Estimating the Urban Heat Island in Residential Areas in the Netherlands Using Observations by Weather Amateurs

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ABSTRACT

A better quantification of the urban heat islands (UHIs) in the Netherlands is urgently needed given the heat stress–related problems in the recent past combined with the expected temperature rise for the coming decades. Professional temperature observations in Dutch urban areas are scarce, however. Therefore, this research explores the use of observations from weather stations that were installed and maintained by weather amateurs. From a set of over 200 stations, suitable and representative data have been selected from 20 stations, using a set of objective selection criteria that are based on metadata. One year of data (January–December 2010) was considered. From these data, estimates have been obtained of the magnitude of the UHI in Dutch low-rise residential areas. A positive relation (linear model with $r^2 \approx 0.7$) was derived between the summer-averaged UHI and the (neighborhood scale) population density around the observational sites. It was found that the UHI in summer is strongest in nighttime conditions and that it increases with decreasing wind speed, decreasing cloud cover, and increasing sea level air pressure. The summer-averaged UHI was ~0.9°C. During nighttime in a relatively warm 1-month subperiod of the summer, the average UHI was ~1.4°C. During spring and autumn, the UHI was lower than in summer; during winter, no significant UHI was observed. The agreement in results among the different stations and the accordance of the magnitude and variation of the observed UHI with those described in the literature show that automatic observations from weather amateurs can be of sufficient quality for atmospheric research, provided that detailed metadata are available.

1. Introduction

In the past in the Netherlands, research on the urban heat island (UHI) has been scarce. Two published observational studies in Dutch cities are known: one intensive observational campaign in the early 1970s in the city of Utrecht by Conrads (1975) and one new study by Steeneveld et al. (2011). Although a fair number of observational studies have been done in other countries, because of differences in climatic conditions and building manners it is unclear to what degree quantitative estimates and relations from these studies are valid for the Dutch situation. In recent years, social interest and scientific interest in the UHI have strongly increased, mostly driven by heat stress–related health problems among citizens in recent summers (e.g., Huynen et al. 2001; Vandentorren et al. 2004), increasing the need for more knowledge about possible measures to mitigate heat stress. These issues are becoming increasingly relevant with respect to the observed and projected climatic warming. The Dutch UHI is now subject to several studies, addressing the issue from (in situ and remote) observational as well as modeling perspectives. The study presented here is one of the first of these attempts, aiming at an observational ‘‘quick scan’’ of the magnitude and physical characteristics of the UHI in a number of Dutch cities. In the absence of sufficient professional observations, the use of observations from voluntary private observers was explored. Several hundreds of these ‘‘weather amateurs’’ are active in the Netherlands, recording meteorological observations on their premises, using commercially available automatic weather stations that are connected to the Internet.

Observations from weather amateurs in the Netherlands have previously been explored in one climatological study by Steeneveld et al. (2011). Their focus and interpretation were concentrated more on the effects of the UHI on heat stress and human comfort, whereas this study has its focus on the physical behavior and

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dependencies of the UHI. In contrast to this study, Steeneveld et al. (2011) do not describe a formal procedure for the selection of suitable stations; for example, they included two stations that lack radiation shielding. Stations that showed unrealistic behavior in the timing of the maximum UHI were excluded from their station set, however. Furthermore, they have used observational time series from time periods that mostly differ from those in this study. Steeneveld et al. (2011) mainly studied the diurnal maximum UHI, whereas this study focuses on the diurnal average UHI. As a result of these differences, both studies can be regarded as complementary.

The magnitude and impact of the UHI strongly depend on the type and scale of the urban development at the considered location. Larger cities, and parts of cities with high and close-set buildings, having lower sky view factors (SVFs), show stronger heat islands (Yamashita et al. 2003). To quantify the relation between the degree of urban development and the magnitude of the UHI, it has often been attempted to connect population numbers to observed temperatures. In many studies the magnitude of the UHI has been linked to the total number of inhabitants of a city. Oke (1973) and Park (1986) demonstrated a linear relation between the magnitude of the UHI and the logarithm of the population of a city. Although the total number of inhabitants as a measure is convenient to use and is widely available, it has some important drawbacks as a predictor for UHI magnitude. The number of inhabitants strongly depends on physically irrelevant factors such as the administrative division of the considered area, and it incorporates little information about the density of the urban development since cities with similar population numbers can have very different surface areas and building typologies.

In this study we have linked the UHI to the local-scale *population density* (PD). The PD has a stronger connection to building typology than does total city population, and it is well linked to SVFs (Giridharan et al. 2004). See section 2d for more information about this parameter. Furthermore, instead of total city population, PD can be considered at the level of separate neighborhoods, as is done in this study. This opens the possibility of spatially describing the UHI within urban areas on the basis of the spatial distribution of the PD over different neighborhoods, if such data are available.

In midlatitude regions the UHI shows a distinct diurnal course. The UHI is strongest during nighttime. It often shows a decline shortly after sunrise, and around sunset it increases again (Watkins et al. 2002; Oke 1982; Oke and Maxwell 1975; Hamdi and Schayes 2008). For the annual cycle, the UHI is mostly strongest during the summer half of the year (e.g., Oke 1982; Conrads 1975; Fortuniak et al. 2006; Arnfield 2003), although in some studies the UHI is strongest in winter (e.g., Kim and Baik 2004). There is also a strong dependency on the weather situation, the UHI being strongest in calm weather situations for which there is little wind and few clouds (Oke 1982; Morris et al. 2001; Johnson et al. 1991).

In previous research the magnitude of the UHI has been characterized by various metrics. Sometimes one measure is needed that characterizes the UHI of one city or neighborhood independent of spatial and temporal variation. In these cases often the maximum observed UHI (UHI_{max}) is used (e.g., Park 1986; Oke 1973; Sakakibara and Matsui 2005). UHI_{max} focuses on the UHI at the moment of strongest impact on society. Drawbacks of UHI_{max} are that its value may strongly depend on the length of the considered observational period and that it does not include information about the frequency of occurrence of its value. When looking at the temporal variation and physical behavior of the UHI it may be more appropriate to use the (conditional) average UHI (UHI_{avg}) as a measure.

