QUANTIFYING THE URBAN HEAT ISLAND EFFECT IN THE NETHERLANDS BY EXPLORING OBSERVATIONS FROM HOBBY METEOROLOGISTS

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1. INTRODUCTION & BACKGROUND

Urban areas experience a substantially different meteorology than their rural counterparts. Physical properties of cities and buildings result in a modified surface radiation and energy budget.

First, building clusters interact with solar radiation such that multiple reflections between buildings and roads occur before the solar radiation is reflected to space. Therefore, cities have a smaller albedo than crops or grasses. In addition, buildings limit the sky view of the surface and therefore emission of thermal radiation to space is limited. It is evident that the aspect ratio of building height to road width is a governing parameter (Toudert and Mayer, 2006; Kanda, 2007). Also, building configurations provide additional friction to the flow, which impact wind speed in the cities, but also downstream of cities. Finally, anthropogenic activities result in a significant, but currently poorly quantified, heat emission (Souch and Grimmond, 2006).

Altogether, these properties result in the formation of a so-called urban boundary layer. Especially the daytime heat storage in buildings and the heat release after sunset results an urban heat island effect (UHI): the city temperature is higher than in the rural neighborhood.

During warm summer periods, the special meteorological properties are of major impact for vulnerable groups, e.g. the elderly, young children, people with cardiovascular diseases. On time warning of these groups could limit adverse affects and improve their comfort.

The aim of this study is to quantify the UHI in the Netherlands based on observations by a network of hobby meteorologists. There are several motivations to study urban meteorology for Dutch cities. First, until recently the UHI was found to be relatively unimportant for Dutch conditions since the Netherlands are located in the mild Cfb climate, and is located close to the sea. Hence information regarding the Dutch UHI is completely lacking, both from observational and model perspective. Second, 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 of canals (Fig. 1), and one can expect that this special feature will influence the UHI, which might differ from other (European) cities. Finally, the Netherlands, and especially the western part, is densely populated with 398 and 918 inhabitants per km^2 respectively, and is ranked 27 out of 236 countries.

One expects that the projected future climate change will also affect livability, and heat stress in particular, in Dutch cities and that adaptation and mitigation measures are required to minimize the adverse effects. Such measures can range from modification of city structure, building material, introduction of vegetation (on roofs) in cities. Before starting these activities, the quantification of a baseline for UHI and heat stress is required.

Fig. 1: Dutch cities, e.g. Delft (photo), are characterized by canals and high water availability.

2. MATERIAL AND METHODS

Since urban meteorology was not given substantial attention during the last decade, observations are scarce (Floor, 1970; Conrads, 1975). Also, the nature of the city inhibits instrumentation setup following the WMO guidelines for rural terrain. It is only since very recent that the WMO provided guidelines for observation in urban areas.

The arguments above motivate us to use observations by hobby meteorologists in the Netherlands (see Table 1 and Fig. 2). These stations have been selected based on the available record

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length and on city size, i.e. we intend to cover the range of large cities (10^6 inhabitants) to small villages (10^3 inhabitants). Most instruments are located in gardens and are well ventilated and shielded. Also, the urban cover ranges 35-90%.

Our observations 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.

Our analysis focuses on the determination of the largest UHI effect during a diurnal cycle (UHI_{max}), and the statistical distribution of this maximum daily UHI value. In order to detect the UHI, each urban station has been coupled to meteorological observations at the closest KNMI (Dutch weather service) rural station (Table 1). 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. Apart from climatological information, we also aim to quantify the differences between cities by quantifying the sensitivity of the recorded UHI to wind speed and recorded solar radiation S. Hence, for each city we calculate $dUHI_{max}/dS$. A similar exercise is performed to quantify the sensitivity to wind speed U. Physical intuition suggests an inverse relation between UHI_{max} and U, e.g. $UHI_{max} \sim \exp(b*U)$. For each city we quantify coefficient b.

Finally, also the heat stress in urban neighborhoods has been estimated using the wet bulb globe temperature (WBGT) as heat stress indicator:

$$\text{WBGT} = 0.7 \bullet T_w + 0.2 \bullet T_g + 0.1 \bullet T_a \qquad (1)$$

Because the black globe temperature (T_g) is missing, we need to approximate WBGT by (BOM, 2008):

$$\text{WBGT} = 0.567 \bullet T_a + 0.393 \bullet e + 3.94, \qquad (2)$$

with T_a the air temperature, e the water vapor pressure (hPa). Note effects of wind and direct solar radiation are lacking in this approximation.

