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Atmospheric Measurement Techniques Discussions

A new approach for highly resolved air temperature measurements in urban areas

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Abstract

In different fields of applied local climate investigation, highly resolved data of air temperature are of great importance. As a part of the research programme entitled City2020+, which deals with future climate conditions in agglomerations, this study focuses on increasing the quantity of urban air temperature data intended for the analysis of their spatial distribution. A new measurement approach using local transport buses as "riding thermometers" is presented. By this means, temperature data with a very high temporal and spatial resolution could be collected during scheduled bus rides. The data obtained provide the basis for the identification of thermally affected areas and for the investigation of factors in urban structure which influence the thermal conditions. Initial results from the ongoing study, which show the temperature distribution along different traverses through the city of Aachen, are presented.

1 Introduction

Since residents living in urban areas are especially affected by extreme temperature events (e.g. Clarke and Bach, 1971) urban climate studies are gaining in importance. Currently, more than half of the world's population already lives in cities (United Nations Population Division, 2009), which accentuates the major role agglomerations must play in mitigation and adaptation to climate change (EEA, 2009). However, recommendations regarding behavioural patterns during heat stress situations and urban planning measures require a comprehensive understanding of the inner urban temperature distribution including the identification of thermal hot spots.

Urban temperature data are a prerequisite for all investigations on the urban heat island (UHI) effect. They are usually either based on remote sensing techniques or on air temperature measurements. Remote sensing data like infrared surface temperature from airborne measuring instruments may have a very high spatial resolution and are presently available for many urban areas. This spatial resolution is appropriate to

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exhibit typical urban structures that are expected to cause the UHI effect. Nevertheless, information on surface temperature cannot replace air temperature data, since – beside the problem that the former are typically only available for single days – there is no fixed relation between surface and air temperatures. Hence, research on the UHI effect requires air temperature data. However, their spatial and/or temporal resolution is still not optimal (Mirzaei and Haghighat, 2010). Especially for systematic analyses of the relationship between urban structures and temperatures for different weather situations a large data basis is desirable.

Air temperature data can be obtained from mobile measurements, measurements at permanent or temporary weather stations. On the one hand, the use of weather stations provides high data accuracy using a well-known standard technology. On the other hand, the spatial representation of weather station data within the urban environment, which is characterized by the surface composition including buildings, infrastructure and different types of land use, is very limited. Consequently, since the beginning of the 20th century, many efforts have been made to identify temperature patterns in urban areas with high spatial resolution instead of only using single point information. Already in the 1920s, Peppler (1929) and Schmidt (1930) arranged mobile measurements using cars equipped with meteorological instruments as tools for urban climate research. With the impetus of these investigations, various studies in Europe followed using mobile measurements (e.g. Lossnitzer and Freudenberg, 1940; Sundborg, 1950; Conrads and van der Hage, 1971; Kuttler, 2001). These measurements permit an improved detection of the UHI but they are of limited resolution either in space or time. For a higher spatial resolution, mobile carriers like pedestrians or bicycles (e.g. Klemm and Müskens, 2006; Heusinkveld et al., 2010) have been used. This method is suitable for small-scale investigations within individual urban districts. In order to cover a larger area, trams have been equipped with measuring instruments (Yamashita, 1996). Both variants are based on relatively small data samples and are typically restricted to a certain period of the day.

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Within the present study the advantages of different earlier approaches and of new technology were combined. The measurement concept was designed to meet the requirements of an urban climate investigation consisting of:

- a data collection system with a manageable temperature and GPS data logger providing adequate accuracy,
- a reliable long-term carrier system,
- an evaluation software that allows optimized data processing.

The approach applied comprises temperature data loggers and global positioning systems that are attached to local transport buses belonging to the municipal traffic company ASEAG (Aachener Straßenbahn und Energieversorgungs-AG). Continuous recording on several bus routes simultaneously throughout the day and on a large number of days results in very high spatial and temporal resolution (Fig. 1).

