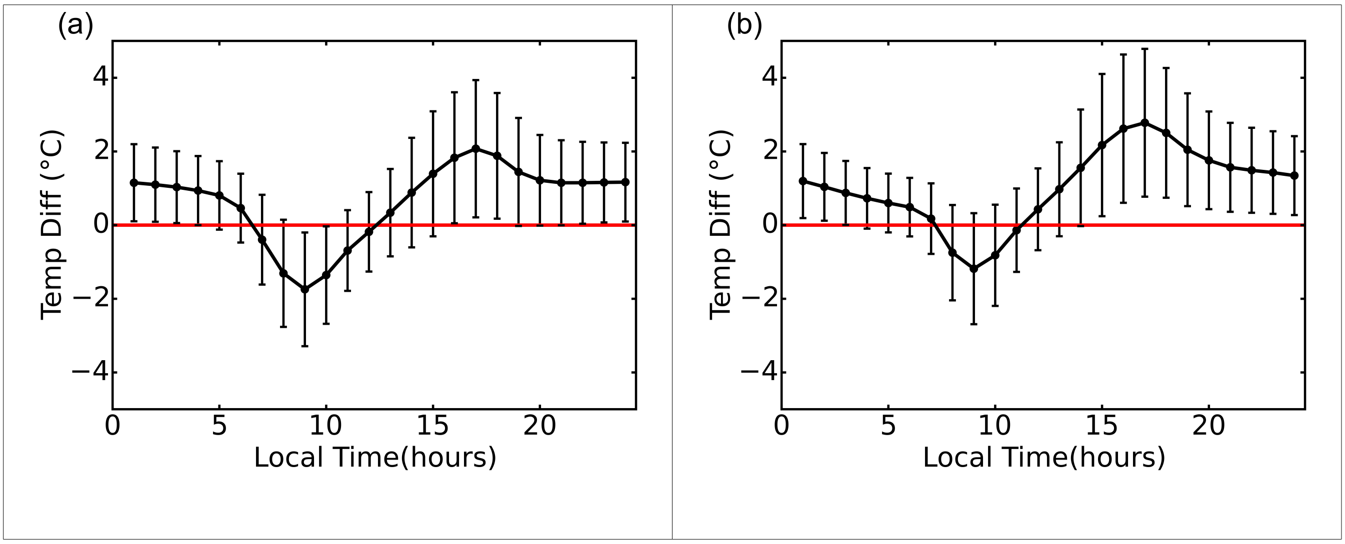

Figure 3: Diurnal evolution of temperature differences between (a) ES1 and MSEast, and (b) ES1 and MSSouth. Vertical lines represent standard deviation.

3.2 Influence of sea breeze and dry and warm air masses

The influence of the sea breeze was verified by taking a case study as example. On August 6th 2013 at 1300 LT, the temperature difference between ES1 and MSSouth stations was 10.5 °C and between ES1 and MSEast was 5.9 °C. At this time, the relative humidity and the wind velocity for stations MSSouth and MSEast increased as the wind direction changed from NE to SE (not shown here), characterizing a sea breeze flow. One hour later, the whole MRSP was under the influence of the sea breeze flow. Although this was not a typical sea breeze penetration event (usually, the temperature differences are not as high as in this case and the sea breeze penetrates in the MRSP from 1700 LT to 1900 LT), this is a good example of how this phenomenon may influence the calculation of UHI intensity in the MRSP. As observed in Figure 4, the sea breeze penetrates from SE to NW, bringing air with lower temperatures and higher humidity, changing the temperature field on the MRSP. The passage of cold fronts may also cause high temperature differences in the MRSP. However, the cold fronts come from SW and do not follow a diurnal cycle, as the sea breeze does.

