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A simple method to estimate the urban heat island intensity in data sets used for the simulation of the thermal behaviour of buildings

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Abstract

Test Reference Years (TRY) are data sets tailored for use in the context of simulations with respect to the thermal behaviour of buildings. They are based on measurements and observations from weather stations of the German Meteorological Service (Deutscher Wetterdienst, DWD) and represent the climate conditions of a larger area with an order of magnitude of 100 km x 100 km. The data sets cannot, however, be readily applied to urban areas. The air temperature as one of the most important meteorological elements for the building-related simulations frequently is subject to an increase with respect to the conditions outside the city area due to what is called the urban heat island effect. Numerous field measurements have led to the development of empirical relations to assess the urban temperature modification. These relations were implemented in a straightforward method. It applies a set of easily accessible parameters in a combination of different empirical formulae to derive an estimate of the urban air temperature modification. An intercomparison of calculated versus measured air temperature data showed that this method might yield a realistic representation of the urban heat island intensity.

Keywords: test reference years, urban heat island, city size, cloudiness, wind speed, daily cycle of urban heat islandTitle.

1 Introduction

In order to (i) simulate the thermal behaviour of buildings, (ii) estimate their energy consumption and (iii) assess the size of heating, air conditioning and indoor air circulation equipment, distinct climate data sets, so-called "Test Reference Years" [abbreviated as TRY (Blümel *et al.*, 1986; Christoffer *et al.*, 2004)] are commonly used for more than 25 years. These data sets are based on time series of meteorological measurements and observations from weather stations and contain a number of meteorological elements (e.g., air temperature, cloud cover, wind speed, and global solar radiation) in hourly resolution. The selection process of the stations aims at a high degree of representativity with respect to 15 German climate regions. In response to user needs and request, an update yielded new TRY which were generated from a more current data base. The most recent version was finalized in April 2011 and is available at www.dwd.de/TRY.

The standard locations of weather stations that take meteorological measurements and observations used in the TRY representing each of the 15 German climate regions are usually open, non-urban areas. Therefore characteristics of the local climate as they would occur for example in urban areas, e.g., as urban heat islands, are not sufficiently represented. As the surrounding air temperature plays a key role in simulating the thermal behaviour of buildings, an important aim in the development of new TRY was to implement a method considering the impact of an urban-induced modification of the temperature regime.

The authors acknowledge that there is a complex network of effects and dependencies at the interface of urban areas and the atmosphere. The TRY project explicitly focuses on the sub-systems of this network which are relevant for aspects delineated earlier in this Section. Moreover, a pragmatic approach is sought which may on the one hand leave some aspects uncovered but which on the other hand addresses the reproduction of the thermal effects of urban areas using sources of information that are comparably well accessible. Thus, aspects such as the urban air quality which is comprehensively addressed, e.g., in the ESCOMPTE programme (Cros et al., 2004; Kottmeier et al., 2003), are considered to be of limited relevance for the TRY-specific issues[1]. The same holds true for the large body of research that

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[1]The authors are aware that pollutants contribute to temperature and water vapour contents, thus influencing the long-wave radiation regime. This is known as the Local Greenhouse effect (e.g., Montávez et al., 2008), Yet, it is depending on the urban type and the UHI module to the TRY aims at a straightforward applicability for an 'average city'.

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is devoted to aerodynamic effects due to the shape of urban structures (e.g., street canyons). The BUBBLE-Programme (Rotach et al., 2005) comprehensively deals with the related matters, yet some results from the remote sensing segment of that programme will be considered for estimating the magnitude of urban effects. Urban agglomerations are affecting the precipitation regime as well, which was, e.g., studied and established by the METROMEX experiment (Changnon, 1981). Yet, the precipitation influence is of limited relevance to the thermal issues affecting the TRY for simulating the thermal behaviour of buildings.