Table 1: Participating urban units, their number of inhabitants (/1000), data series, weather station, ventilation, shadow effect, land use cover, and KNMI reference station.

#	City	Lat Lon	#Inhabitants	Start data	End data	System, Roof (R)/ Garden (G)	Measurement height	Ventilated (Y/N)	Degree of shadowing	Percentage buildings /green/ water	KNMI station
1	Rotterdam	51.917, 4.43	588	12/2007	03/2009	-, R	9	-	Neglectable, shielded	75/20/5	Rotterdam AP
2	The Hague	52.04, 4.24	483	07/2007	04/2009	Davis Vantage Pro+, G	1,5	Y	5 hours, shielded	70/20/10	Valkenburg
3	Delft	51.98, 4.34	97	01/2007	03/2009	LaCrosse	1,5	-	Completely, northside -	90/10/0	Rotterdam AP
4	Voorburg	52.08, 4.35	40	01/2006	12/2008	Davis Vantage Pro,R	14	Y	Neglectable, shielded	85/15/0	Rotterdam AP
5	Haarlem	52.37, 4.66	149	12/2005	02/2008	Ultimeter 2000, G	1,5	Y	Not much, shielded	75/25/0	Schiphol
6	Purmerend	52.49, 4.93	79	01/2008	03/2009	WS2350, G	1,5	-	Only in the summer till 12:00 the sun shines, blinds for sun so a radiation shield	80/20/0	Berkhout
7	Almelo	52.35, 6.65	72	03/2009	04/2009	La Crosse WS 3600, G	-	-	-	-/-/-	Twente
8	Leeuwarden	53.206, 5.810	94	01/2007	03/2009	-, G	-	Y	Completely, northside. Only early morning and evening sun,Has a radiation shield	-/-/-	Leeuwarden AP
9	Assen	53.01, 6.568	65	01/2007	03/2009	Davis Vantage Pro 2, R	2	N	Neglectable, shielded	85/15/0	Eelde
10	Houten	52.033, 5.166	47	07/2006	04/2009	Davis Vantage Pro2, R	12	Y	Neglectable, shielded	80/20/0	De Bilt
11	Apeldoorn	52.200, 5.933	136	01/2008	06/2009	WMR918, G	1.5	-	Not -	60/40/0	Deelen
12	Wageningen	51.97, 5.67	35	01/2008	03/2009	-, G	1.5	N	Completely, shielded	55/45/0	Wageninen Univ.
13	Heemskerk	52.499, 4.683	39	01/2005	12/2005	Weather-monitor II, G	1,5	-	Evening -	80/20/0	Schiphol
14	Heerhugowaard	52.670, 4.847	50	01/2005	04/2009	Davis Vantage Pro 2, G	1.5	Y	Early morning and late evening Has radiation shield	65/35/0	Berkhout
15	Leiden	52.162, 4.540	117	03/2004	03/2009	La Crosse WS 3600, G	1.5	Y	Completely, north side. Only early morning and evening sun. No radiation shield	50/35/15	Schiphol AP
16	Doornenburg	51.890, 6.00	2.7	01/2009	06/2009	Vantage pro, G	4	-	Afternoon -	55/45/0	Deelen
17	Losser	52.255, 7.00	23	01/2003	12/2008	CRESTA WXR 815, G	3.8	Y	?	60/40/0	Twente
18	Damwoude	53.291, 5.978	5.5	01/2005	04/2009	Vantage pro2+ 24-h FARS, G	3	-	Almost Completely, northside. Only early morning and evening sun -	35/65/0	Leeuwarden AP
19	Ijsselmuiden	52.570, 5.928	12	07/2005	07/2009	WS2305, G	1.5	Y	Afternoon (3/5) Neglectable, shielded	75/25/0	Heino
20	Groningen	53.216, 6.567	198	01/1999	03/2009	Davis WM-2, G	1.5			-/-/-	Eelde

