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Bioclimatic characterisation of an urban area: a case study in Bologna (Italy)

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Abstract Summer bioclimatic discomfort is a significant public health problem. Bioclimatic characterisations of populations living in urban areas are usually very poor, although the risks are relatively higher in cities because of the phenomenon known as the “urban heat island”. We compared airport, rural, and urban bioclimatic conditions in terms of apparent temperature, Thom index, and temperature alone in several sites within a radius of approximately 25 km from the city of Bologna (Italy). The comparison between meteorological monitoring stations within and near the urban area showed the large impact of the urban heat island effect. Nighttime data showed the largest differences among the investigated sites. Minimum apparent temperatures at rural stations were about 3.5°C lower than the urban 30 m reference station, and 6°C lower than the 2 m urban site. The 2 m apparent temperature values within the urban area were several degrees higher (typically 2°C) than those taken above the roof, both for minimum and maximum values. Temporal trends in the different sites were highly correlated (generally above 0.90), but regression residuals were sometimes quite large. Finally, epidemiological implications are briefly addressed.

Keywords Summer bioclimatic discomfort · Discomfort indices · Apparent temperature · Thom index · Urban heat island

Introduction

Summer bioclimatic discomfort is a significant public health concern (Stafoggia et al. 2006; Medina-Ramon et al. 2006). Events such as those experienced during the summer of 2003 in southern and central Europe can lead to substantial emergency challenges for public health systems (Filleul et al. 2007), and they reveal the need for suitable warning and prevention systems. Furthermore, because of the predicted consequences of global warming and, in particular, the increased frequency, intensity, and duration of heat waves, heat-related diseases might assume a major role in the coming decades.

Health risks are higher for people living in urban environments (Kalkstein 1993), where anthropogenic emissions, coupled with the physical properties of materials used for building and street construction, give rise to the phenomenon known as the “urban heat island” (Landsberg 1981). Although this phenomenon is well known by meteorologists, urban meteorological monitoring has only recently gained attention in connection to the needs of both heat-related health risk studies and air quality modelling.

Urban meteorological monitoring is difficult to address due to the high spatial variability of meteorological parameters within urban environments and the consequent low spatial representativeness of measurements. In 2006, the World Meteorological Organization (WMO) published

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Table 1 Description of the measuring sites

	Silvani-roof	Silvani-street	Airport	Sant'Agata Bolognese	Zola Predosa	Sasso Marconi
Type of station (area)	Urban	Urban	Airport	Rural	Rural	Rural
Distance from the centre of the urban area of Bologna (km)	1	1	6	25	11	16
Altitude (m a.s.l.)	50	50	36	20	65	275
Measuring height above ground (m)	30	2	2	2	2	2

the *Initial guidance to obtain representative meteorological observations at urban sites* (WMO 2006), defining proper approaches for monitoring meteorological variables in urban environments. Current urban meteorological networks, however, very rarely follow WMO directives, and almost all epidemiological studies and heat warning systems use airport or rural meteorological data to characterise the exposure of populations living in town centres and neighbourhoods. This work aims to compare airport and rural data with different urban data by using different bioclimatic discomfort indicators. Special emphasis will be given to apparent temperature.

Materials and methods

We analysed urban bioclimatic conditions in terms of maximum, minimum, and mean daily values of apparent temperature (AT; Steadman 1979) and Thom index (TI; Thom and Bosen 1959). These indices are used frequently in epidemiological studies (AT: Smoyer et al. 2000; Stafoggia et al. 2006; TI: Zauli Sajani et al. 2002; Katsouyanni et al. 1993; Giles et al. 1990), and they combine the two main bioclimatic parameters, i.e. temperature and humidity. According to several epidemiological studies (Basu and Samet 2002a; Curriero et al. 2002; Hajat et al. 2005), simple temperature was also taken as a possible reference bioclimatic variable.

The study area was the urban district of Bologna, the main city of the Emilia-Romagna region of Italy. The city is located at the foot of the Apennines in the Po Plain, a vast flat area in the north of Italy. The urban population is about 420,000 persons, and the urban area covers about 60 km^2.