There have been numerous field campaigns concerning the empirical determination of city-related atmospheric properties. Several urban areas and major cities have been extensively studied. A review of developments can be found e.g. in Arnfield (2003), Parker (2010) or Baklanov et al. (2011). A very fruitful detail can, e.g., be found in Tab. III of Arnfield (2003) where generalizations of urban heat island factors are listed and juxtaposed with related studies.

2 Estimation of the maximum urban heat island intensity

Urban heat islands (UHI) develop to an intensity which depends on a number of impact parameters (Hupfer and Kuttler, 2005 or Baklanov et al. 2011) such as the degree of sealed surface, built-up density, physical properties of building materials and anthropogenic heat production. Furthermore, the UHI intensity depends on different weather conditions. Cloudless and calm weather conditions cause the most intense urban warming rates. Increasing cloudiness and wind speed reduce the UHI until it virtually disappears.

The concept of an urban climate modification had been introduced almost 200 years ago in Howard, (1818). Since then, there were numerous attempts to improve the understanding of the urban effect and to quantify it. Modern studies and field campaigns which took the recent developments of climate but also that of cities into account led to the publications of empirical approaches. Some of these also incorporated descriptions of the physical processes and feedbacks at work, adding to an emerging vast body of literature. An aspect that is well-studied and documented extensively is the strong interdependence of the UHI magnitude and the number of inhabitants of an urban area. Empirical relations which, interestingly, highly depend on the earth's region in which the cities are being built, hinting at an influence of factors such as culture, architectural style, urban planning or energy efficiency, have been published, e.g. in Oke (1973), Kraus (1979), Landsberg (1981) or Park (1986). Publications, e.g., by Kuttler (1997) or Matzarakis (2001) compile and compare the different findings. Superimposed is a dependency with latitude due to the varying radiation budget as described in Wienert (2002). Since the region for which the TRY are designed is constrained to Central Europe, it is assumed that this latter dependency can be neglected.

Any approach that aims at the reproduction of the UHI magnitude needs to prominently implement this population/location aspect. For cities in Central Europe the best results are obtained from a relation based upon the common logarithm of the number of inhabitants, as shown in Eq. (1).

$$UHI_{max}, = 2.01 \cdot \log(In) - 4.06 \qquad (1)$$

UHI_{max} := maximum urban heat island intensity [K]
In := number of inhabitants of a city [1]

According to this relation, the UHI_{max} extends to a magnitude of about 6 K for 100,000 inhabitants or to about 9 K for 3 million inhabitants. Moreover, there is the influence of local weather conditions as well as their daily and annual cycles which affect the UHI intensity. The subsequent sections of this paper present these influencing factors and their implementation in the UHI module of the TRY. The overall concept is to define a maximum magnitude of the UHI and then superimpose the reducing factors some of which are dynamic, i.e., determined by weather conditions and some of which are static, i.e., determined by daily and annual cycles of the UHI intensity.

3 Dependence of the urban heat island on weather conditions

There are two main weather elements which influence the intensity of the UHI: wind speed and cloudiness. The former is adding turbulence and vertical mixture to the air over the urban area, thus reducing or eliminating temperature differences between the densely populated area and the "unperturbed" surroundings. According to empirical studies (see, e.g., Oke, 1973 or Böhm and Gabl, 1978) a limiting wind speed (hourly mean of the wind speed) can be derived using the relation shown in Eq. (2). It takes into account the city size (by ways of incorporating the number of inhabitants) and denotes the wind speed above which the UHI cannot be traced.

$$v_g = \left(\frac{1.91 \cdot \log In - 1.73}{3.37}\right)^2 \qquad (2)$$

v_g := limiting wind speed (hourly mean) [m/s]
In := number of inhabitants [1]

The next step is to introduce a function which quantifies the influence of the wind speed on the UHI intensity. This function has a range from 0 (wind speed = v_g) to 1 (wind