In the urban climate system, momentum, heat, and moisture near the surface are exchanged along a three-dimensional complex of differently oriented surfaces. The layer in which these exchanges occur is often called the urban canopy layer (UCL). According to Oke (2006), the depth of the UCL is approximately equivalent to that of the main roughness elements such as buildings and trees. All observations done within the UCL are to some degree influenced by the effects of these individual objects and surfaces. To obtain data that are representative of the local scale (the scale of neighborhoods, having a length of one to several kilometers; Oke 2006), these microscale influences should be minimized. We therefore applied a number of objective criteria to select representative stations from the initial set using detailed metadata. We think that for UHI studies such a formal selection procedure is especially recommended, since insufficient radiation shielding and sensor ventilation may introduce observational errors that share characteristics with the UHI effect, such as observing higher temperatures and a negative dependency of temperature on wind speed.

For the stations that meet the selection criteria, we have statistically investigated the relationship between temperature and the PD of neighborhoods. Then, a threshold of 4000 persons per kilometer squared was set to distinguish between urban and nonurban stations. This threshold was based on the average UHI intensities observed at the stations. For the urban stations the magnitude of the UHI was estimated, considering its average and its distribution over several percentiles. The diurnal and annual cycle of the UHI and its dependencies on wind speed, temperature, cloud cover, and sea level air pressure have been investigated.

The Netherlands has a typical midlatitude oceanic climate, with prevailing westerly winds, ~800 mm of rain per year, and average minimum and maximum temperatures of roughly 0° and 5°C in winter and 10° and 20°C in summer. One year of observations (January–December 2010) was archived and was used in this study, mostly focusing on the summer period. In the center of the Netherlands (De Bilt), the summer of 2010 was roughly 1°C warmer than normal, with 17% more sunshine. The whole year 2010 was 0.7°C cooler than normal, with 14% more sunshine.

2. Data and methods

a. *Amateur weather stations*

Although potentially large amounts of such observations are available in most western countries, temperature observations from automatic weather stations installed and maintained by weather amateurs have not often been used in climatic research. This is probably due to the supposed lack of professional control over observational sites and to difficulties with data gathering, handling, and archiving. For this study, the observations were obtained from a popular Dutch Internet site for weather amateurs (http://www.hetweeractueel.nl), where data from hundreds of weather amateurs throughout the Netherlands are gathered and aggregated automatically every hour.

All (>200) participating weather amateurs used commercially available, semiprofessional automatic weather stations. Most of these were part of the Vantage Pro series by Davis Instruments Corp. (Hayward, California). Temperature observations from Davis Vantage Pro or similar weather stations have been used in recent scientific literature outside climatology and meteorology (e.g., McLaren et al. 2005; Eigenberg et al. 2003; Watanabe et al. 2006; Wiacek et al. 2007) and in one recent climatological study by Steeneveld et al. (2011). All temperature sensors used in the current study were shielded against precipitation and radiation by a white multiplate screen. Forced ventilation was applied to the screen in some stations. All stations were located in the direct vicinity of a house, in areas with PD ranging from 20 to 10 000 persons per kilometer squared (landscapes ranging from rural, to smaller villages, up to more intensely developed residential areas). Most stations observed temperature at levels near standard height (1.5 m). The locations were usually sheltered, typically in small gardens surrounded by hedges or fences. Around 25% of the stations observed temperature at heights above 2.0 m. These stations often measured at a level above any garden fencing or around roof level, where there is much less shelter. Because away from objects (see next section) the air temperature gradients are slight within the UCL (Nakamura and Oke 1988), this difference in measurement height should not lead to significant error.

b. *Station selection*

The placement and surroundings of the temperature sensor varied greatly among the available amateur observational sites. In many situations the observed temperatures were not representative for the local scale around the site. To obtain representative and intercomparable observations, a number of criteria were applied to select representative stations from the initial set. This selection used detailed metadata, obtained by means of a questionnaire about the observational circumstances of each station, photographs, and personal communication with participants in case of insufficient information. The applied criteria are based on established ideas about in situ urban temperature observations, as summarized in Oke (2006), and on a subjective assessment of the observational data at a number of locations. The criteria are listed below.

1) Distance to nearby objects

Sometimes observations were made too close to the (microscale) boundary layers of individual objects such as walls and ponds or too close to the ground. Therefore we have only used data from stations that have no surfaces within 1.5 m of the temperature sensor, both horizontally and vertically. Air temperature gradients within the UCL are slight at distances of more than 1 m from the nearest surface (Nakamura and Oke 1988).

2) Thermometer screen ventilation

At stations situated in low-lying, sheltered areas such as gardens there may not be sufficient wind to ventilate the thermometer screen to prevent the temperature sensor from overheating because of radiation exposure (Nakamura and Mahrt 2005). At some stations we have indeed observed such a ''radiation error'' as an unrealistically strong, positive response of the observed temperature to solar radiation. To prevent such errors, we have only used observations from sheltered weather stations if forced ventilation was applied to the temperature sensor. See also Oke (2006): ''. . .an assembly placed in the lower UCL may be too well sheltered, so forced ventilation is recommended.'' ''Sheltered'' was defined such that, on a scale of tens of meters, the station is surrounded on multiple sides by flow-blocking objects as high as or higher than the station itself.

3) Distance to the nearest rural station

The rural ''background climate'' of the amateur weather stations was derived from observations at the nearest