The investigation area, the city of Aachen, is situated in a basin with differences in altitude of up to 285 m causing significant local climate phenomena during situations with low wind speed. With a size of approximately 160 km^2 and 245 000 residents (31 December 2009) (Stadt Aachen, 2010) the urban area is located between the Eifel Low Mountains in the south and the German Lowlands in the north. Situated concentrically within the urban area the city centre is surrounded by traffic rings along former ancient city walls. Within the inner city district the building structure is characterized by high building density. A high degree of surface sealing can also be observed in the industrial and commercial areas east of the city core. The southern and western parts of Aachen are distinguished by open spaces and a less dense building structure while the southern suburban area of Aachen is covered by forest.

2 Method

2.1 Data collection

Local transport buses belonging to the municipal traffic company are equipped with a self-built measurement device consisting of a temperature data logger and a GPS logger. The benefits of mounting the device on local transport buses are environmental acceptability as well as time and cost savings since no additional vehicle has to be used. Due to the use of automatic instruments during scheduled bus rides, the working hours of the personnel are also not excessively stressed. Operating cycle and procedure are traceable and maintenance of the equipment is performed during regular maintenance of the buses.

For temperature measurements, data loggers of the type Hobo Pro v2 (Onset 2009) are used. They record at intervals of 5 s with an accuracy of ±0.2 °C and a memory capacity of 42 000 measurements. Date and time are saved on the logger at each measurement as well.

Location data are recorded every 15 s by a GPS logger type Winner Fly (Mobile Action, 2010). If the public transport bus exceeds a driving speed of 50 km h^{-1} the interval is lowered to 10 s. The memory can store 65 000 waypoints. Temperature and GPS loggers are combined in a common enclosure (Fig. 2). A solid plastic tube protects the instruments from undesirable outside influences like damage by tree branches. This tube, in turn, is fixed to a flexible stake which fits into a mounting device. The top of the unit is covered with two radiation shields between which the external temperature sensor is placed.

To ensure fast temperature adaption by intense ventilation, fin heat sink elements with heat conducting paste enlarge the surface of the temperature sensor and thus provide a maximized contact surface for wind ventilation.

As the engine is at the back of the vehicle, the device is attached to the front of the bus. To minimize the impact of warm air streaming outside the bus when opening the doors at each stop, the location of the logger was chosen to be on top of the bus on the driver's side (left).

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Since March 2010, temperature data has been recorded during scheduled public bus rides within several measurement campaigns (Table 1). The time-lag between the measurements was at least one day because only one set of measurement devices was available so that a routine maintenance timeout was necessary. The routes chosen for this study form a network of four different traverses through the city – covering all kinds of local climate zones (Fig. 1) – with individual lengths between 12 and 36 km (Table 2). Hence, urban/suburban temperature differences and inner city temperature differences can be detected. Depending on the particular bus and route the running time for one route varies between 40 min and 1 h 30 min. The instruments log temperature data continuously from about 4 a.m. to about midnight.

Data evaluation is mainly focused on predefined points along the traverses that represent typical urban structures like urban canyons, different building densities, crossroads and green spaces (Fig. 3).

In order to specify the limiting conditions for data analysis, especially the minimum distance between the evaluation points along the bus routes, the loggers' adaptability to changing temperatures needs to be ascertained. As defined by Liljequist and Cehak (1984), the adaption time of thermometers can be described by a coefficient of thermal inertia. It is the time interval that is necessary to cover 63% of a given temperature difference. For this study two test series were carried out. In each case, two loggers were cooled down and then exposed to approximately 29.1 °C. One logger was ventilated with a wind speed of about 5 ms^{-1}, representing the bus driving at low speed. The other logger was not ventilated. A much faster adaption was achieved by the ventilated loggers (Fig. 4), which registered a temperature change of about 21.7 °C (18.8 °C) within 10 min. Thus, 63% of the temperature range was reached within the first 48 (52) s (average: 50 s), which represents the coefficient of thermal inertia. This coefficient of thermal inertia is then used to determine a minimum distance between the evaluation points along the bus routes to secure accuracy and, thus, avoid spatial uncertainty.