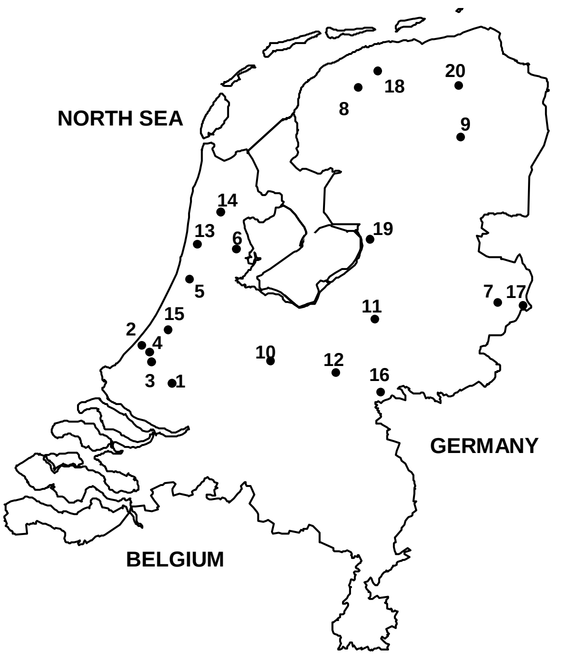

Fig. 2: Location locations with available observations.

General threshold values for WBGT are not available, but largely depend on a person's activities and clothing. For light work one should be careful for WBGT > 30. For moderate and heavy work these thresholds read 26.7 and 25 respectively (Sobane, 2008). For the general public, a WBGT < 27.7 represent conditions without heat stress. For 27.7 <WBGT < 32.2 the heat stress increases, and once WBGT > 32.2 great heat stress danger occurs. WBGT>31 usually result in cancellation of events. Physical training is not advised for WBGT > 29.4.

3. PRELIMINARY RESULTS

a) Urban heat island

As a first example we show the UHI_{max} distribution for Houten. Houten experiences a skewed UHI_{max} distribution, with a median of 1.2 K and a 95 percentile of 3.0 K (Fig. 3a). Fig. 3b and c show a typical dependence of UHI_{max} on its main atmospheric forcings, namely that UHI_{max} is approximately linear in the received solar radiation, and inverse proportional to the wind speed. $dUHI_{max}/dS \cong 0.035$ and $b \cong -0.38$. The WBGT seems to be normally distributed, and the threshold values are not exceeded.

The results for Rotterdam are of particular interest. Despite its location close to the coast, and its high water availability in the harbors, the UHI is particularly large with a median and 95 percentile of 3.4 K and 9.8 K respectively, especially when one keeps in mind that the observations have been done at the northern edge of the city. It is worth noting that a relatively small city as Losser is subject to relatively high values of the UHI and also to heat stress (see below). However, this city is located far inland and experiences a land climate.

Table 2 summarizes the mean value and the 95 percentile of the UHI_{max} in a diurnal cycle. The mean UHI_{max} amounts 2.4 K and the mean 95 percentile records 5.7 K. However, the difference between locations can be relatively large. Except for some outliers, the UHI sensitivity to radiation and wind speed corresponds rather well.

The current results for the Netherlands can be compared with model and observational results for other cities Europe. Johnson (1985) found a mean UHI_{max} of 4.7 K for Birmingham while Eliassen (1996) reports an UHI_{mean} of 4 K for Göteborg. Oke (1973) reviewed the UHI for European cities found 5.7< UHI_{max} <10.0 K, and for the only Dutch city, Utrecht, *UHI* ~6 K was reported. More recently, the *UHI* for Toulouse was found 5 K (Hidalgo et al., 2008). Fig. 4 shows the comparison of the Oke (1973) and Memon et al. (2009) results compared with the current results. It is evident that the spread in the current observations is larger than those for Oke (1973). This suggests other variables or parameters than city population govern the UHI_{max} in the Netherlands.

b) Heat stress

Concerning the heat stress, we find a relatively low mean value for the WBGT (Table 3). However, the 95 and 98 percentile for the cities are close to the threshold values. Rotterdam reports a 95 percentile of 29.7 which is substantially above the threshold value of 27.7. Its 98 percentile is even 32.3, which is also above the upper limit for event cancellation. In addition, in 7 of the 20 cities the threshold for heat stress onset is exceeded for the 98 percentile. In other words: 35% of the cities under investigation experiences heat stress for 7 days a year.

Table 2: Median, 95 percentile (95P), and UHI sensitivity to solar radiation and wind speed.