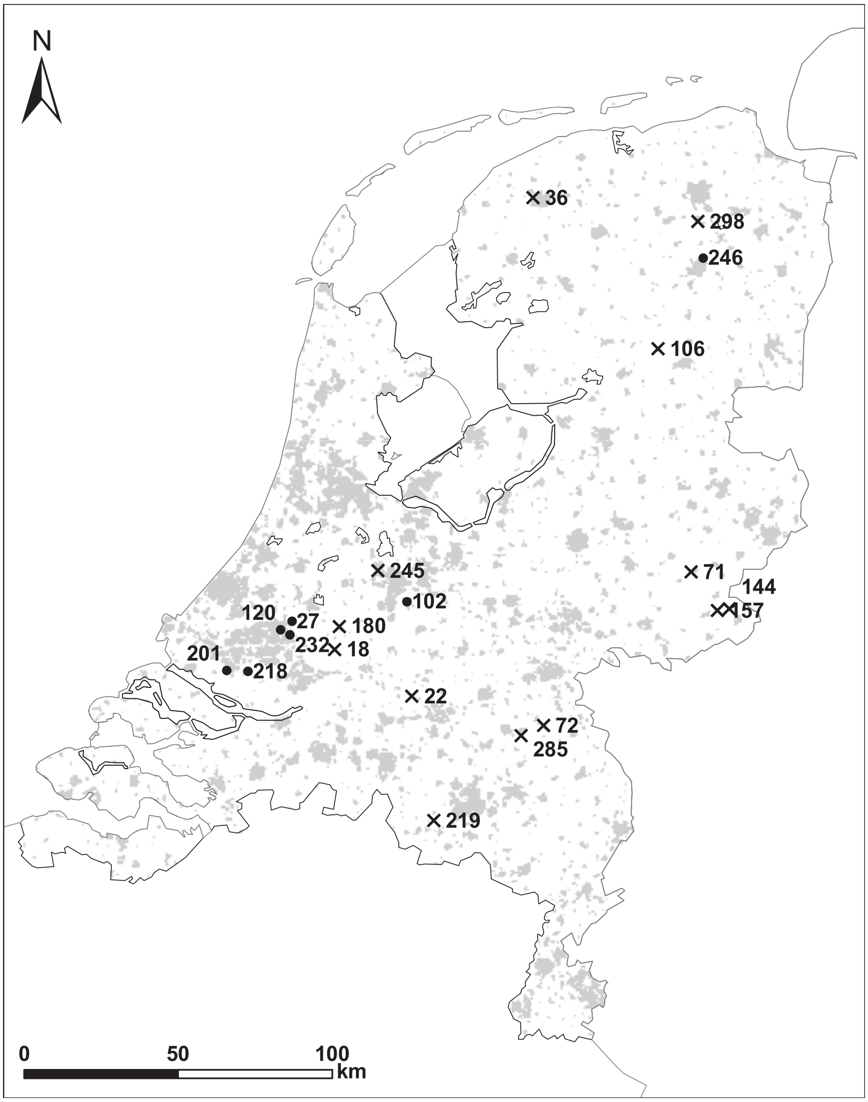

FIG. 1. Locations of the amateur weather stations that were used. Stations marked with dots are located in neighborhoods with PD greater than 4000 persons per kilometer squared and are specifically studied as urban stations in our analyses. Gray shading indicates urban areas.

Royal Netherlands Meteorological Institute (KNMI) rural station. To accurately represent this background climate, the rural station should be sufficiently nearby. Therefore only amateur weather stations have been used that were less than 15 km away from the nearest rural KNMI station. Because near the coast the gradient in the background climate is particularly large, we have only used amateur weather stations for which the distance to the coast is larger than that to the nearest rural station.

4) AVAILABILITY OF DATA

All of the observational series from amateur weather stations contained some gaps within the considered period (January–December 2010). The availability of data diverged widely. For any specific analysis we have only used stations for which data were available for 85% or more of the time. Because of this constraint, for analyses considering different time periods the selection of stations used varies slightly.

In total, data were available from over 200 amateur weather stations. After the application of the abovementioned selection criteria, 20 stations remained for our analyses. Most rejections were due to unavailability of a sufficiently nearby rural station. Figure 1 shows the locations of all stations that have been used at least once in our analyses. In this figure, urban areas are indicated with gray shading. This information is derived from the "LGN5" national land use database (Hazeu 2006).

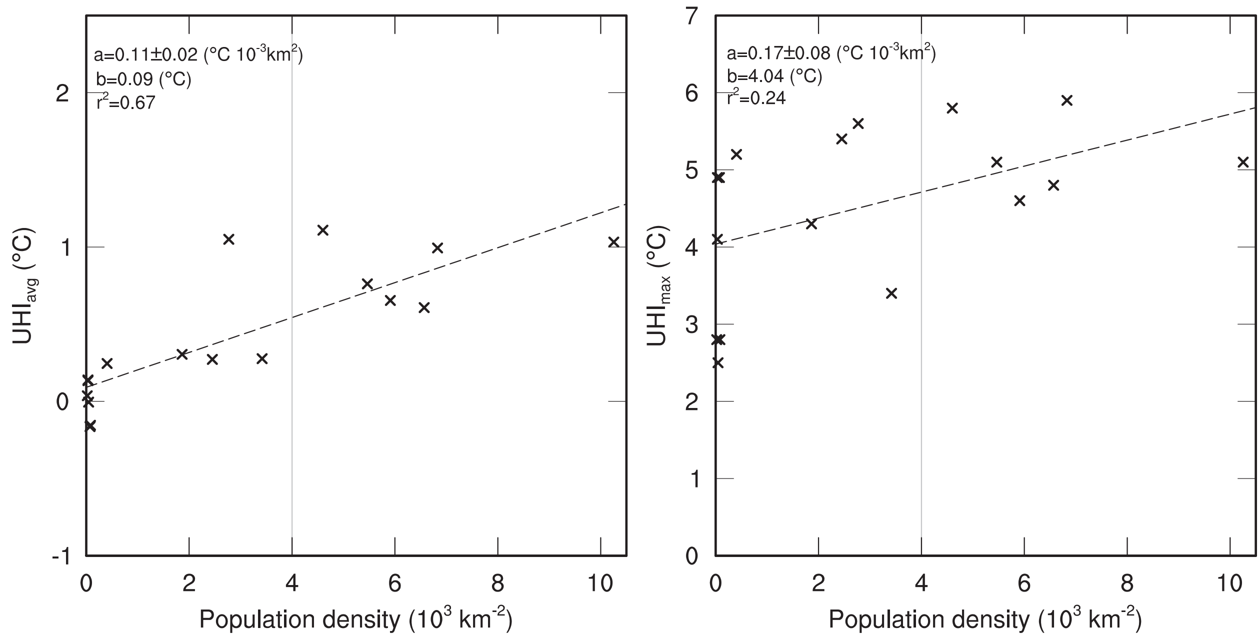

FIG. 2. (left) UHI_{avg} and (right) UHI_{max} vs PD during the summer (JJA) of 2010, with linear trend line (least squares estimate). Here *a* and *b* are coefficients of the trend line according to $y = ax + b$, and *r* is the correlation coefficient. Positive correlation is significant at $P < 0.0005$ (UHI_{avg}) and $P < 0.025$ (UHI_{avg}); the standard deviation of the estimated parameter is indicated by $\pm$. Stations to the right of the vertical gray line (located in neighborhoods with PD of >4000 persons per kilometer squared) are specifically studied as urban stations in our analyses.