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Taking all available data records from the bus rides into consideration, 90% of all measured temperature changes along the routes were smaller than 0.01 °C s^{-1}. Within the time of thermal inertia (50 s) and a driving speed of 5 ms^{-1} a distance of 250 m can be covered. Thus, 90% of all temperature measurements are expected to register a temperature change of less than 0.5 °C per 250 m at a driving speed of 5 ms^{-1}. Due to thermal inertia, this value of 0.5 °C represents only 63% of the real temperature change (100% = 0.79 °C). The difference between measured and expected real temperature changes results in a bias of 0.29 °C. Although a bias of 0.29 °C is considered to be acceptable as it is in the same order of magnitude as the accuracy of the instrument, the average bias is assumed to be smaller. The driving speed of 5 ms^{-1} is defined as the minimum speed for data evaluation and the distance of 250 m is chosen as the typical distance between the predefined evaluation points.

Since the bus routes have different road and traffic conditions and cover different urban structures, the real distances between the points differ. In the city centre, a high density of points was favoured because temperature differences are expected to be small and the driving speed often reaches the minimum value of 5 ms^{-1}. However, 90% of the predefined points have a minimum distance of 236 m, which is close to the aspired distance of 250 m.

2.2 Data processing

The evaluation software uses the GPS coordinates to select the closest temperature data and then interpolates them for their exact location. These values are finally assigned to predefined points. A similar approach, but manually performed, was used by Conrads and van der Hage (1971) who studied the influence of crossroads and open spaces on temperature in the city of Utrecht (Netherlands).

In order to make measurements from different points comparable in time, the measured temperature data is transformed into anomalies to simultaneously observed data from the reference weather station (WS) Aachen-Hörn (measuring interval = 10 min). WS Aachen-Hörn is operated by the Department of Geography at RWTH Aachen

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University. The station (50°47′ N, 06°04′ E, 198 m a.s.l.) is situated approximately 1.5 km west of the intersection of the bus routes in the city centre of Aachen (Fig. 1) on a hill within the Aachen basin in a suburban setting with residential and university buildings.

Spatial temperature distribution is produced by means of GIS based data processing software from the first temperature measurement campaigns. Temperatures at the predefined points are allocated to route sections with the predefined points serving as central points for each segment.

The data is separately processed for different time sections of the day in order to analyze the temperature distribution in the course of the day and to investigate the varying influence of urban factors during different periods. Five time periods represent the early morning (approx. 04:00 a.m.–07:30 a.m.), morning (07:30 a.m.–12:30 p.m.), afternoon (12:30 p.m.–05:30 p.m.), evening (05:30 p.m.–10:30 p.m.) and night hours (10:30 p.m.–approx. 12:00 a.m.). For an initial analysis, all data (comprising all measurement days) relating to a specific time of the day are averaged to obtain general results for the whole measurement period.

3 Preliminary results from the first measurement campaigns

By the end of 2010 the number of measurement days had reached 26, representing 9% of all days of the period. About 60 000 temperature values were measured for 256 points along 4 bus routes with a temporal resolution of mainly less than 2 h for each measurement point along the bus routes.

Figure 5 shows the average differences between temperatures recorded during bus rides and temperatures observed at the WS Aachen-Hörn for the afternoon situation including the time of air temperature maximum (12:30 p.m.–05:30 p.m.) and an evening situation including the cooling phase between 05:30 p.m. and 10:30 p.m. While areas in the inner city district exhibit positive temperature anomalies, lower temperatures than at WS Aachen-Hörn occurred at forest sites and suburban locations. This is in

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accordance with previous urban climate investigations in the city of Aachen (Havlik and Ketzler, 2000). A pronounced UHI within the inner city area is mainly produced by a high building density and a high degree of surface sealing accompanied by only few urban green spaces as well as reduced nocturnal cooling and restrained air exchange. This effect is pronounced for the evening situation during which temperature anomalies are increased by a factor of approximately 3. Even the aggregated data indicate intra-urban differences such as alternating warm and cool zones in residential areas, which are not only related to the general position in the city.

