CITY WEATHERS: METEOROLOGY AND URBAN DESIGN 1950-2010

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EXPLORING THE URBAN HEAT ISLAND INTENSITY OF DUTCH CITIES

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Abstract

In the present study, an up-to-date assessment of the magnitude of the current UHI-intensity in urban areas in the Netherlands has been made. The underlying question is whether or not thermal comfort will be a critical issue considering urbanization and climate change in the next decades. This assessment is based on results from meteorological observations reported in the literature, recent meteorological observations in the urban canopy in Rotterdam and Arnhem, and datasets provided by hobby meteorologists.

Preliminary measurement results, as well as weather amateur observations, show a large consistency. All point to the existence of a considerable UHI_{max} in densely built areas in the Netherlands under favorable meteorological conditions, i.e. under calm and clear (cloudless) conditions, with 95 percentile values ranging from 3 to 10 K. The assessed UHI_{max} values for Dutch urban areas, are of the same order of magnitude as those reported for other cities in Europe. However, no clear effect of city size, defined as the logarithmic value of the number of inhabitants, on UHI intensity could be assessed suggesting that other factors such as population density and/or city district or neighbourhood characteristics may be more important in determining the magnitude of the UHI intensity. Our results indicate that considering future developments in climate and urbanization, thermal comfort and heat stress will likely become a critical issue in many urban areas in the Netherlands.

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1. Introduction

In contrast to many countries in the world, where urban meteorology has been studied for more than 3 decades (Arnfield, 2003), urban meteorology was not an issue in the Netherlands until recently. The Urban Heat Island (UHI) was considered to be relatively unimportant for the Netherlands because of its mild climate and its location close to the sea. Moreover, a large part of the Netherlands is located below sea level, and water levels are artificially maintained at a high level. Dutch cities are known for their high density and one can expect that this special feature will influence the UHI, which might be different from other European cities. This view altered after the heat waves in 2003 and 2006 causing an excess mortality between 1400 and 2200 (Haines et al., 2006). These numbers are relatively high as compared to those reported for other European countries (EEA, 2008). Particularly in the cities excess mortality rates were high which made many people realize that the projected future climate change, with an increase in the frequency of hot summer days, may also have an impact on the liveability of Dutch cities.

The Netherlands and especially the western part, is heavily populated with 398 to 918 inhabitants per km^2, and is ranked 27 out of 236 countries. Urbanization, particularly in the western part of the country, will continue in the next decades. Future projections show a large expansion of the urban landscape of up to 20% (Nijs et al. 2002; MNP, 2002). The projected trends in urbanization and future climate projections may have large consequences for thermal comfort and human health. Hence, there is now a sense of urgency to implement adaptation measures in order to reduce the vulnerability of cities to climate change.

However, with the exception of a study carried out in 1969-1970 on the UHI effect of Utrecht (Conrads, 1975) and a recent study to assess the long term validity of KNMI temperature time series (Brandsma et al. 2003), no systematic meteorological data records for Dutch towns and cities are available.

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Within the Dutch Climate *changes* Spatial Planning Programme and the Knowledge for Climate Research Programme, a start was made with data gathering and exploration of these to estimate urban meteorology and climatology in the Netherlands (Van Hove et al, 2010, 2011). An up-to-date assessment of the magnitude of the current UHI-intensity in urban areas in the Netherlands has been made. The underlying question is whether thermal comfort already is or will become a critical issue in the next decades. The assessment was based on results from meteorological observations reported in the literature with particular focus on assessed relationships between maximum nocturnal UHI intensity (UHI_{max}) and city features, such as city size and urban configuration and structure. Also results from recent meteorological observations in the urban canopy in Rotterdam and Arnhem have been used. Furthermore, historical datasets for 19 towns and cities provided by hobby meteorologists have been analyzed to obtain a more nationwide coverage. The results of these pilot studies resulted also into the initiation of the Dutch national research programme 'Climate-Proof Cities'' (Theme 4, KfC, 2010-2014), which main aim is to develop effective adaptation strategies and measures to mitigate future climate impacts on the urban environment.

2. Urban Heat Island Intensity

Mobile traverse measurements in the city of Rotterdam and Arnhem

The UHI intensity of Rotterdam was mapped for the first time on 6 August 2009. Maximum and minimum air temperature at that day, measured at Rotterdam airport, were 29.7 and 16 °C respectively. The measurements were performed using two cargo bicycles as a mobile platform, equipped specifically for urban meteorological measurements (Heusinkveld et al. 2010).