We used data from several monitoring stations located in different areas within a radius of approximately 25 km from the city centre. The data came from six stations (Table 1): one rural station located in the flat area north of the city (S. Agata Bolognese; 20 m a.s.l.), another station in the flat area but close to the hills (Zola Predosa; 65 m a.s.l.), one in the hills (Sasso Marconi; 275 m a.s.l.), another located within the airport compound, situated in a peripheral area (Borgo Panigale; 36 m a.s.l.), and one in the city centre on the flat roof of the Regional Meteorological Service building (Silvani-roof; 50+30 m a.s.l.). Figure 1 shows the geography of the Bologna region and the locations of the stations. All measurements were made at a height of 2 m except those from the Silvani-roof urban station, which is part of a regional network designed for urban meteorological monitoring. The network aims at characterising local climate attributable to each urban area, avoiding extraneous microclimatic influences, and, following WMO directives, it is located at about 30 m above ground level. Moreover, an additional thermo-hygrometer was deployed in the period 5 July 2006–5 September 2006 close to the Silvani-roof station, but at street level (Silvani-street, 2 m), to investigate bioclimatic conditions experienced by passers-by walking in the same area. Although the Silvani-street urban measuring site could not be considered strictly representative of the mean 2 m bioclimatic discomfort field within the urban area, it was chosen carefully so as to make it as representative as possible of street-level conditions.

For the purposes of this report, we restricted analysis of data from all stations to the 2-month period (5 July 2006–5 September 2006) of availability of the Silvani-street station data. The variability in the meteorological variables during the 2-month period was reasonably representative of the

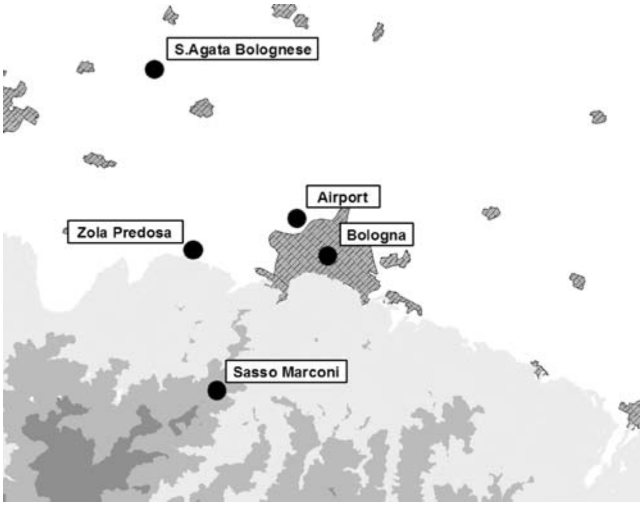


Fig. 1 Map of the spatial distribution of the meteorological stations considered in this study. Bologna lies at 44.51°N and 11.35°E. The map size is 60×40 km. The highest peaks of the portion of the Apennines shown in the bottom left corner of the domain reach about 900 m a.s.l

variability of a typical summer season. The mean value and standard deviation of temperature were 19.2 and 3.0 for the 2-month period and 22.2 and 4.0 for the period May–September 2004–2006, respectively.

Results

Figure 2 shows the typical daily trends of temperature, relative humidity, AT, and TI data at the selected monitoring stations during the 2-month period. Typical daily behaviours of other rural stations not shown in this study were very similar (differences in AT less than 1°C) to the S. Agata Bolognese rural station data. Table 2 summarises the statistics of the differences between maximum, mean, and minimum ATs recorded by all monitoring stations and the urban reference station Silvani-roof.

The largest differences among the measuring sites were found with respect to minimum values. Among the urban stations, the differences in AT between the Silvani-street and Silvani-roof stations were typically (i.e. with respect to median values) 2.8°C (range 1.5–5.5°C). The largest differences were found between the urban stations and rural stations in the flat area north of the city (in this paper, we show S. Agata Bolognese). The median values of the daily differences in minimum AT were about 3.5°C lower than the urban 30 m reference station, and 6°C lower than the 2 m urban station Silvani-street. The range of these differences was 0.1–8.1°C (Silvani-roof vs S.Agata Bolognese). Early morning data recorded by the monitoring stations located at the airport and in the hills (Sasso-Marconi) were typically very similar, showing values about 1°C lower than the Silvani-roof. The range of the differences between the Silvani-roof and the non-urban stations (including the airport station) was almost the same (about 7–8°C), with a slightly lower value for the hilly station Sasso Marconi. Rural/urban spatial trends with respect to humidity and temperature patterns were opposite to each other. Typical maxima of relative humidity (taking place mainly at night) ranged from 60% in the urban area up to