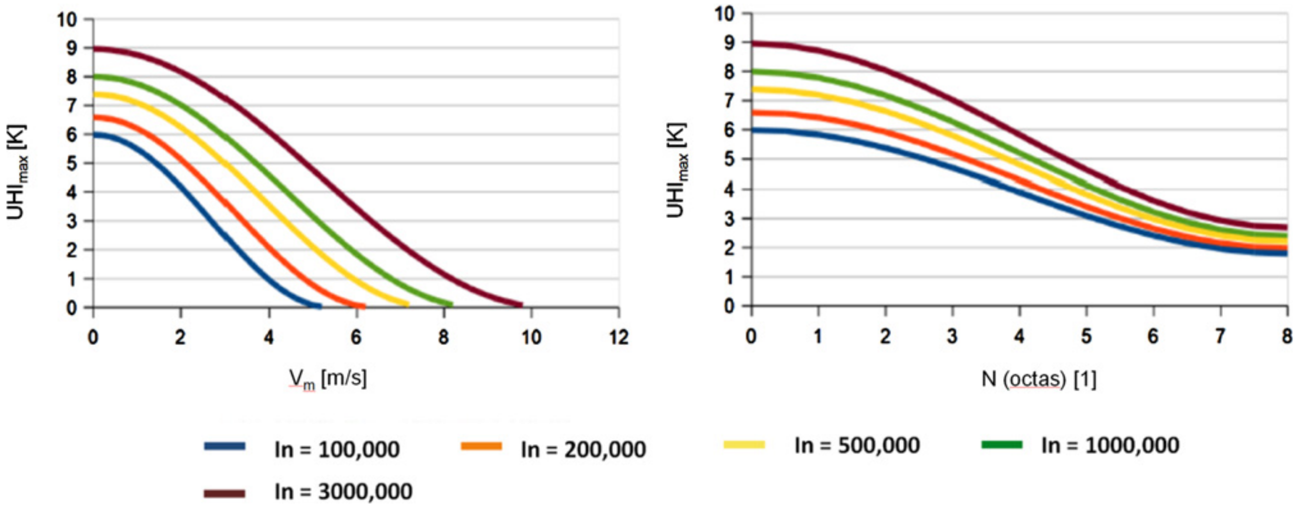

Figure 1: Dependence of the maximum UHI intensity (UHI_{max}) on mean hourly wind speed (v_m), as described in Section 3 and mean hourly cloud cover (N), as described in Section 3, for cities of different size, i.e., with different numbers of inhabitants (In) (cf. SPEKAT *et al*., 2010).

speed = 0). It is used to compute the impact of the wind speed on the UHI intensity and is shown in Eq. (3) (cf. SPEKAT et al., 2010).

$$f_v(v_m) = \frac{1 + \cos\left(\frac{v_m}{v_g} \cdot \pi\right)}{2} \quad (3)$$

$f_v(v_m)$:= correction of the UHI intensity due to the influence of the wind speed [1]

v_m := mean hourly wind speed [m/s] over the past 24 hours.

v_g := limiting wind speed (hourly mean) [m/s], according to Eq. (2)

The averaging over 24 hours takes into account that the UHI develops and changes with a certain inertia. The left-hand part of Fig. 1 visualizes the wind-dependent reduction of the UHI.

The second weather-dependent effect is due to the influence of cloudiness on the urban radiation regime. The amount of cloud cover reduces the UHI intensity. Empirical relations are, e.g., documented in NÜBLER, 1979, KUTTLER, 1997 or MORRIS et al., 2001. According to the latter, the quantification of the UHI reduction due to cloudiness can be stated in the shape of a power function ($y=x^{-z}$) but the nature of the dependency can be expressed by a cosine-dependent law as well, found by the other authors and shown in Eq. (4) (cf. SPEKAT et al, 2010). It has a range from 0.3 (maximum cloudiness) to 1 (no clouds) and thus takes into account that the UHI cannot vanish by cloudiness alone which constrains this reduction asymptotically, a strategy also supported by MORRIS et al. (2001).