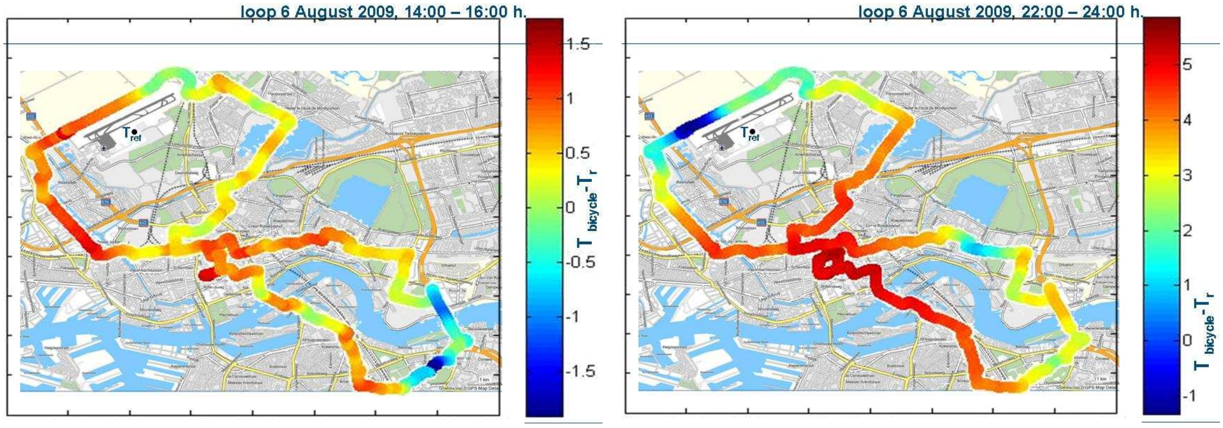

Fig.1 North and south loop of the mobile traverse measurements in Rotterdam on 6 August 2009. Air temperature differences between cargo bike and reference station (Rotterdam airport) at 14-16 (left panel) and 22-24 CET (right panel). Note the differences in scale.

In the early afternoon (14-16 CET), relatively small temperature differences were measured with the cargo bikes. Air temperatures in the densely built areas were 1-2 K higher than the temperatures measured at Rotterdam airport, whereas lower air temperatures (1– 2 K) were measured in the city park along the route (Fig. 1, lef panel). In contrast, large differences were measured during the late evening (22-24 CET, Fig. 1 right panel). The air temperature of the city centre was about 5 K higher than Rotterdam airport (21 ℃) and the difference between the city and the surrounding countryside amounted to more than 7 K during nocturnal hours. These preliminary results clearly demonstrate the existence of a considerable UHI in the city centre and other densely built areas in Rotterdam.

Also mobile traverse measurements have been carried out for the city of Arnhem (146,000 inhabitants) which is located more inland. The measurements were carried out as part of the Future Cities project (EU Interreg IVb). Air temperatures measured during the afternoon (14-16 LT) varied from 27.5 to 30.5 at the measuring day (19 August 2009). Also these measurements show a large nocturnal temperature difference (~7 K) between the city centre and the rural area because of a much slower cooling down of the city centre.

Long-term measurements in the city of Rotterdam

Since September 2009 a small measuring network consisting of three Automatic Weather Stations (AWS) is operational in the city of Rotterdam. The stations, labelled as Rotterdam-Centre, –East and –South, represent the densely built commercial area, the relatively green suburban living neighbourhood and the densely built up living neighbourhood respectively. The measurement results of these stations are compared with those of a reference AWS located in the rural area, north of Rotterdam (….).