Eighteen of the stations were of the Vantage Pro series mentioned in section 2a; the two other stations (manufactured by Ultimeter Weather Stations and by Oregon Scientific) had similar design and radiation shielding, and their results did not show any alarming deviation from the other stations.

c. *Rural sites*

For all amateur weather stations, the UHI was derived on an hourly basis, as

$$UHI = T_{urban} - T_{rural}, \tag{1}$$

where T_{urban} is the temperature observed at the urban site and T_{rural} is the temperature observed at the rural site. The rural sites are part of the observational network of KNMI. Temperatures are observed according to World Meteorological Organization guidelines for rural stations. For KNMI station De Bilt it has been estimated that urban heat advection from the nearby city of Utrecht is around +0.1°C on average (Brandsma et al. 2003). Judging from spatial characteristics, urban heat advection may be similar at the rural station Rotterdam; at the other rural stations it is most likely much smaller or absent. It is likely that this value represents an upper limit for the rural stations used here.

d. *Population densities*

Population density information was obtained from the Dutch Central Bureau for Statistics for the neighborhood around each amateur weather station. The borders of these neighborhoods are based on differences in landscape or socioeconomic differences, and in urban areas they are largely determined by differences in building design. For the stations treated as urban in this study (see section 4), these neighborhoods had an average area of 0.23 km^2, with standard deviation of 0.09 km^2. The other stations were located in more rural neighborhoods with an average area of 5.23 km^2, with standard deviation of 6 km^2 (the distribution of the area of these neighborhoods is strongly positively skewed). The PD values used in this research are gathered between 2008 and 2010, assuming representativeness for 2010, when the observations were carried out.

3. UHI versus population density

Figure 2 shows the summer-averaged UHI (UHI_{avg}) and the summer-maximum UHI (UHI_{max}) for the summer [June–August (JJA)] of 2010 versus the PD, for all selected stations, with a linear regression line obtained by least squares estimation. UHI_{avg} is the average UHI over the whole period; UHI_{max} is its maximum

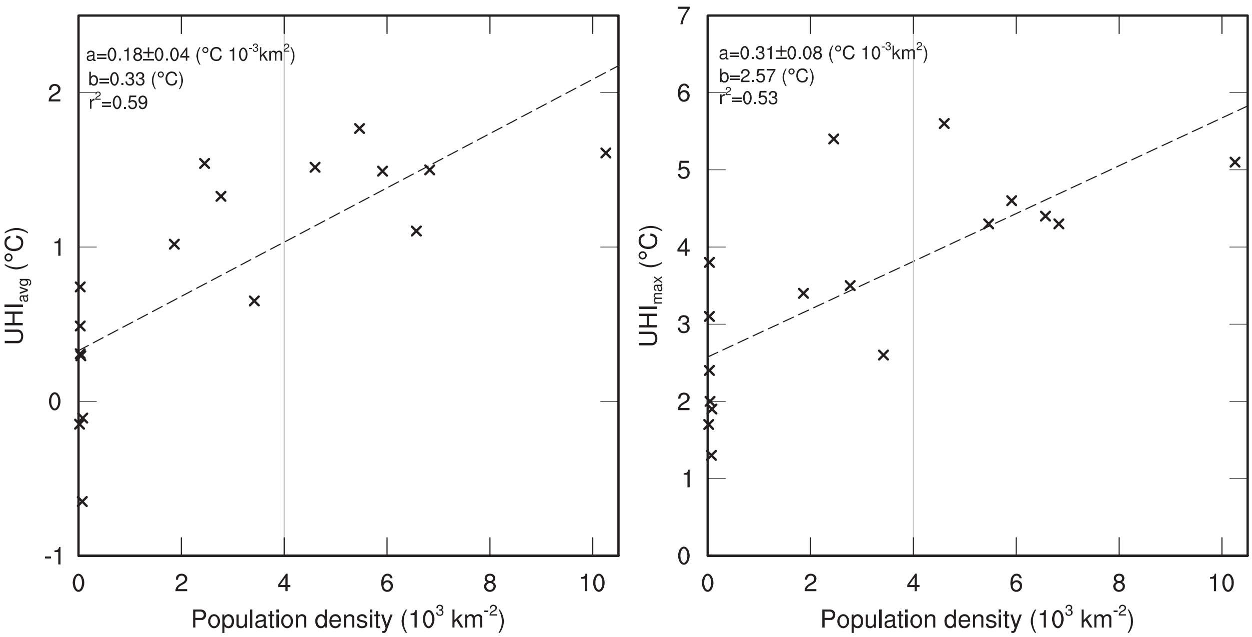

FIG. 3. As in Fig. 2, but from 2300 until 0500 LT from 24 Jun until 23 Jul 2010.

observed value. For both UHI_{avg} and UHI_{max} there is a significant positive relation with the PD, with $r^2 = 0.67$ and 0.24, respectively. The regression has a slope of 0.11°C $(10^3\ km^{-2})^{-1}$ for UHI_{avg}/PD and 0.17°C $(10^3\ km^{-2})^{-1}$ for UHI_{max}/PD. For UHI_{avg}/PD the regression line has an intercept of 0.1°C, close to the expected value of 0°C for a rural climate with PD = 0. The regression intercept for UHI_{max}/PD is much higher (4°C), indicating that strong positive (and negative) instantaneous temperature deviations can still exist when the summer average temperature difference is near zero.

In a similar regression analysis, Steeneveld et al. (2011) defined exponential relations between the neighborhood-scale PD and the median and 95th percentiles of the diurnal maximum UHI. Linearized around PD = 3136 persons per kilometer squared (the PD averaged over the stations in Fig. 2), these relations give UHI/PD slopes of 0.19°C $(10^3\ km^{-2})^{-1}$ for the median diurnal maximum UHI and 0.38°C $(10^3\ km^{-2})^{-1}$ for its 95th percentile. These values are larger than the slopes for UHI_{avg} and UHI_{max} derived in this study. Differences in method—most important, the fact that both studies apply different metrics for the UHI and the fact that Steeneveld et al. (2011) looked at the UHI year-round whereas this study concentrates on the summer months—hinder a detailed interpretation of these differences.

For a location in the center of Utrecht, Conrads (1975) found a summer-averaged UHI of 1.3°C. Assuming that the urban structure has not changed much since (the location is in a historical neighborhood), we can extrapolate the above discussed linear relation for UHI_{avg} to the present PD of 10.259 in this neighborhood. This yields an estimate for the summer-averaged UHI of 1.2°C—close to the value of 1.3°C found by Conrads (1975).

Figure 3 shows UHI_{avg} and UHI_{max} versus PD for observations between sunset and sunrise between 24 June and 23 July, which is the 30-day subperiod of 2010 with the highest average temperature at De Bilt, the main climatological station in the Netherlands. The average daily maximum temperature, minimum temperature, and sunshine duration in this subperiod at De Bilt were 26.7°C, 13.7°C, and 9.8 h, respectively, as compared with 21.9°C, 11.9°C, and 6.4 h averaged over all summers in the period 1981–2010. According to the linear regression, in this subperiod UHI_{avg}/PD has a slope of 0.18°C $(10^3\ km^2)^{-1}$, 64% more than averaged over the whole summer (Fig. 2). In a similar way, UHI_{max}/PD has a slope of 0.31°C $(10^3\ km^2)^{-1}$, 82% more than averaged over the whole summer (Fig. 2).