4 Discussion and conclusions

In order to obtain a large air temperature data set for the assessment of the urban temperature distribution, a mobile measuring system based on scheduled bus rides was developed. Measurements along different bus routes covering the inner city of Aachen as well as its surroundings permit a detailed analysis of temperatures for different periods of the day. High spatial and temporal resolution is obtained through a high frequency of temperature records along the bus routes. An initial evaluation of the first 26 measurement days reveals that spatial and temporal temperature patterns reflect the effects of (densely) built-up areas, green sites and open spaces on air temperature and confirm the expected temperature distribution in the investigation area with a heated up inner city and cooler areas at suburban sites. However, findings also indicate overlaying small-scale effects which will be subject to further investigation. To what extent different urban structures modify local temperature will be examined and evaluated in conjunction with air quality issues during further progress of the project. The present study focuses rather on an introduction of a measurement concept that permits the amount of air temperature data to be increased.

In addition to clear sky conditions, which are considered in most case studies, the fixed course of the campaigns produces a certain random representation of weather situations. This yields representative results for the whole measuring period and permits a detailed analysis of the general temperature patterns throughout the day in the urban area of Aachen. An increasing amount of data in the near future will produce a greater representativeness of the temporal distribution of all weather types and will allow for comprehensive correlations between urban climate effects, urban structures and specific weather situations. Furthermore, the daily temperature course and the rate of temperature change for different periods of the day will be taken into consideration in order to analyse the varying influence of urban environmental parameters on air temperature.

An even higher resolution could be obtained by using temperature loggers with a faster temperature adaption. Nevertheless, factors which determine the feasibility and transferability such as size, weight, price, accuracy and response time of the measuring instrument were weighed up against each other carefully in order to facilitate the establishment of the method in other cities. The use of temperature loggers installed on public buses is a promising approach that can be transferred to other regions as public bus networks generally operate within and outside inner city districts.

A higher resolution could also be achieved by a higher density of predefined points. However, this approach has various disadvantages. Since a driving speed of at least $5\,\text{m}\,\text{s}^{-1}$ is needed to ensure sufficient ventilation, data recorded at lower speeds are not considered. Establishing a higher density of predefined points will not increase the amount of available data in total nor provide more data for a particular location. Artificial ventilation would not solve this problem either because in case of traffic jams or longer stops at bus stops, waste heat from the bus itself or other cars cannot be controlled properly.

Due to logistic issues and the dependence on scheduled bus rides, mobile measurements could not be performed during the whole night. However, due to the fact that high nighttime temperatures may cause adverse health consequences (McGeehin and Mirabelli, 2001), nocturnal measurements need to be added in ongoing investigations. The involvement of medical and social aspects (e.g. diseases due to heat stress, especially affected population groups, population structure, social networks) further permits a detailed risk assessment.

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Additional bus routes would also contribute to a more comprehensive view on the urban temperature structure of the city of Aachen. Especially in the inner urban districts of Aachen a closer network of routes would be helpful to analyse the climatic situation and its influencing factors in different urban districts.

The measurements will continue in 2011 and will be arranged to obtain data from at least another 60 days (5 measurement days/month) representing daily courses of air temperature for all relevant weather situations. Beside the local limiting conditions mentioned above, it can basically be operated nearly continuously and produce data comparable to the temporal resolution of automatic weather stations.

According to preliminary data analysis this methodological approach – combining data of high spatial and temporal resolution with geographical attributes – opens new perspectives in the detection of urban temperature structures that influence air temperature patterns within cities. Using bus lines as carriers together with highly resolved measuring equipment, the former disadvantages of low spatial or low temporal representation can be overcome. A better identification of main factors such as building characteristics (e.g. height, density, area, building use) or land use (e.g. urban green, streets, continuous urban fabric) contributing to heat stress situations further indicates a mitigation potential that can be implemented in urban planning measures.

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Table 1. Measurement days, daily temperature (maximum, mean, minimum), temperature amplitude and wind conditions at WS Aachen-Hörn.