$$f_N(N) = 0.3 + 0.7 \cdot \frac{1 + \cos\left(\frac{N}{8} \cdot \pi\right)}{2} \quad (4)$$

$f_N(N)$:= correction of the UHI intensity due to cloudiness [1]

N := average total cloud cover in octas (0 to 8) [1] over the past 24 hours

Again the averaging over 24 hours takes into account that the UHI develops and changes with a certain time lag. It should be noted that the cloudiness effect also depends on the *type* of clouds. However, the recorded hourly station data available to compute the related UHI-reducing effect do not provide cloud type information. The relation shown in Eq. (4) has been derived considering that the net effect of using the total cloud cover instead needs to be minimized which is adequate for the purpose of incorporating the UHI in long-term simulations of the thermal behaviour of buildings.

The right-hand part of Fig. 1 visualizes the cloudiness-dependent reduction of the UHI.

4 Daily and annual cycle of the urban warming

Among the UHI generalizations set up in OKE (1982, 1987) and compiled in ARNFIELD (2003) three are dealing with issues of daily and annual cycles: (i) UHI intensity is greatest at night; (ii) UHI may disappear by day or the city may be even cooler than the rural environment and (iii) UHI intensity is best developed in the summer or the warm half of the year. ARNFIELD (2003) lists numerous empirical studies in which these generalizations were confirmed. The authors considered a field study conducted in Düsseldorf (Germany) and published in KUTTLER (1997) for the *qualitative* assessment of daily and annual cycles. Differences in 2m temperature between the city center and its surroundings were evaluated in that paper.

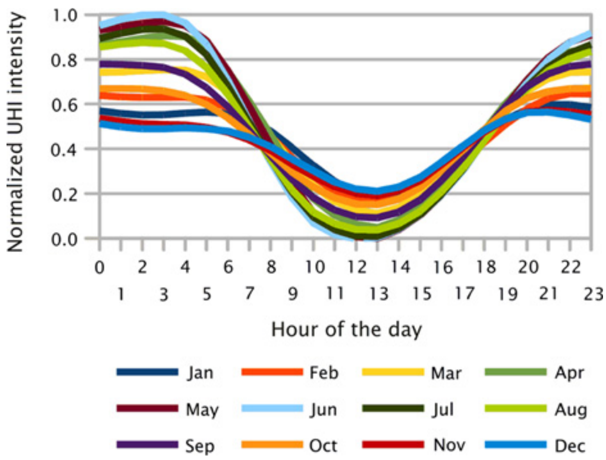

Figure 2: Dependence of the UHI intensity on the hour of the day and the month of the year. Displayed is the normalized and smoothed analysis of the results of a city-vs.-surrounding temperature measurement campaign published in KUTTLER (1997).

The aim was to define a function that covers a range from 0 (no influence on the UHI) to 1 (maximum influence on the UHI) in two dimensions: 24 hours of a day and 12 months of a year. Using a graphical display of the measurement campaign's results in KUTTLER (1997), normalizing and smoothing was applied to extract the general features. The result is displayed in Fig. 2. The most intense UHI occurs in the early morning hours, but the magnitude of this effect varies over the months of the year, being largest in June and smallest in December. Then, using a Fourier analysis for each of the graphs in Fig. 2, a quantification is achieved, cf. Eq. (5)

$$f_t(t) = const + a_1 \cdot \cos(t) + \ldots + a_n \cdot \cos(n \cdot t) + \ldots$$
$$\ldots + b_1 \cdot \sin(t) + \ldots + b_n \cdot \sin(n \cdot t) \qquad (5)$$

$f_t(t)$:= correction of the UHI due to the daily cycle [1]
t := time as hour of the day (0 to 23 h) [h]
const := constant of the Fourier series [1]
a_n, b_n := Fourier coefficients [1]
n := number of Fourier coefficients [1]