As an application of the latter relationship we have considered the largest city in the Netherlands, Amsterdam, having 783 364 inhabitants (as of April 2011). The neighborhood of Amsterdam (and all of the Netherlands) with the highest PD is Transvaalbuurt, with 25 200 persons per square kilometer in 2010. Extrapolating the linear relations derived above to this value of the PD yields estimates of UHI_{max} of 8.3°C (on the basis of the summer-maximum UHI) and 10.4°C (on the basis of the

TABLE 1. The 5% and 95% quantiles of exceedance of the hourly UHI during the summer (JJA) of 2010, and UHI_{avg} and UHI_{max} (°C) for all weather amateur stations treated as urban. The PD values are per square kilometer.

No.	PD	95%	UHI_{avg}	5%	UHI_{max}
201	10 254	−0.8	1.0	3.1	5.1
232	6829	−0.6	1.0	3.2	5.9
246	6569	−0.7	0.6	2.4	4.8
102	5911	−0.5	0.7	2.5	4.6
120	5464	−0.7	0.8	2.7	5.1
218	4600	−0.7	1.1	3.2	5.8
Mean	6605	−0.7	0.9	2.9	5.2

TABLE 2. The 5% and 95% quantiles of exceedance of the hourly UHI, and UHI_{avg} (°C) from 2300 until 0500 LT, from 24 Jun until 23 Jul 2010, for all amateur weather stations treated as urban. The PD values are per square kilometer.

No.	PD	95%	UHI_{avg}	5%	UHI_{max}
201	10 254	−0.9	1.6	4.4	5.1
232	6829	−0.9	1.5	3.4	4.3
246	6569	−0.4	1.1	3.3	4.4
102	5911	−0.4	1.5	3.5	4.6
120	5464	−0.3	1.8	3.5	4.3
218	4600	−1.2	1.5	4.1	5.6
Mean	6605	−0.7	1.5	3.7	4.7

maximum UHI in nighttime situations in the warmer subperiod) as the estimated "ceiling" value of the UHI for any Dutch settlement. The relation between UHI_{max} and total city population derived by Oke (1973) for European settlements ($UHI_{max} = 2.01 \log P - 4.06$) for Amsterdam estimates UHI_{max} to be 7.8°C. The positive deviation in our estimate may be caused by the fact that Oke (1973) defined UHI_{max} as the UHI observed under calm and clear weather conditions whereas in this study the absolute maximum observed value is taken and by the fact that the UHI values considered by Oke (1973) are valid for complete settlements rather than for the neighborhood with the highest PD. Last, it may be that a *linear* extrapolation of the found relationship to values as high as PD = 25 200 is not realistic, so that an exponential regression such as was applied in Steeneveld et al. (2011) would give a better representation.

4. The occurrence of UHI intensities

In this and the following sections several characteristics of the UHI are analyzed for a subset of stations treated as *urban* stations. No independent definition for urban locations on the basis of PD could be obtained. Therefore, we have chosen the arbitrary threshold of 4000 persons per square kilometer as based on the observations of summer-averaged UHI (see Figs. 2 and 3). The stations with PD above this threshold all showed a summer-averaged UHI_{avg} of >0.5°C (only one station with a PD of <4000 persons per square kilometer showed a value of UHI_{avg} of >0.5°C).

To quantify further the magnitude of the UHI on these stations, we have derived a number of characteristics of the empirical statistical distribution of the UHI. Table 1 shows 5% and 95% quantiles, and UHI_{avg} and UHI_{max} during the whole summer of 2010, for all urban stations separately and averaged over the stations. From Table 1 it follows that the summer-averaged UHI ranged between 0.6° and 1.1°C, with an average over the stations of 0.9°C. Five percent of the time the urban stations were on average 0.7°C or more *cooler* than the rural environment (a "negative UHI"). This condition mostly occurred during mornings (see section 6 for further explanation). Also, 5% of the time the UHI was 2.4°C or more. In extreme cases (UHI_{max}), the UHI exceeded 5°C.

All stations were located in residential areas with mostly low-rise development, which can be considered as typical for Dutch cities. These estimates are considered to be representative of such residential areas, and we expect higher UHI intensities in more intensely developed urban areas such as city centers. Relative to many studies (e.g., Kim and Baik 2005; Gaffin et al. 2008) our estimates may be considered to be on the low end, although differences in research setup make one-to-one comparisons difficult. The relatively low values are likely due to the absence of observations in city centers, to the relatively small size and building magnitude of Dutch cities in comparison with cities in some other countries, and to the climatic conditions in the Netherlands, being cooler and less stable than areas considered in many other studies. Furthermore, urban heat advection on some of the rural stations may have caused a slight underestimation of the observed UHI (see section 2).

Table 2 shows the same information as is in Table 1, but for nighttime situations within the earlier defined subperiod of warmer weather conditions (see section 4). UHI_{avg} and the 5% largest UHI intensities (the 5% quantile of exceedance) are much higher in these situations, with respective increases of 75% and 143%. The 5% smallest UHI intensities and UHI_{max}, however, do not change much.

5. Predictors of the UHI during summer

We have linked the observed UHI to different meteorological parameters to study their mutual relationships. Figure 4 shows the course of the average UHI as a function of the time of day, wind speed, temperature,