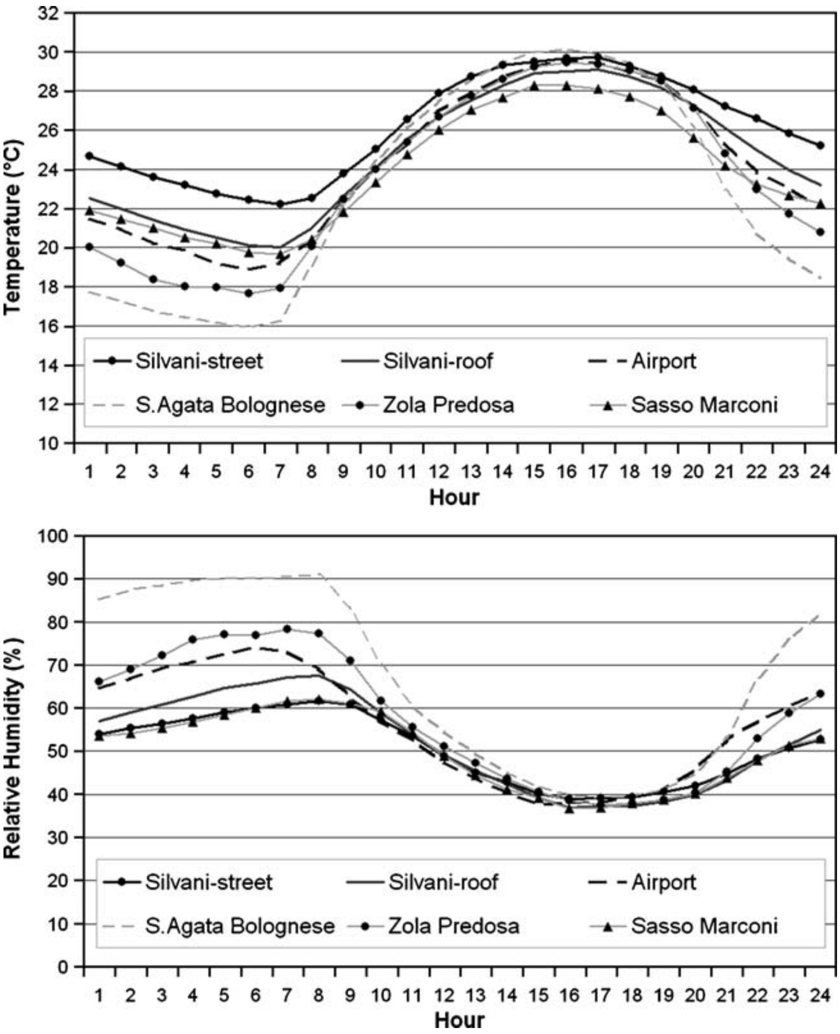
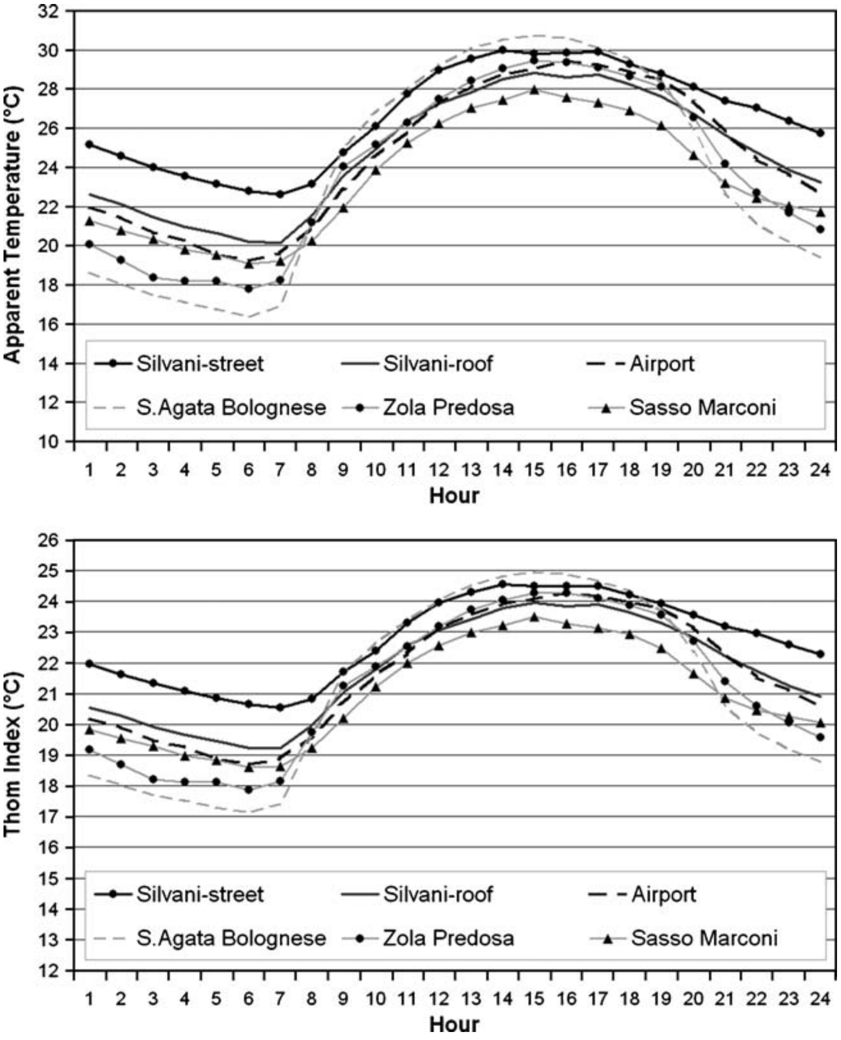