City	Median UHI	95P UHI	Median Shadow effect	Radiation slope	Wind-slope
Rotterdam	3.4	9.8	-0.7	0.073	-0.51
The Hague	2.2	5.3	-1.6	0.041	-0.43
Delft	1.7	4.8	-1.5	0.025	-0.26
Voorburg	2.4	5.6	-1.3	0.019	-0.28
Haarlem	2.5	5.7	-1.7	-	-
Purmerend	2.5	4.6	-1.6	0.018	-0.41
Almelo	2.6	5.8	-1.9	0.097	-0.14
Leeuwarden	1.1	3.0	-0.6	0.013	-0.43
Assen	1.8	4.0	-0.5	0.017	-0.40
Houten	1.2	3.0	-0.9	0.017	-0.44
Apeldoorn	2.9	6.2	-1.4	0.037	-0.56
Wageningen	2.4	5.6	-1.3	0.040	-0.43
Heemskerk	2.8	5.9	-2.0	0.018	-0.41
Heerhugowaard	2.4	6.2	-1.0	0.022	-0.24
Leiden	3.2	5.6	-0.8	0.014	-0.40
Doornenburg	2.6	5.7	-1.3	0.067	-0.17
Losser	2.9	6.8	-1.6	0.040	-0.43
Damwoude	1.3	3.2	-0.9	0.012	-0.25