It proved to be sufficient to use n=3 Fourier coefficients, in order to constrain the difference between the given and the reconstructed graph to < 0.01 for each hour. As can be deduced from Fig. 2, the components *const*, a_n and b_n are different from month to month, because the daily cycle varies in shape according to an annual cycle. It does so in a way that can be described by a second Fourier analysis, which allows to smoothly approximate the month-to-month change of shape. For the UHI module of the TRY a scheme was implemented which derives the values $f_{dcac}(t)$ of the correction (between 0 and 1) for 24 hours of the day and each of the 365 days of the year. The subscript *dcac* denotes that it represents the daily cycle (*dc*) and the annucal cycle (*ac*).

5 Evaluation of the method

From the synthesis of the considerations that were dealt with in Sections 2 through 4 a special application tool for considering the urban temperature modification in TRY-data sets used for simulating the thermal behaviour of buildings was developed. The concept that a maximum UHI is reduced by several influencing factors which depend on time and the local weather is expressed in Eq. (6); its parts have been introduced in Sections 2 through 4:

$$UHI(t) = f_v(v_{24}) \cdot f_N(N_{24}) \cdot f_{dcac}(t) \cdot UHI_{max} \qquad (6)$$

$UHI(t)$:= UHI-intensities at time t [K]
t := time of day (day hour 0 h to 23 h) [h]; the subscript *dcac* in the equation's third factor indicates that a daily (*dc*) as well as an annual cycle (*ac*) are considered
v_{24} := mean wind speed (hourly mean) over the last 24 h before t [m/s]
N_{24} := mean total cloud cover over the last 24 h before t [1]
UHI_{max} := maximum intensity of the UHI [K]

Based on the relation given in Eq. (6) a temperature excess due to an urban area of x inhabitants can be computed, modifying the time series in the TRY[2]. Fig. 3 illustrates the UHI intensity over the course of one year computed with data of the weather station Mannheim, i.e., for a city with 500,000 inhabitants. The UHI_{max} according to Eq. (1) amounts to about 7.5 K. As can be seen in Fig. 3, the conditions for the development of an UHI of *maximum* intensity are not entirely met, i.e., the effect of the reducing factors is always present, although a magnitude of 5 K and more is frequently reached. Comparing this to measurement studies by GAFFIN et al. (2008) for New York and TOROK *et al.* (2001) for Australian cities or remote sensing studies for Los Angeles and Paris (DOUSSET and GOURMELON, 2003) as well as Berlin (MUNIER and BURGER, 2001) confirms that the maximum possible magnitude of the UHI could not be detected. It should be noted, however, that remote sensing studies deal with the surface temperature, whereas the UHI module of the TRY, ground-based measurement and campaigns take the temperature at a reference height (usually 2m) which usually is below the temperature of the surface at day and above it at night.

6 Case Study

In a case study (SPEKAT et al., 2010) it was tested whether the method for estimating the UHI intensity

[2]In the TRY module the modification of the time series due to the UHI includes a second procedure which should be briefly mentioned: A raised temperature level results in a reduced relative humidity (RH). Therefore the saturation water vapour pressure is re-calculated using the increased temperature, thus correcting RH.