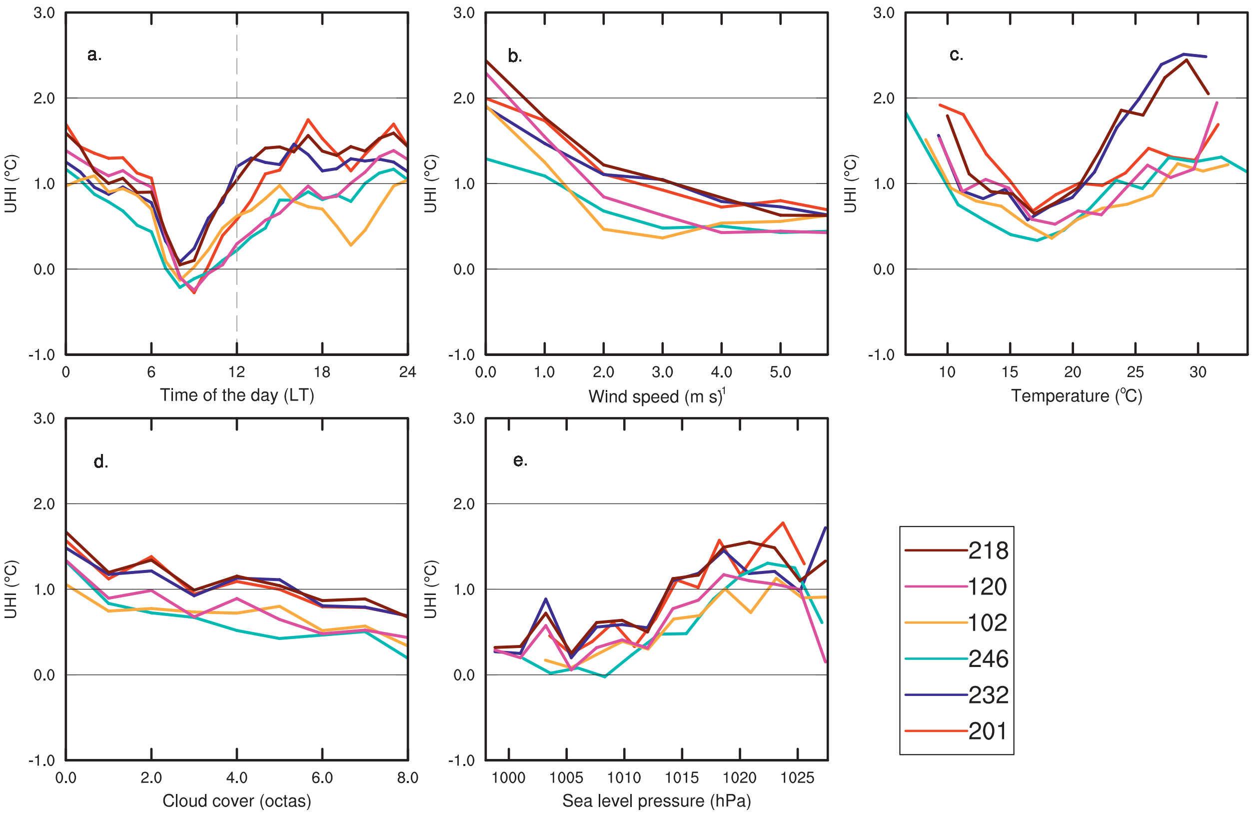

FIG. 4. Relation of the average 2010 summer (JJA) UHI, with (a) time of day, (b) wind speed, (c) temperature, (d) cloud cover fraction, and (e) air pressure for all available amateur stations in the urban area.

cloud cover, and sea level air pressure. The same subset of urban stations was used as in Tables 1 and 2, again taking observations from the whole summer of 2010. For these analyses, the average UHI was calculated within different intervals (bins) of the independent variable. For the time of day, wind speed, and cloud cover these intervals cover single units. For temperature and sea level pressure the bin width was selected as an optimum between resolution (having as many bins as possible) and representativeness (having enough observations in each bin to ensure a representative average). Averages were only displayed if obtained from eight or more hourly observations of the UHI. Observations of wind speed, temperature, cloud cover, and air pressure were obtained from the nearest rural KNMI weather station, the same station from which the observations of ‘‘rural’’ temperature were obtained. Wind speed was measured at 10-m height.

Figure 4a shows a distinct diurnal course of the average UHI. The UHI is strongest in the nighttime hours between sunset and sunrise, mostly between 1° and 1.5°C on average. In the morning hours, around or just after sunrise [0526 local time (LT) 1 June; 0650 LT 31 August], the UHI steeply declines and even disappears upon reaching a minimum of about 0°C. The UHI gradually recovers in the course of the morning and afternoon. The strong UHI during nighttime hours, followed by a decrease just after sunset, is in accordance with the literature. Many authors (e.g., Watkins et al. 2002; Oke 1982), however, describe a UHI that, unlike in our findings, remains approximately constant at a certain, positive, level during the day and increases again only around sunset. Hamdi and Schayes (2008) found, both in observations and in a one-dimensional model, a diurnal course much like that in Fig. 4a with a strong decrease until ~0°C shortly after sunrise and a subsequent, gradual, increase during the morning and afternoon. They attribute the strong decline and even disappearance of the UHI in the morning to the effective heat capacity of the urban surface and to shadowing, causing it to warm more slowly than the rural area in the morning hours when the solar elevation is low. They found that, in simulations, locations with a larger urban canyon height-to-width ratio *H*/*W* show a stronger drop in the UHI magnitude during the morning that is due to more effective shadowing. Thus, the location of the amateur weather stations, near shadowed places such as (fenced) gardens near a house, may have caused the observed

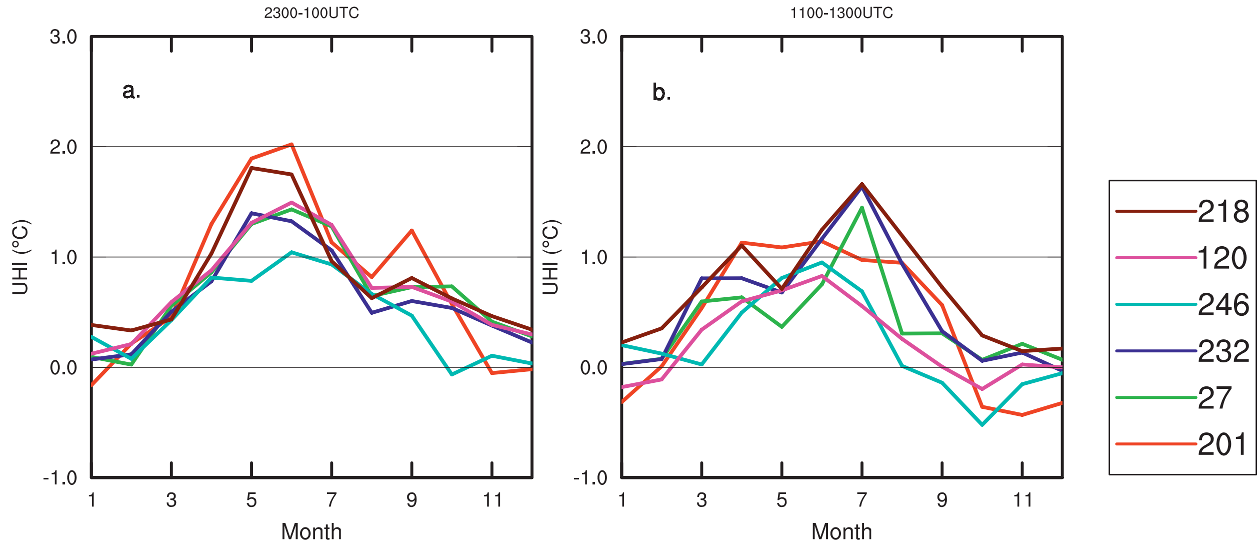

FIG. 5. Annual course of the monthly averaged UHI in 2010 around (a) 0000 UTC (0100 or 0200 LT in summer or winter, respectively) and (b) 1200 UTC (1300 or 1400 LT), for all available amateur stations in the urban area.