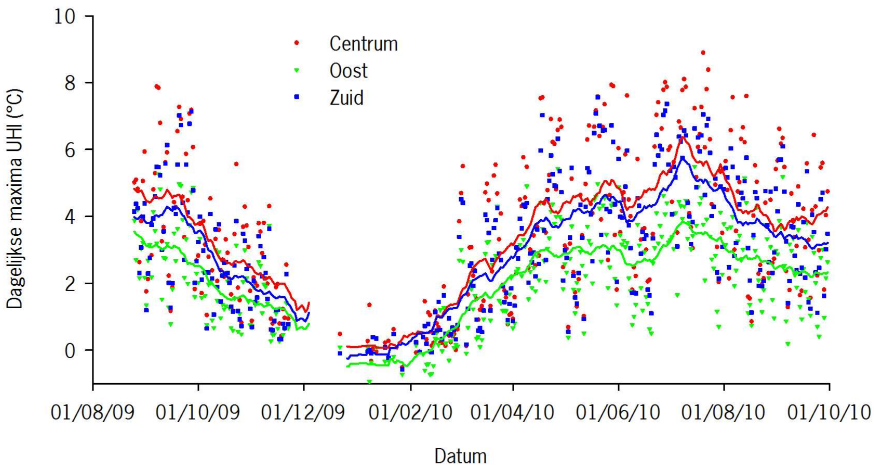

Fig. 2. : Maximum daily UHI intensity in K for the monitoring locations Centre, East and South during the period September 2009 to October 2010.

Figure 2 shows the variation in UHI intensity for the 3 monitoring locations in Rotterdam determined for the period September 2009 to October 2010. Plotted are the values for the maximum UHI intensity during a 24h period (UHI_{max},). The highest UHI intensities were found during the summer months (JJA) whereas a small or no effect was found during the winter months (DJF).

The maximum UHI intensity (UHI_{max}) is reached during the evening hours, and a minimum or sometimes even negative difference is observed after sunrise. A typical diurnal pattern can be observed: after sunset UHI intensity strongly increases, remains more or less constant during about 8 hours, followed by a strong decrease around sunset.

From all determined half-hourly values of UHI intensity for the summer period, the median and 95 percentile values were calculated. The same was done for the determined UHI_{max} values. Table 1 shows that temperature differences between the urban and rural area are substantial. The location City Centre shows the largest UHI intensity followed by the locations South and East Rotterdam, respectively.

Table 1. Median and 95 percentile values (95P) for half -hourly mean values of UHI intensity and for UHI_{max} values for the summer of 2010 (JJA), for the monitoring locations Rotterdam City centre, East and South

Locatie	coordinates	UCZ[2]	UHI		UHI_{max}[1]	
			median	95P	median	95P
City centre	51°55'24.18"N 4°28'10.35"O	1	1.4	5.9	4.7	7.9
East	51°53'16.59"N 4°29'17.83"O	2	0.6	3.2	3.2	4.8
South	51°55'31.41"N 4°32'54.13"O	3	1.3	5.1	4.5	6.9

[1]: one value per day (N=93); [2]: Urban Climate Zone classification of Oke (2006)

Meteorological observations from hobby meteorologists

In order to obtain a more nationwide coverage, the possibility was examined to make use of the frequent observations of hobby meteorologists. The meteorological observations for 19 urban sites in the Netherlands have been collected, including air temperature and humidity, wind speed, and for some stations also incoming solar radiation (Steeneveld et al. 2010). The selection of the stations was based on the available record length, quality of the dataset, site characteristics and used instrumentation. Also the city size have been taken into account, since we intend to cover the range of large cities (10^6 inhabitants) to small villages (10^3 inhabitants). Fig. 3. shows the geographical locations of the urban weather stations. The selected stations cover the northern part of the country rather well, but long-term observations are lacking in the south. On the other hand the majority of the largest cities in the western part, i.e. Rotterdam, Delft, The Hague (and its suburbs), Leiden, Haarlem have been included. In order to detect the UHI, each urban station has been coupled to meteorological observations at the closest KNMI (Royal Netherlands Meteorological Institute) rural station. The UHI has been determined as the city air temperature minus the rural air temperature at screen level, and has been recorded based on hourly data.