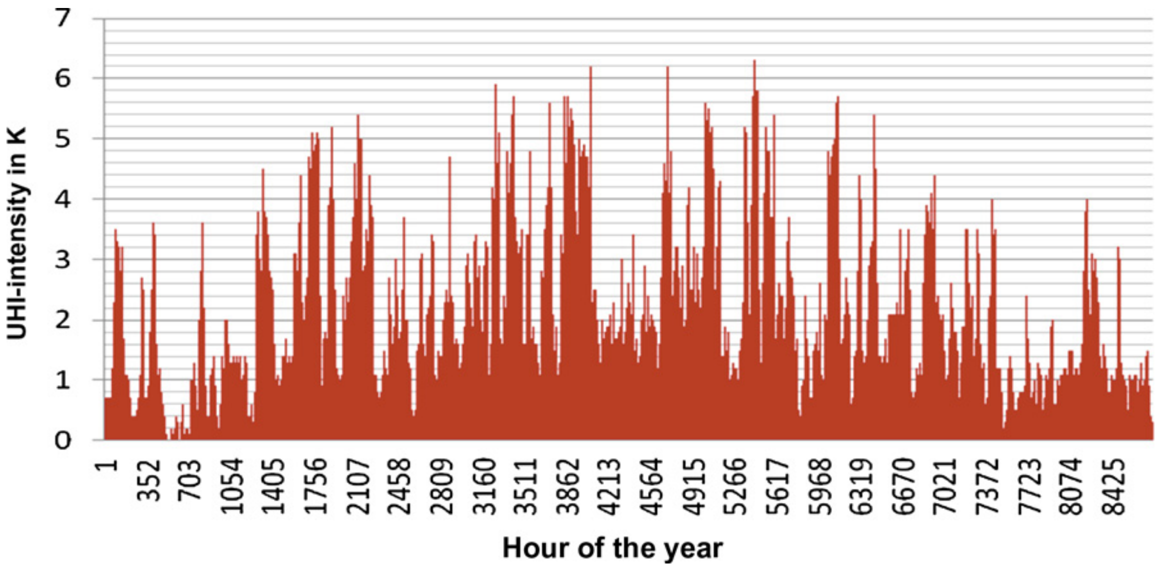

Figure 3: Urban heat island intensity for a city of 500,000 inhabitants in hourly resolution based on the application of the UHI module, described in Sections 2–4, to a Test Reference Year (TRY). Meteorological data are derived from the station Mannheim which is representative for theTRY-specific climate region "Upper Rhine Valley-Lower Neckar Valley" in the SW of Germany.