Fig. 2 Typical daily trends of temperature, relative humidity, apparent temperature (AT), and Thom's index (TI) at the measuring sites. Hours are in LMT (local mean time)

Fig. 2 (continued)



90% at rural stations. Spatial patterns for temperature were similar to those found for AT, with slightly smaller differences between urban and rural areas.

Daytime differences between stations were substantially smaller than nighttime differences. Daily maximum AT values were recorded not in the urban area but in the S. Agata Bolognese rural station (1.9°C higher than Silvani-roof and 0.9°C higher than Silvani-street). The rural hill station (Sasso Marconi) showed the lowest typical maximum ATs (0.8°C lower than Silvani-roof). The range of the differences between the urban and rural stations was 4–5°C. Relative humidity and temperature fields were also quite uniform. Typical minimum relative humidity levels (mostly during early afternoon) were around 35% for almost all stations, leading to temperature differences between urban and rural data nearly equal with respect to temperature and AT.

Daily mean ATs were quite uniform among the stations. Only the Silvani-street 2 m urban station showed substantially higher values then the others (2°C higher than the 30 m roof station). Data dispersion statistics were also the smallest, with a range of differences of about 3–4°C.

A regression analysis was carried out to investigate the strength of the relationships between the temporal trends of measurements from different measuring sites. Table 3 summarises the results of the linear regression analysis. Linear determination coefficients (R^2) calculated between the Silvani-roof and the non-urban stations ranged from 0.80 to 0.90 with respect to minimum values, from 0.95 to 0.99 for mean values, and from 0.93 to 0.97 for maximum values. R^2 values obtained between the Silvani-roof and Silvani-street data were 0.96, 0.98, and 0.94 with respect to minimum, mean, and maximum AT, respectively. The highest R^2 values were obtained for mean AT, followed by maximum and minimum.

The standard deviation of the residuals were from 0.42 to 0.82°C for mean AT, from 0.62 to 1.04°C for maximum AT, and from 0.72 to 1.59°C for minimum AT.

The ranges of the residuals of the regression between the Silvani-roof and rural stations were about 6–7°C for

Table 2 Distribution of the daily differences in apparent temperature (AT) between the different measuring sites and the urban reference station (Silvani-roof)