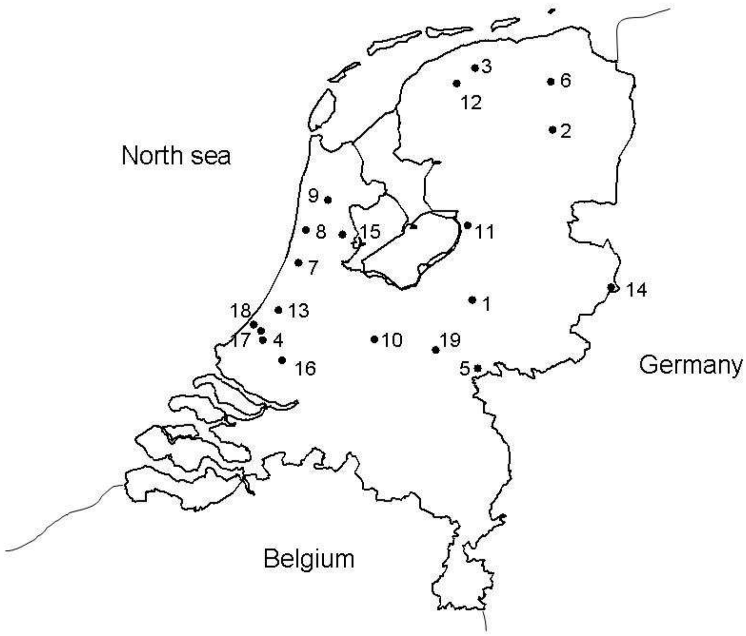

Fig. 3. Locations of the urban weather stations

Table 3 shows the median values and the 95 percentile UHI_{max} values. Large values are obtained for Rotterdam which is in agreement with our own measurement results.

However, it should be noted that also for a small, more inland located settlement as Losser, relatively large median and 95P UHI_{max} values are obtained.

Conversely, relatively small UHI intensities are found for Groningen, Assen, Damwoude and Leeuwarden. These cities are located in the North of the country and relative close to the sea.

Most urban weather stations are located outside the city centres and table 3 shows that the source area of 15 out of 19 stations can be classified as UCZ ≥3 (Oke, 2006). This would imply that the reported air temperatures by the hobby meteorologists are lower than can be found in more densely developed city centres with UCZ classification of 1-2.

Table 3. Median and 95 percentile (95P) values for the maximum urban heat island intensity (UHI_{max}) in a diurnal cycle.

	City	**Number of inhabitants (x1000)**	**UCZ[1]**	**UHI_{max}**	
				median	**95P**
1	Apeldoorn	160	5	2.9	6.2
2	Assen	65	3	1.8	4.0
3	Damwoude	5.5	5-7	1.3	3.2
4	Delft	97	2-3	1.7	4.8
5	Doornenburg	2.7	5	2.6	5.7
6	Groningen	198	3	1.5	3.1
7	Haarlem	149	3	2.5	5.7
8	Heemskerk	39	3	2.8	5.9
9	Heerhugowaard	50	3-5	2.4	6.2
10	Houten	47	3	1.2	3.0
11	Ijsselmuiden	12	3	3.1	6.8
12	Leeuwarden	94	3-5	1.1	3.0
13	Leiden	117	3	3.2	5.6
14	Losser	23	3-5	2.9	6.8
15	Purmerend	79	3	2.5	4.6
16	Rotterdam	588	2-3	3.4	7.6
17	The Hague	483	3-5	2.2	5.3
18	Voorburg	40	2	2.4	5.6
19	Wageningen	35	3-5	2.4	5.6

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Comparison between Dutch cities and other European cities

In figure 4, the UHI_{max} values reported in the literature for European cities and those found in the present study for Dutch cities have been plotted against the logarithm of population (log(P)). It can be concluded that the UHI_{max} values assessed for Dutch cities

are substantial and of the same order of magnitude as those found for other European cities.

However, no significant relationship between UHI_{max} and log(P) could be assessed suggesting that other factors such as population density and and/or city district or neighbourhood characteristics may be more important in determining the magnitude of the UHI intensity.