steep decline of the UHI shortly after sunrise, followed by a gradual recovery in the subsequent morning and afternoon. We think that the effect of heat storage and shadowing described by Hamdi and Schayes (2008) may be strengthened by the larger density of cold air, allowing it to remain in the lower urban canyon for a period after sunrise, especially in wind-sheltered places.

Station 102 shows a remarkable drop in the summer-averaged UHI around 2000 LT, followed by a quick recovery. Advection over a lake that is 100–200 m wide, located ~100 m to the southwest of the station, may be responsible for some cooling effects; we are, however, unable to explain the timing of the observed feature.

At all stations the UHI increases with decreasing wind speed (Fig. 4b), which is a known property of urban heat islands and of microclimates in general. At lower wind speeds, because of the smaller influence of advection and mixing, local circumstances become a stronger determinant of temperature. Moreover, wind speeds are generally smaller during nighttime, so that situations with lower wind speeds will mostly be nighttime situations, which tend to have a stronger UHI (see above). On average the UHI is ~1.5°C stronger in calm conditions (0 m s^{-1}) than in windy conditions (>4 m s^{-1}). This course is steeper than the 0.16°C (m $s^{-1})^{-1}$ found by Morris et al. (2001) on the basis of nighttime situations in summer in Melbourne. For the study presented here, when taking only nighttime situations (not shown), the difference increases until it is more than 2°C. Differences in climate, building architecture, and city size between Melbourne and the Netherlands make a physical intercomparison difficult.

The response of the UHI to temperature (Fig. 4c) has a U shape, showing a stronger UHI with low temperatures and with high temperatures. Between, these extremes a minimum is observed at temperatures of ~17°C. Low temperatures indicate cold nighttime situations. High temperatures in summertime in the Netherlands indicate warm daytime situations. Cold nights as well as warm days generally occur with "fair" weather, with little wind and clear skies, which indeed according to literature and to our observations (see the previous and following paragraphs) are favorable for strong UHI development.

The average UHI increases from ~0.5°C in overcast situations to ~1.5°C in clear conditions (Fig. 4d). This variation of 1°C is similar to the variation of 1.1°C found by Morris et al. (2001) for nighttime situations in the city of Melbourne. Taking only nighttime situations (not shown), the variation in our observations is ~1.3°C. Under clear weather conditions surface-based radiative fluxes are stronger, enhancing the effects of the differences in radiative properties between the urban and rural surface and hence increasing temperature differences.

The response of the UHI to sea level air pressure (SLP) shows a variation from ~0.3°C at SLPs of ~1000 hPa to ~1.2°C at SLPs of ~1025 hPa (Fig. 4e.). Given that in the summer in the Netherlands high SLPs tend to occur concurrently with cloudless, calm weather conditions, this link confirms the relations observed in Figs. 4b–d.

6. Annual course of the UHI

Figure 5 shows the course of the monthly averaged UHI over the whole year of 2010. In the previous section it was concluded that there are significant differences between the average magnitude of the nighttime and daytime UHI. To exclude a direct influence of the annual cycle in the length of the daylight period, Fig. 5 considers not the daily average UHI but rather the UHI averaged over the 3 h around midnight (UTC) and the 3 h around noon (UTC).

A distinct annual course is evident. During both daytime and nighttime the UHI is strongest during the summer half-year. The UHI is smallest during winter—close to 0°C (no UHI) on average. A "dip" in average UHI is visible in August. This is most likely caused by the very wet, dull, and cool August of 2010 (a below-normal average temperature and 2.7 times the normal average rainfall in De Bilt, in the center of the Netherlands). Possible causes for this annual variation are the annual variation in insolation, causing stronger energetic differences due to differences in surface radiative properties in summer, and the fact that in the Netherlands average wind speeds are higher during winter, causing stronger advection of rural air into urban areas.

The amplitude of this annual variation is comparable to that in other studies of the UHI in midlatitude regions, although differences in methods make a quantitative comparison difficult. Conrads (1975) found minimum temperatures in the city center of Utrecht that were in summer 2.7°C higher and in winter 1.7°C higher than at a nearby rural site. This amplitude of 1°C is similar to the amplitude in nighttime UHI in Fig. 5a. The difference in the type of measurement site [city center in Conrads (1975) vs residential areas in this study] may account for the fact that Conrads (1975) found a significant UHI in winter whereas we did not. Wilby (2003) found a similar amplitude of the annual cycle in the nighttime minimum temperature UHI in London, ranging from 2.2°C in July to 1.1°C in January.

7. Discussion and conclusions

This study explores the use of observations from automatic weather stations installed and maintained by weather amateurs for estimating the magnitude of the urban heat island effect in urban areas in the Netherlands. After a selection procedure for suitable and representative stations, about 10% of the available stations remained for use. For these stations we have found that the UHI increases with increasing population density and that it is strongest in nighttime conditions in calm weather. For annual variation, the daytime and nighttime UHI were found to be strongest in summer and on average near zero during winter months. One year of observations was used.

The results suggest that PD at the scale of neighborhoods may be a promising predictor for the UHI. The PD has a stronger link to the local building characteristics than does total city population and may be more easily available than building characteristics with more direct physical meaning, such as (spatially averaged) height-to-width ratios or sky-view factors. It may be worthwhile to investigate further the link between UHI and PD using longer observational records and wider and more detailed ranges of PDs.

The results of this study seem physically sound and agree well with the literature, with no alarming variation between the observational sites. For very small population densities the average observed UHI was near zero. This indicates that the applied station selection based on metadata was effective in excluding inappropriate data. A selection of automatic observations from weather amateurs appears to be of sufficient quality for atmospheric scientific research, provided that detailed metadata are available and are used to carefully select suitable stations.