Variable [a]	Percentiles	Silvani-street	Airport	Sant'Agata Bolognese	Zola Predosa	Sasso Marconi
AT_{min}	Min	1.5	-4.8	-8.1	-7.1	-4.1
	5° perc	1.7	-2.6	-6.7	-5.4	-2.8
	25° perc	2.4	-1.2	-5.3	-3.9	-1.9
	50° perc	2.8	-0.7	-4.1	-2.9	-1.2
	75° perc	3.3	-0.3	-2.4	-2.0	-0.2
	95° perc	3.7	0.8	-0.7	-0.9	1.1
	Max	5.5	2.7	-0.1	1.2	1.6
AT_{mean}	Min	0.7	-1.3	-2.7	-2.3	-2.1
	5° perc	1.0	-0.6	-2.4	-1.7	-2.0
	25° perc	1.5	-0.4	-1.6	-1.2	-1.7
	50° perc	2.0	-0.1	-0.8	-0.9	-1.5
	75° perc	2.2	0.1	-0.3	-0.5	-1.0
	95° perc	2.5	0.4	0.3	-0.1	-0.3
	Max	2.6	1.8	1.4	1.3	0.1
AT_{max}	Min	-1.8	-2.0	-1.5	-0.9	-2.4
	5° perc	-1.1	-0.6	0.2	-0.4	-2.3
	25° perc	0.2	0.0	1.3	0.3	-1.2
	50° perc	1.0	0.5	1.9	0.5	-0.8
	75° perc	1.5	0.9	2.6	0.9	-0.4
	95° perc	2.0	1.7	3.7	1.1	0.6
	Max	3.7	2.6	4.3	3.5	2.0

[a] AT_{min} minimum apparent temperature, AT_{mean} mean apparent temperature, AT_{max} maximum apparent temperature

minimum AT, 4–5°C for maximum AT, and 3–4°C for mean AT. The ranges of the residuals between Silvani-roof and Silvani-street were 4.1, 5.5, and 1.92, respectively.

The results of the analyses in terms of TI and temperature alone were very similar (not shown) to those found for AT.

Discussion

The comparison between the meteorological monitoring stations inside and around the city of Bologna revealed the large impact of the urban heat island effect. Statistical analyses were carried out according to different daily

Table 3 Results of the linear regression analysis between AT recorded at Silvani-roof and at other stations

Variable [a]	Silvani-roof vs	Slope (Inf 95%; Sup 95%)	Intercept (Inf 95%; Sup 95%)	R2	SD residuals	Percentiles			
						Min	5°	95°	Max
AT_{min}	Silvani-street	0.97 (0.92;1.02)	−2.17 (−3.35;1.00)	0.96	0.72	−2.78	−0.9	1.07	1.33
	Airport	0.92 (0.84;1.00)	2.23 (0.73;3.74)	0.90	1.12	−3.69	−1.69	1.7	3.88
	Sant'Agata Bolognese	0.76 (0.66;0.85)	7.71 (6.15;9.27)	0.80	1.59	−4.35	−3.01	2.63	2.92
	Zola Predosa	0.85 (0.75;0.95)	5.46 (3.83;7.10)	0.84	1.44	−4.48	−2.06	2.29	3.84
	Sasso Marconi	0.98 (0.88;1.07)	1.55 (−0.26;3.37)	0.87	1.28	−2.74	−2.2	1.76	3.07
AT_{mean}	Silvani-street	0.97 (0.94;1.01)	−1.14 (−2.04;−0.24)	0.98	0.46	−0.76	−0.62	0.8	1.16
	Airport	0.98 (0.95;1.01)	0.69 (−0.05;1.43)	0.99	0.42	−1.97	−0.58	0.41	1.25
	Sant'Agata Bolognese	0.91 (0.86;0.97)	2.98 (1.64;4.32)	0.95	0.82	−2.48	−1.07	1.25	1.68
	Zola Predosa	0.97 (0.93;1.01)	1.66 (0.71;2.60)	0.98	0.55	−2.24	−0.66	0.79	1.28
	Sasso Marconi	0.98 (0.94;1.02)	1.83 (0.93;2.72)	0.98	0.53	−1.28	−1.11	0.63	0.85
AT_{max}	Silvani-street	0.93 (0.87;1.00)	1.29 (−0.73;3.31)	0.94	1.00	−2.9	−1.52	1.77	2.61
	Airport	0.96 (0.91;1.00)	0.82 (−0.60;2.25)	0.97	0.73	−2.29	−1.08	1.08	2.21
	Sant'Agata Bolognese	0.92 (0.86;0.99)	0.60 (−1.49;2.68)	0.93	1.04	−2.65	−1.61	1.48	3.17
	Zola Predosa	1.00 (0.96;1.04)	−0.61 (−1.87;0.66)	0.97	0.62	−2.95	−0.56	0.94	1.45
	Sasso Marconi	1.02 (0.97;1.08)	0.10 (−1.53;1.72)	0.96	0.81	−2.7	−1.25	1.5	1.73

bioclimatic indexes (AT, TI, and temperature alone) and different daily statistics (maximum, minimum, and mean daily values). No substantial differences were found for the different bioclimatic indices. In contrast, the results with respect to the different daily indicators were quite different.