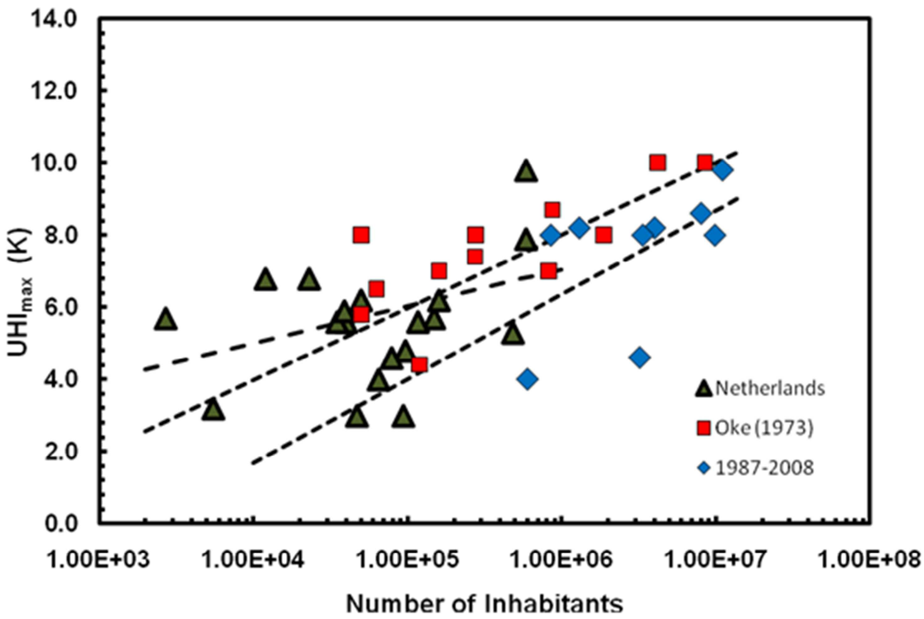

Fig.4. UHI_{max} (95 percentile values, in K) for Dutch cities compared with UHI_{max} values reported for European cities. Dashed lines are the linear regression lines calculated for the results of Oke (1973), for literature results 1987-2006 respectively, and for Dutch cities (Table 4).

3. Thermal comfort

From the meteorological observations of the hobby meteorologists, the Wet Bulb Globe Temperature (WBGT) index was calculated. This is an empirical derived index that is being used to describe thermal comfort. Because the black globe temperature is not measured by hobby meteorologists, an approximation has been used instead (BOM, 2008; Steeneveld et al., 2010). General threshold values for WBGT are not available, but largely depend on a person's activities or work load. For the general public, a WBGT value of 27.7 represents a threshold value above which most people start feeling discomfort. Physical training is not advised for WBGT > 29.4 and WBGT > 31 usually results in cancellation of sport events (Sobane, 2008).

Table 4. Median, 95 and 98 percentile values for the
Wet Bulb Globe Temperature (WBGT) as an indicator of heat stress.
Bold: exceedance of the threshold WBGT values of 27.7 ℃.

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	City	#inhabitants (x1000)	UCZ	WBGT		
				median	95P	98P
1	Apeldoorn	136	5	14.5	24.5	25.1
2	Assen	65	3	15.8	25.0	26.4
3	Damwoude	5.5	5-7	16.0	25.2	26.9
4	Delft	97	2-3	16.6	25.2	27.5
5	Doornenburg	2.7	5	10.5	14.3	15.2
6	Groningen	198	3	16.2	26.4	**28.7**
7	Haarlem	149	3	-	-	-
8	Heemskerk	39	3	13.7	21.3	24.1
9	Heerhugowaard	50	3-5	16.6	25.6	**27.8**
10	Houten	47	3	12.8	20.8	23.0
11	Ijsselmuiden	12	3	16.6	25.4	**27.8**
12	Leeuwarden	94	3-5	15.8	24.1	26.0
13	Leiden	117	3	18.5	26.6	**28.2**
14	Losser	23	3-5	16.3	26.2	**28.0**
15	Purmerend	79	3	14.0	23.2	24.8
16	Rotterdam	588	2-3	15.1	29.7	**32.3**
17	The Hague	483	3-5	16.0	25.3	26.9
18	Voorburg	40	2	17.5	25.8	**28.5**
19	Wageningen	35	3-5	17.6	25.6	27.6

Relatively low median values – far below the afore mentioned threshold values - for all cities are found. However, the 95 and 98 percentile values are close to the threshold values. The 95 percentile value of Rotterdam is above the threshold value and its 98 percentile value is even above the upper limit for event cancellation. In addition, in 7 of the 18 cities the threshold for heat stress onset is exceeded for the 98 percentile. In other words: 39% of the cities under investigation experiences heat stress for 7 days a year.