IJsselmuiden	3.1	6.8	-1.9	0.041	-0.47
Groningen	1.5	3.1	-0.8	0.011	-0.48

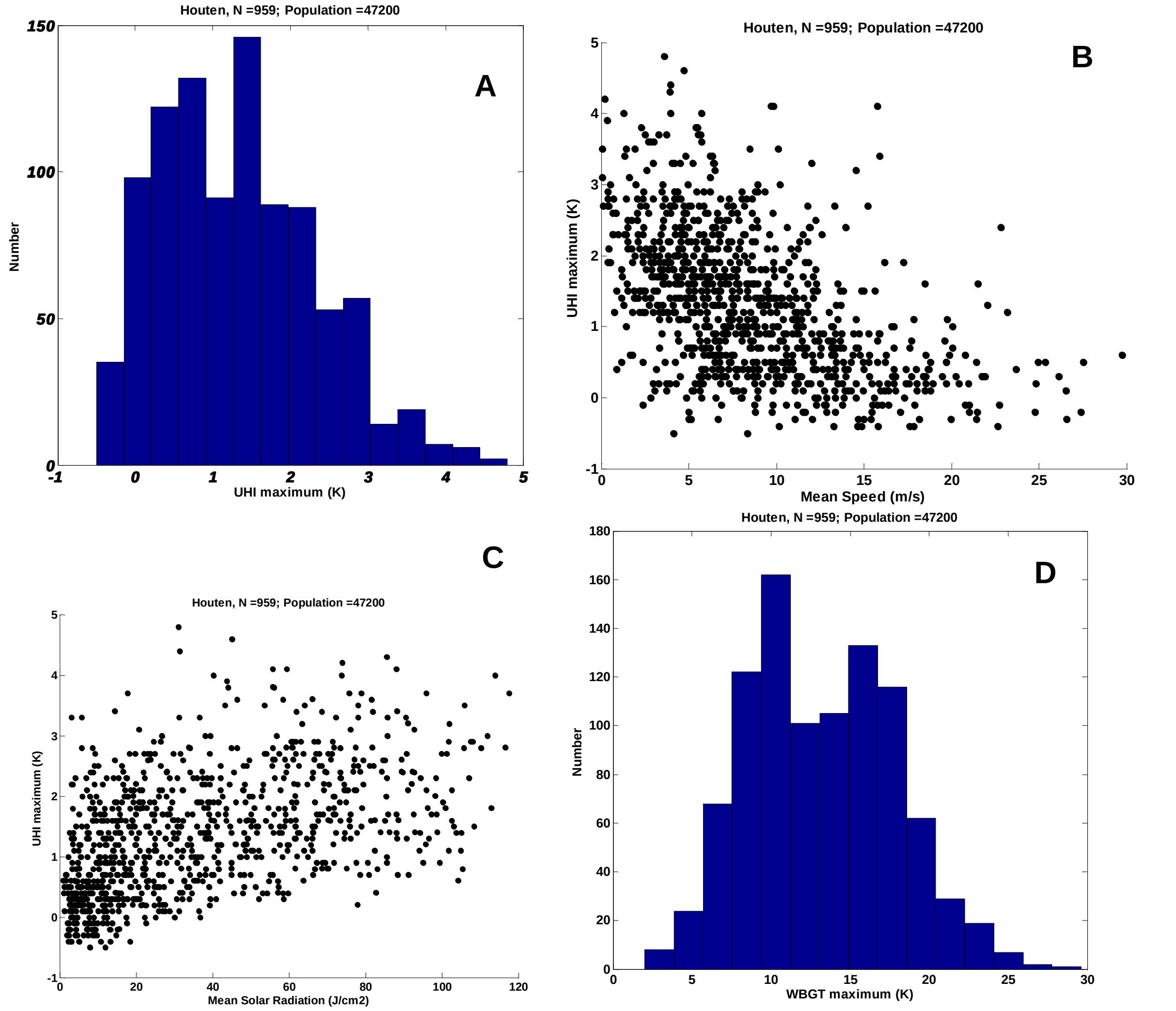

Figure 3: Distribution of the daily maximum UHI (a) and WBGT (d), sensitivity of the UHI on wind speed (b) and solar radiation (c) for Houten.

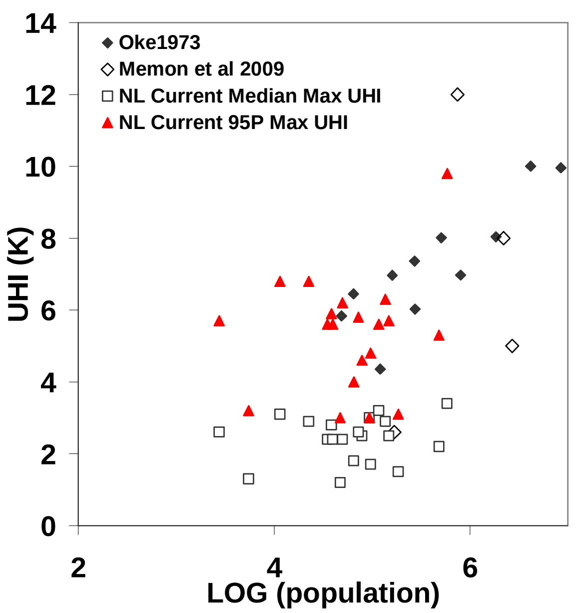

Fig 4: UHI for Dutch cities (●) and for other European cities (o).

In addition to the heat stress, cities also experience a so-called shadow effect. Buildings at the edge of a city inhibit penetration of sunlight into the city canyon during the first hours after sunrise. As a result, during the early morning hours cities can be colder than the rural surroundings (Oke, 1982). Table 2 shows that all cities in the Netherlands experience this shadow effect. The median of the UHI_{min} amounts -1.4 K.

In addition to the distribution of the maximum values of the WBGT, which only counts for the frequency of the events, the duration population is exposed to heat stress is of similar importance. Here we introduce and study the dosis defined as the exposure time to a WBGT above the critical value of 27.7:

$$\text{Dosis} = \frac{1}{N}\sum_{n=1}^{N}(\text{WBGT} - 27.7) \qquad (3)$$

Note that threshold values for this dosis do not exist at the moment. Table 3 shows the dosis observed per city. Especially Rotterdam, Groningen and Voorburg seem to be hotspots while surprisingly The Hague and Delft are subject to a smaller dosis.

c) Extreme value statistics

In order to quantify the degree of extremity of the current observations, and to learn whether these fit a statistical distribution for extreme value problems, we fit our observations to the General Extreme Value (GEV) distribution

$$F(x) = \exp\left(-\left[1-\frac{\kappa}{\alpha}(x-\mu)\right]^{1/\kappa}\right) \quad \text{for } k \neq 0,$$

and we use the L-momenten approach to estimate the parameters κ, α and μ (see Overeem et al., 2008 for methodological details). Herein μ is middle value measure, and κ the shape parameter, and α the scale parameter. Fig. 5 shows that the observations for Houten follow the GEV distribution rather well, and this has been confirmed for most of the other observational stations. As such the GEV seems a useful tool for UHI analysis. Note that substantial differences have been found for the parameters for different cities (Table 4). However, the physical reasons behind these differences are unknown and yet under investigation.