Even such a selection of observations from weather amateurs is to some extent affected by microscale phenomena, however, and lacks professional control over observational circumstances. They may therefore not be as accurate and representative as professional observations made at a priori selected sites equipped with scientific instruments. Thus, this study should be seen as exploratory, and further research is needed. More observations should be gathered in Dutch cities, obtaining longer (multiyear) records in more controlled circumstances. Such future research should also include more densely developed urban landscape types such as city centers.

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REFERENCES

Arnfield, A., 2003: Two decades of urban climate research: A review of turbulence, exchanges of energy and water, and the urban heat island. *Int. J. Climatol.,* **23,** 1–26.

Brandsma, T., G. Können, and H. Wessels, 2003: Empirical estimation of the effect of urban temperature advection on the temperature series of De Bilt (The Netherlands). *Int. J. Climatol.,* **23,** 829–845.

Conrads, L. A., 1975: Observations of meteorological urban effects: The heat island of Utrecht. Ph.D. thesis, University of Utrecht, 84 pp.

Eigenberg, R. A., J. A. Nienaber, and T. M. Brown-Brandl, 2003: Development of a livestock safety monitor for cattle. American Society of Agricultural and Biological Engineers Paper 032338, 4 pp.

Fortuniak, K., K. Klysik, and J. Wibig, 2006: Urban–rural contrasts of meteorological parameters in Lodz. *Theor. Appl. Climatol.,* **84,** 91–101.

Gaffin, S. R., and Coauthors, 2008: Variations in New York City's urban heat island strength over time and space. *Theor. Appl. Climatol.,* **94,** 1–11.

Giridharan, R., S. Ganesan, and S. S. Y. Lau, 2004: Daytime urban heat island effect in high-rise and high-density residential developments in Hong Kong. *Energy Build.,* **36,** 525–534.

Hamdi, R., and G. Schayes, 2008: Sensitivity study of the urban heat island intensity to urban characteristics. *Int. J. Climatol.,* **28,** 973–982.

Hazeu, G., 2006: Land use mapping and monitoring in the Netherlands (LGN5). *Proc. Second EARSeL Workshop on Land Use and Land Cover,* Bonn, Germany, Center for Remote Sensing of Land Surfaces. [Available online at http://www.zfl.uni-bonn.de/research/earsel/special-interest-group-on-land-use/323-329_hazeu.pdf.]

Huynen, M. M. T. E., P. Martens, D. Schram, M. P. Weijenberg, and A. E. Kunst, 2001: The impact of heat waves and cold spells on mortality rates in the Dutch population. *Environ. Health Perspect.,* **109,** 463–470.

Johnson, G., T. Oke, T. Lyons, D. Steyn, I. Watson, and J. Voogt, 1991: Simulation of surface urban heat islands under 'ideal' conditions at night part 1: Theory and tests against field data. *Bound.-Layer Meteor.,* **56,** 275–294.

Kim, Y.-H., and J.-J. Baik, 2004: Daily maximum urban heat island intensity in large cities of Korea. *Theor. Appl. Climatol.,* **79,** 151–164.

——, and ——, 2005: Spatial and temporal structure of the urban heat island in Seoul. *J. Appl. Meteor.,* **44,** 591–605.

McLaren, C., J. Null, and J. Quinn, 2005: Heat stress from enclosed vehicles: Moderate ambient temperatures cause significant temperature rise in enclosed vehicles. *Pediatrics,* **116,** doi:10.1542/peds.2004-2368.

Morris, C. J. G., I. Simmonds, and N. Plummer, 2001: Quantification of the influences of wind and cloud on the nocturnal urban heat island of a large city. *J. Appl. Meteor.,* **40,** 169–182.

Nakamura, R., and L. Mahrt, 2005: Air temperature measurement errors in naturally ventilated radiation shields. *J. Atmos. Oceanic Technol.,* **22,** 1046–1058.

Nakamura, Y., and T. Oke, 1988: Wind, temperature and stability conditions in an east–west oriented urban canyon. *Atmos. Environ.,* **22,** 2691–2700.

Oke, T., 1973: City size and the urban heat island. *Atmos. Environ.,* **7,** 769–779.

——, 1982: The energetic basis of the urban heat island. *Quart. J. Roy. Meteor. Soc.,* **108,** 1–24.

——, 2006: Initial guidance to obtain representative meteorological observations at urban sites. Instruments and Observing Methods Tech. Rep. 81, WMO/TD-No. 1250, 47 pp.

——, and G. Maxwell, 1975: Urban heat island dynamics in Montreal and Vancouver. *Atmos. Environ.,* **9,** 191–200.

Park, H.-S., 1986: Features of the urban heat island in Seoul and its surrounding cities. *Atmos. Environ.,* **20,** 1859–1866.

Sakakibara, Y., and E. Matsui, 2005: Relation between heat island intensity and city size indices/urban canopy characteristics in settlements of Nagaro Basin, Japan. *Geogr. Rev. Japan,* **78,** 812–824.

Steeneveld, G. J., S. Koopmans, B. G. Heusinkveld, B. Van Hove, and A. A. M. Holtslag, 2011: Quantifying urban heat island effects and human comfort for cities of variable size and urban morphology in the Netherlands. *J. Geophys. Res.,* **116,** D20129, doi:10.1029/2011JD015988.

Vandentorren, S., F. Suzan, S. Medina, M. Pascal, A. Maulpoix, J.-C. Cohen, and M. Ledrans, 2004: Mortality in 13 French cities during the August 2003 heat wave. *Amer. J. Public Health,* **94,** 1518–1520.

Watanabe, S., T. Sano, H. Kamada, and H. Ezura, 2006: Reducing gene flow from pollen dispersal of genetically modified plants in special screened greenhouses. *Plant Biotechnol.,* **23,** 129–135.

Watkins, R., J. Palmer, M. Kolokotroni, and P. Littlefair, 2002: The London heat island: Results from summertime monitoring. *Build. Serv. Eng. Res. Tech.,* **23,** 97–106.

Wiacek, A., J. R. Taylor, K. Strong, R. Saari, T. E. Kerzenmacher, N. B. Jones, and D. W. T. Griffith, 2007: Ground-based solar absorption FTIR spectroscopy: Characterization of retrievals and first results from a novel optical design instrument at a new NDACC complementary station. *J. Atmos. Oceanic Technol.,* **24,** 432–448.

Wilby, R. L., 2003: Past and projected trends in London's urban heat island. *Weather,* **58,** 251–260.

Yamashita, S., K. Sekine, M. Shoda, K. Yamashita, and Y. Hara, 2003: On relationships between heat island and sky view factor in the cities of Tama River basin, Japan. *Atmos. Environ.,* **20,** 681–686.