Date	Prevailing wind direction	T_{max}	T_{mean}	T_{min}	T_{amp}
16 Mar 2010	SW	8.1	4.3	2.7	5.4
18 Mar 2010	SW	18.7	13.0	7.1	11.6
22 Mar 2010	SW	13.2	8.6	6.7	6.5
24 Mar 2010	S	21.3	14.4	8.7	12.6
26 Mar 2010	SW	12.3	8.8	7.6	4.7
03 May 2010	NW	8.4	6.8	5.4	3.0
05 May 2010	NE	11.9	8.1	1.9	10.0
07 May 2010	WNW	8.3	5.6	3.4	4.9
10 May 2010	NNE	12.2	8.2	6.2	6.0
12 May 2010	WNW	7.3	5.3	3.2	4.1
21 June 2010	SW	20.1	13.9	8.3	11.8
23 June 2010	NE	25.5	20.3	10.3	15.2
25 June 2010	NNE	26.6	21.2	14.6	12.0
30 June 2010	W	28.7	22.9	15.5	13.2
02 July 2010	S	35.2	29.8	22.0	13.2
08 Sep 2010	S	22.5	16.2	12.5	10.0
10 Sep 2010	SW	18.5	15.3	13.0	5.5
13 Sep 2010	WSW	18.3	14.1	10.6	7.7
17 Sep 2010	W	15.8	10.9	8.0	7.8
20 Sep 2010	SW	19.5	15.5	11.7	7.8
22 Sep 2010	SSW	24.0	17.1	9.5	14.5
24 Sep 2010	WSW	16.2	13.4	12.3	3.9
11 Oct 2010	ENE	16.4	10.2	4.9	11.5
15 Oct 2010	WNW	10.9	9.2	8.0	2.9
18 Oct 2010	WSW	9.9	7.4	5.5	4.4
20 Oct 2010	W	8.7	4.9	3.3	5.4

Weather station information: weather station Aachen-Hörn operated by the Department of Geography at RWTH Aachen University (50°47′ N, 06°04′ E, 198 m a.s.l.), measurement interval is 10 min.

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Table 2. Overview of the different bus lines and their route characteristics.

Bus line	Running time	Route length	Route direction	Covered local climate zones
2	50 min	15 km	Southwest to east	Suburban areas, forest and densely built residential sites
7	40 min	12 km	South to northwest	Densely built residential sites and industrial area
11	1 h 30 min	36 km	Southeast to northeast	Suburban areas, forest, densely built residential sites, industrial area and open spaces
45	50 min	14 km	West to southeast	Suburban areas and densely built residential sites

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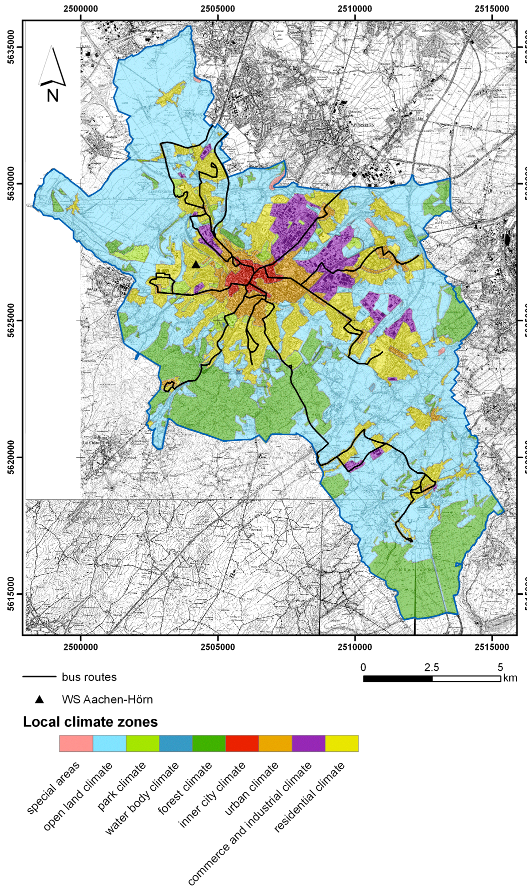

Fig. 1. Local climate zones for the city of Aachen (Havlik and Ketzler, 2000) and bus routes along which the mobile measurements are carried out.