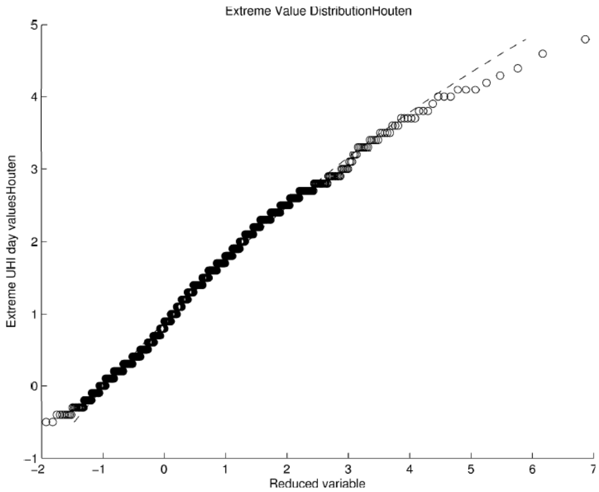

Fig. 5: Observed UHI_{max} versus the reduced variable. The reduced variable = $-\log(-\log(n/(n_{tot}+1)))$, with n the n^{th} ranked observation and n_{tot} the total number of observations. The dashed line indicates the fit to the GEV distribution.

4. CONCLUSIONS

This paper quantifies the magnitude of the urban heat island effect, and the heat stress for Dutch cities and villages. Due to lack of official observations, our analysis is based on high quality observations by hobby meteorologists. The average maximum UHI during a diurnal cycle amounts 2.4 K, although the average 95 percentile over all cities amounts 5.7 K. It is found that approximately 50% of the urban areas in this research are subject to heat stress for ~7 days per year. The city of Rotterdam exceeds the heat stress threshold value for ~18 days per year. Also, it appears that most of the current observations follow a GEV distribution closely. Further research to the exposure time during day with heat stress is recommended. Therefore the current results should be considered as preliminary.

Table 3: Median, 95 and 98 percentile of recorded WBGT (ºC), and mean heat stress dosis (K*h/day) for Dutch cities

City	Median	95%P	98%P	Dosis
Rotterdam	15.1	29.7	32.3	8.9
The Hague	16.0	25.3	26.9	2.0
Delft	16.6	25.2	27.5	1.5
Voorburg	17.5	25.8	28.5	3.8
Haarlem	-	-	-	-
Purmerend	14.0	23.2	24.8	0.0
Almelo	14.1	16.5	16.6	0.0
Leeuwarden	15.8	24.1	26.0	1.6
Assen	15.8	25.0	26.4	2.0
Houten	12.8	20.8	23.0	0.2
Apeldoorn	14.5	24.4	25.1	0.1
Wageningen	17.6	25.6	27.6	3.4
Heemskerk	13.7	21.3	24.1	0.9
Heerhugowaard	16.6	25.6	27.8	2.9
Leiden	18.5	26.6	28.2	0.5
Doornenburg	10.5	14.3	15.2	0.0
Losser	16.3	26.2	28.0	2.9
Damwoude	16.0	25.2	26.9	1.5
IJsselmuiden	16.6	25.4	27.8	3.0
Groningen	16.2	26.4	28.7	5.6

Table 4: Parameter GEV verdeling voor WBGT

City	κ	α	μ (K)
Haarlem	-0.1065	6.234	13.4204
Assen	0.2342	5.2634	14.0601
Houten	0.1993	4.4296	11.3658
Leeuwarden	0.241	5.0681	14.0684
Heerhugowaard	0.2216	5.2224	14.6666
Damwoude	0.2488	5.3946	14.1297
Leiden	0.257	4.6524	16.6853
Rotterdam	-0.0308	4.7946	13.9546
Purmerend	0.1425	4.6135	12.8731
Den Haag	0.236	5.4476	14.7499
Wageningen	0.3843	6.6189	14.8743
Delft	0.2778	5.5247	14.7224
Heemskerk	0.2421	4.75	11.7112
IJsselmuiden	0.2483	5.5238	14.4504
Almelo	0.4734	1.8437	13.1569
Voorburg	0.263	5.2489	15.5498
Doornenburg	0.2452	5.1923	12.5492
Apeldoorn	0.2253	4.9283	13.1365
Losser	0.239	5.6495	14.1896
Groningen	0.2179	5.759	14.1842

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