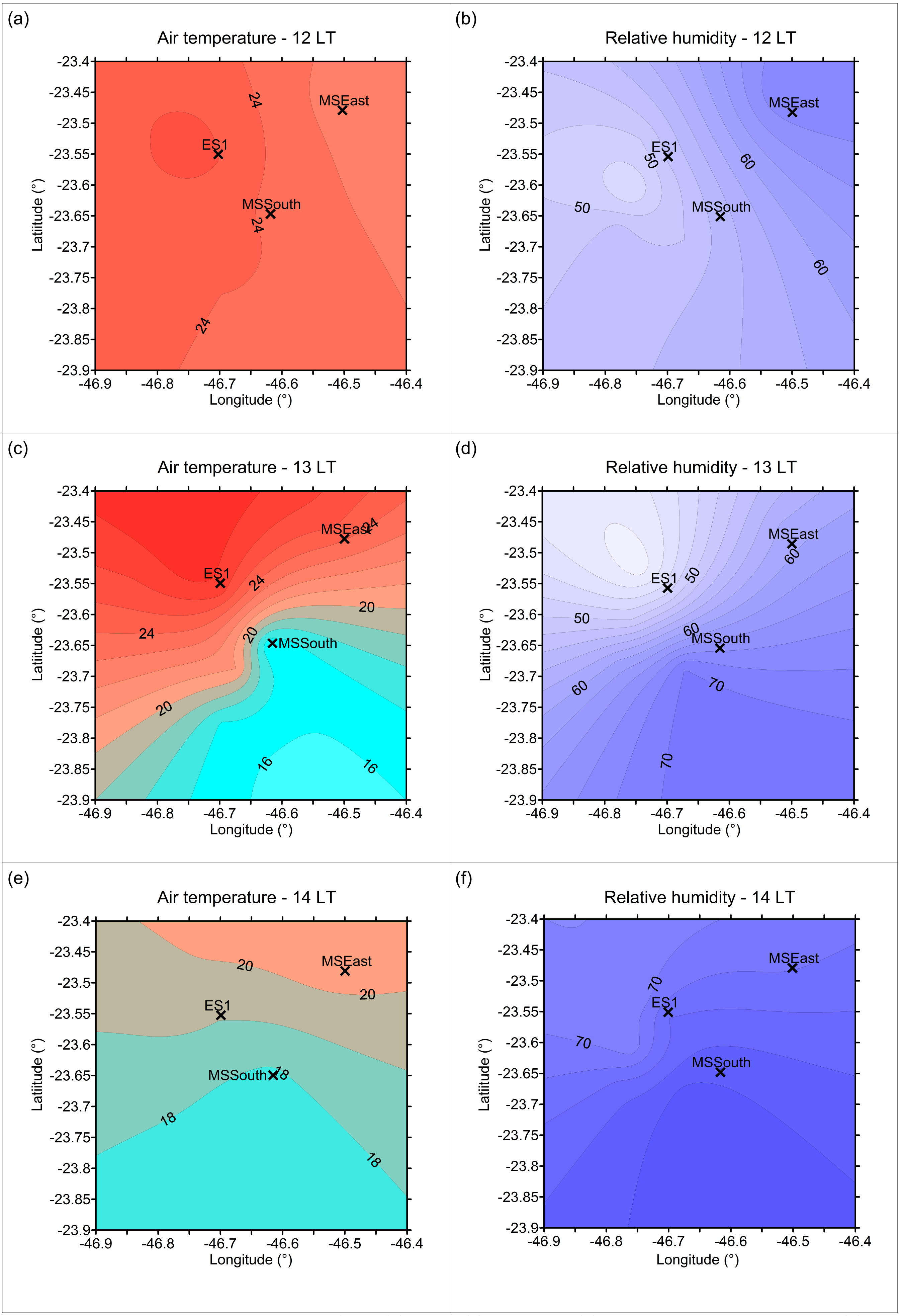

Figure 4: Air temperature over the MRSP at (a) 12 LT, (c) 13 LT, and (e) 14 LT and relative humidity at (b) 12 LT, (d) 13 LT, and (f) 14 LT.

Another example of a larger scale process influencing the UHI intensity is a heat wave that occurred over the MRSP during the austral summer of 2014. During this summer, a hot and dry air mass lingered over the MRSP, increasing the temperature and decreasing humidity and precipitation. Table 2 shows the averages of temperature difference for the austral summer months at daytime and nighttime between station ES1 and MSSouth and ES1 and MSEast, comparing the summer of 2014 and the average of the other years in each dataset. The summer of 2014 presented greater UHI intensity than the other years average (at least by a factor of 2), at daytime and nighttime. This result reinforces the idea that the UHI in the MRSP is highly correlated to the solar radiation.

	Period	Month	ΔT average (°C)	ΔT 2013/2014 (°C)
ES1 – MSEast	Daytime	December	0.05	0.89
ES1 – MSEast	Nighttime	December	0.80	1.73
ES1 – MSEast	Daytime	January	-0.02	0,96
ES1 – MSEast	Nighttime	January	0.65	1.98
ES1 – MSEast	Daytime	February	0.43	0.71
ES1 – MSEast	Nighttime	February	0.76	1.70
ES1 – MSSouth	Daytime	December	0.46	1.13
ES1 – MSSouth	Nighttime	December	0.81	2.32
ES1 – MSSouth	Daytime	January	0.15	0.88
ES1 – MSSouth	Nighttime	January	1.15	2.77
ES1 – MSSouth	Daytime	February	0.37	0.81
ES1 – MSSouth	Nighttime	February	1.38	2.86

Table 2: Temperature differences between urban (ES1) and suburban (MSEast and MSSouth) stations averaged from 2009(2004) to 2012/2013 and for 2013/2014 summer. Daytime corresponds from 0700 LT to 1800 LT and nighttime from 1900 LT to 0600 LT.

4. Conclusions

The UHI in the MRSP is complex, since the area is large and comprises different uses of the soil and the available observations are scarce. Nevertheless, the present work can point to some important characteristics:

1) presence of an Urban Cool Island during morning hours;
2) maximum intensity of the Urban Heat Island at late evening and early nighttime hours, agreeing with previous results (Ferreira et al., 2013);
3) larger averaged UHI intensity at nighttime, since the morning cool island compensates the evening heat island when averaging daytime hours;
4) sea breeze circulation influences the temperature differences within the MRSP;
5) the presence of a hot and dry air mass over the MRSP during the austral summer of 2014 increased the UHI intensity, suggesting that solar radiation is an important process in the modulation of the UHI intensity in the MRSP, as already discussed by other authors (Ferreira et al., 2011).

There still is much to investigate on the UHI in the MRSP, since measurements in the north and west peripheral parts of the metropolitan area are lacking. A numerical model with a proper representation of the urban surface and processes may help to further investigate this complex urban phenomenon.

Acknowledgment

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