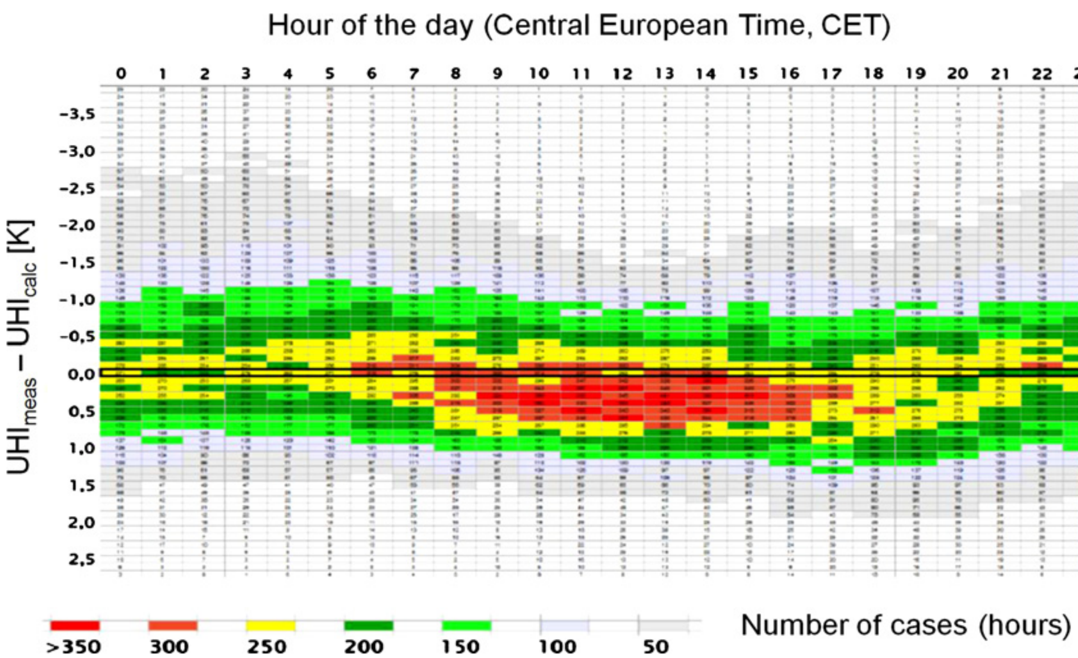

Figure 4: Daily cycle of the difference between a *measured* (UHI_{meas}) and a *computed* heat island (UHI_{calc}). Shown are the frequency distributions for the differences between UHI_{meas} and UHI_{calc}, determined for each hour of the day. The example analyzes the UHI of the city of Berlin (assumption: 3 million inhabitants) using the station pair Berlin-Alexanderplatz (downtown) and Potsdam (at the edge of the Greater Berlin area). The analyzed time frame is the 20-year period 1988-2007 (cf. Spekat *et al.*, 2010).

described above is able to yield realistic results. For this purpose the hourly measurements of the 2m air temperature over a period of 20 years (1988 to 2007) from the downtown weather station Berlin-Alexanderplatz and the weather station Potsdam, which is located in a relatively open, forested area and subject to comparably small urban effects, were analyzed.

Assuming a city of 3 million inhabitants leads to an UHI_{max} of about 9 K. The case study pursued this question: If we were to add the UHI of Berlin to a station series from the surrounding area, presumably unaffected by the Berlin UHI, would we be able to reproduce the average temperature behaviour of the Berlin downtown time series? In the next step a UHI correction according to

Eq. (6) for a city of 3 million inhabitants was applied to the hourly time series from Potsdam, yielding a "Berlin look alike" series with a *computed* UHI. Then, for the 20-year period of the analysis, the difference between the measured temperature contrast Berlin-Potsdam (the *measured* UHI) and the "look alike series" of the *computed* UHI, was determined. The results are shown in Fig. 4. Ideally, the differences should be zero if model and measurements agree. Indeed, the frequency distribution of the differences between measured and computed UHI exhibits a proximity to zero. This is even more pronounced for the times of high UHI potential, i.e. during the night hours. For the daytime hours a slight bias towards the measured temperature difference being higher than the computed one (the model slightly *under*estimates the measurements) can be traced, although, on average, this tends to be well below 0,5 K. Moreover, in 86% of the cases (i.e. hours from a 20-year period) the differences between calculation and measurement do not exceed ±1.5 K. This shows that a rather straightforward and simple method has the potential to realistically represent the UHI influence.

7 Concluding remarks

Using empirically derived relations a rather simple method for estimating the urban heat island (UHI) intensity and to incorporate it into temperature time series has been developed. It requires variables that are well accessible such as the city size (number of inhabitants), local weather conditions (cloudiness, wind speed) as well as information on the time of the day and the day of the year. The method is applied in the context of so called Test Reference Years (TRY) which constitute climate data sets that are essential for simulating, e.g., the thermal behavior of buildings.

Previous issues of the TRY were designed under the assumption of a rather high homogeneity of the "background" climate conditions within a large area (on the order of several 100 km^2). In the dialogue with users of TRY it became clear that there is improvement potential with respect to an incorporation of local temperature modifications as they are exerted by urban agglomerations.

With the UHI module it is possible to produce meteorological time series with an increased degree of realism that in turn are fed into the application model chain. They can, e.g., be used for simulating the characteristics of buildings in different settings and surroundings as well as in sensitivity studies such as those that focus on improving the energy efficiency of buildings or studying sustainability issues in building.

All this is not restricted to the present climate. The UHI module has been designed in such a way that it can be run by using data from climate projections to incorporate urban elements simulating the future thermal properties of buildings in changing climate conditions.

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All authors contributed to the development of the methodology. Moreover, Uwe Wienert co-wrote the paper and co-ordinated the writing/revision process, Frank Kreienkamp developed the software implementation, Arne Spekat co-wrote the paper and Wolfgang Enke participated in the software implementation. All authors read, discussed and approved the final manuscript.

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