From the results of the mobile traverse measurements in Rotterdam, the Physiological Equivalent Temperature (PET) was calculated. This is a more sophisticated bio-meteorological index, based upon a model for the human heat balance that uses all relevant meteorological parameters, as well as physiological factors as input (Fanger, 1970, Höppe 1999). The calculations were made with the Raymann model (Matzarakis et al., 2007). Fig. 5 shows that large spatial differences in PET for the hot afternoon varying from 45-50 °C, i.e. strong and extreme heat stress, to 30-35°C, i.e. moderate heat stress. The highest PET values have been found for the urban area south of the river, in some parts of the city centre, and in the industrial area at the north-west. However, also the rural area north of Rotterdam shows high PET values. After sunset, the highest values, varying from 23 to 27 °C, hav e been found for the city centre and adjacent neighbourhoods (Fig. 5 right panel). These values are exceeding the threshold value for light heat stress. The neighbourhood with the lowest PET values during both daytime and nocturnal hours appears to be an urban configuration with low buildings and extensive green spaces.

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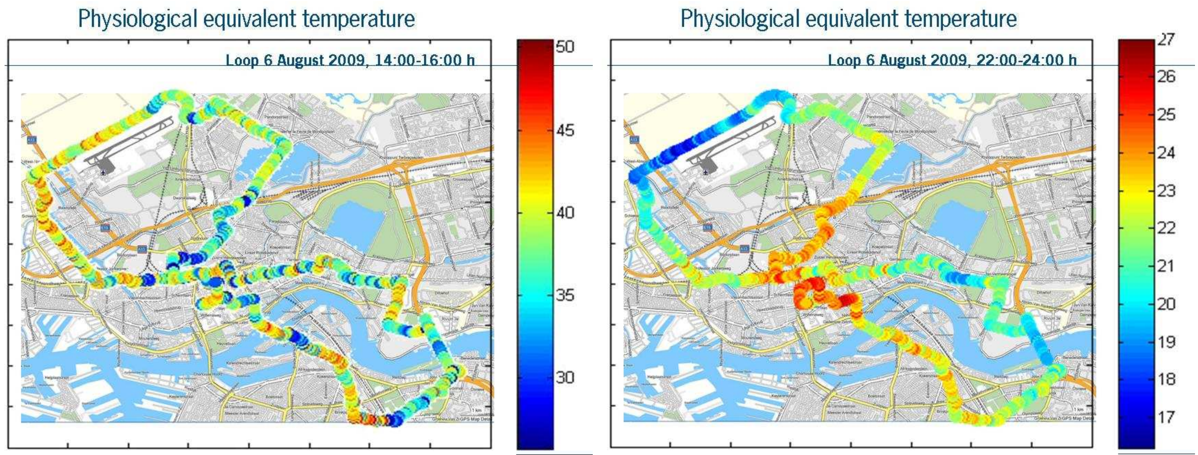

Fig. 5. Physiologically Equivalent Temperatures at 14-16 (left panel) and 22-24 CET (right panel) calculated from the results of the mobile traverse measurements. Note the differences in scales.

PET values have also been calculated from the results of the long-term measurements in Rotterdam. Table 5 clearly shows that the number of hours with thermal discomfort is significantly larger at the urban sites as compared to the rural reference site. The densely built locations Centre and South, in turn, show higher number of days with heat stress than the moderate densely built neighbourhood where the monitoring site East is situated.

Table 5. The number of hours with light, moderate, strong or extreme heat stress assessed for the urban monitoring sites in Rotterdam (Centre, East, South) and for the reference rural site, north of Rotterdam for the period 15 April – 30 September 2010 (total 4032 hrs)

PET (˚C)	Physiological heat stress	Centre	East	South	Reference
23-29	Light heat stress	302	197	224	63
29-35	Moderate heat stress	79	62	67	11
35-41	Strong heat stress	16	12	12	0
>41	Extreme heat	0	0	0	0

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	stress				

4. Conclusions

The measurements in Rotterdam and Arnhem show a large consistency with the observations of the hobby meteorologists. All point to the existence of a considerable UHI-max in densely built areas in the Netherlands under favorable meteorological conditions, i.e. under calm and clear (cloudless) conditions, with 95 percentile values ranging from 3 to 10 K. The UHI-max values in Dutch urban areas, are comparable with those found for other cities in Europe. However, no clear effect of city size, defined as the logarithmic value of the number of inhabitants, on UHI intensity could be assessed suggesting that other factors such as population density and/or city district or neighborhood characteristics may be more important in determining the magnitude of the UHI intensity. Considering future developments in climate and urbanization, thermal comfort and heat stress will likely become a critical issue in many urban areas in the Netherlands.

5. References