According to similar studies conducted in the United States (Basu and Samet 2002b) and Italy (de'Donato et al. 2008), major differences between urban and rural areas were measured during the night. The differences in AT values between the above-roof station (Silvani-roof) and the rural stations located in the flat area north of the city (in the paper, we showed S. Agata Bolognese as a reference) were typically (median value) about 4°C, with values up to 8°C. Smaller but substantial differences were found for the rural station close to the hills west of the city centre. Unexpected results emerged from the analyses of data from the hilly station (Sasso Marconi), where nocturnal values of the bioclimatic indices were very close to those typical of the urban area. This is at odds with the common perception that hills have better bioclimatic conditions. One possible explanation for this apparent inconsistency is that the bioclimatic discomfort indices used in this work did not take into account the wind, likely leading to an overestimation of bioclimatic discomfort in a hilly setting. Bioclimatic conditions measured by means of a station placed within the airport compound, often used in epidemiological studies to characterise population exposure of nearby urban areas (Basu and Samet 2002b; Stafoggia et al. 2006; Medina-Ramon et al. 2006; Curriero et al. 2002), showed small differences compared to urban conditions. It is important to point out, however, that Bologna's airport is very close to the city centre, whereas airports are generally far away from urban centres (de'Donato et al. 2008).

The analysis also addressed the issue of how bioclimatic conditions evaluated at 30 m above the typical roof relate to the 2 m bioclimatic conditions. Both approaches are suggested by the WMO (2006). In particular, the former approach consists of placing sensors on a tall mast in the roughness sublayer (RSL) above the main building height (such as at the Silvani-roof station) to monitor a blended, spatially averaged signal that is representative of the local scale. The latter approach consists of locating the site in the urban canopy layer (UCL), i.e. at a 2 m location representing "typical" 2 m conditions within the urban area. Even if, as stated by WMO, some subjectivity is unavoidable in choosing a location within an urban area, and, even if urban spatial variability of meteorological variables is almost irresolvable in detail, we believe that the Silvani-street temporary monitoring site could be considered reasonably typical. Spatial surveys, however, could be very useful in characterising districts and in defining more objectively mean urban bioclimatic conditions. In our study, we found that the 30 m above street level urban station usually under-estimated the urban heat island effect. In fact, 2 m AT values within the urban area were several degrees higher (typically 2°C) than those taken above the roof, both for minimum and maximum values. Ranges of the differences in minimum, mean, and maximum AT were quite large: 1.5–5.5, 0.7–2.6, and −1.8–3.7, respectively. Thus, to accurately define the peculiar behaviour of summer urban meteorology and to improve heat warning systems, the best choice would be to set up station(s) at both above-roof and street-level.

We analysed the correlation level among the stations to evaluate the size of errors in estimating urban bioclimatic conditions by means of non-urban stations, and the strength of the relation between the 30 m and 2 m temporal trends of bioclimatic indexes within urban areas. Generally speaking, the results showed that, even if correlation levels are high and residuals typically small, the ranges of the residuals were quite broad.

The epidemiological implications of the analysis of differences between urban and non-urban stations could be of some relevance. The first point to highlight is that health effects of bioclimatic discomfort are of a threshold-like type (Kalkstein 1993). Thus, if non-urban stations are used to characterise urban bioclimatic conditions, the analysis of threshold values could be heavily affected by errors, in particular if minimum values, related to the important nocturnal physical recovery (Johnson and Proppe 1996), are chosen as the daily discomfort indicator. These errors are of two types. First, there is a bias effect related to systematic differences in bioclimatic conditions assigned to a population due to the typical differences in bioclimatic conditions in urban and non-urban areas. This effect is especially important in multi-city studies, where fictitious differences among cities in thresholds and risk evaluations could emerge due to such systematic errors. The second type of error is related to the non-perfect correlation between temporal trends in urban and non-urban sites that makes identifying thresholds and risk functions more difficult by adding noise to the relationship between risk factors and health variables. A proportion of the geographical heterogeneity (de' Donato et al. 2008; Michelozzi et al. 2006) found in some epidemiological studies of bioclimatic discomfort is possibly linked to the unsatisfactory bioclimatic characterisation of the populations under study.

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