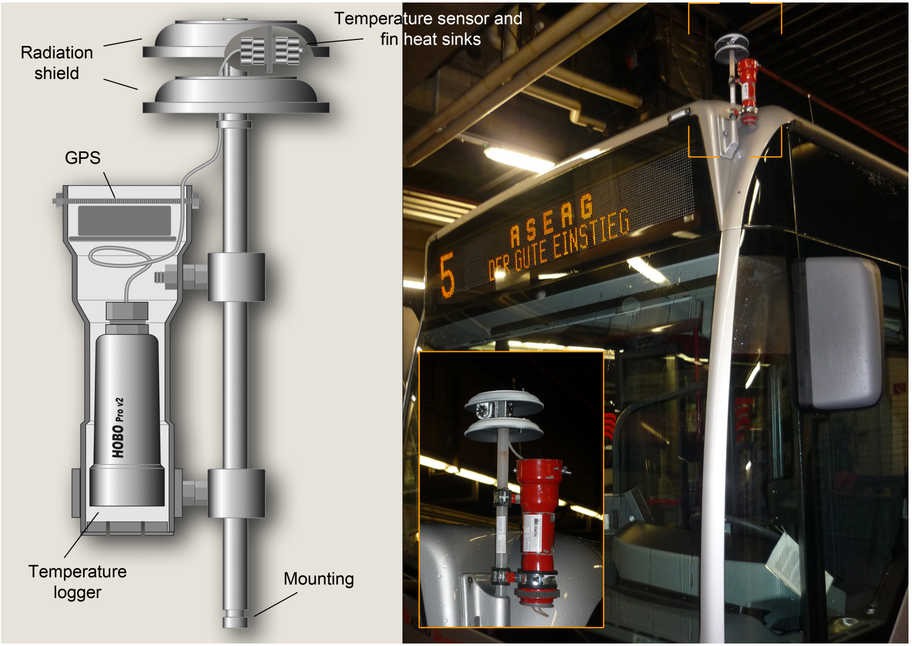

Fig. 2. Measuring instrument including GPS- and temperature logger.

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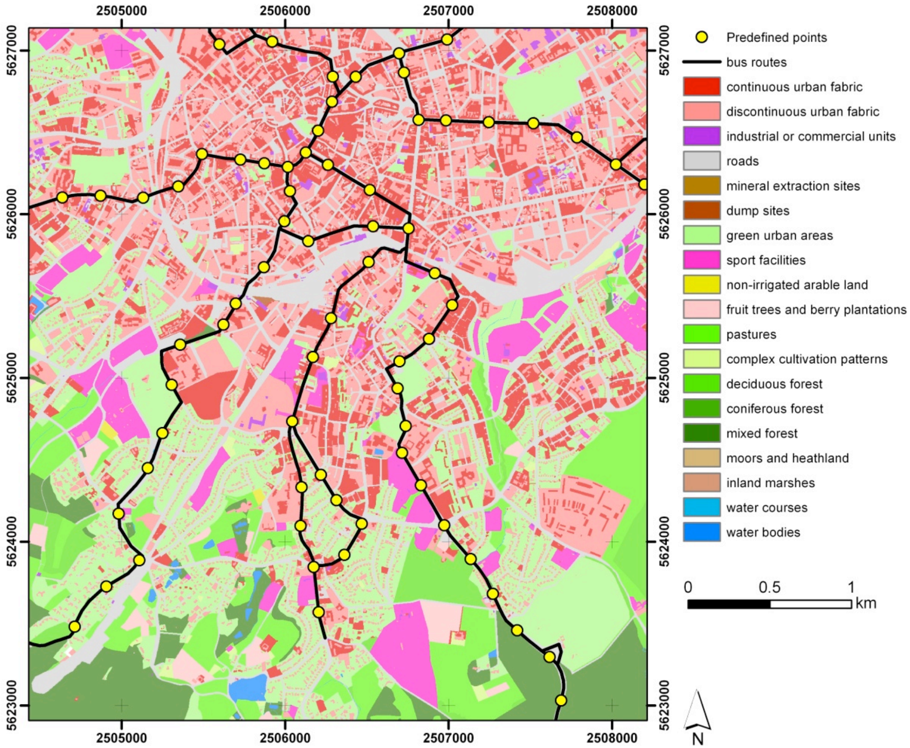

Fig. 3. Locations of the predefined points along the bus routes representing various area characteristics.

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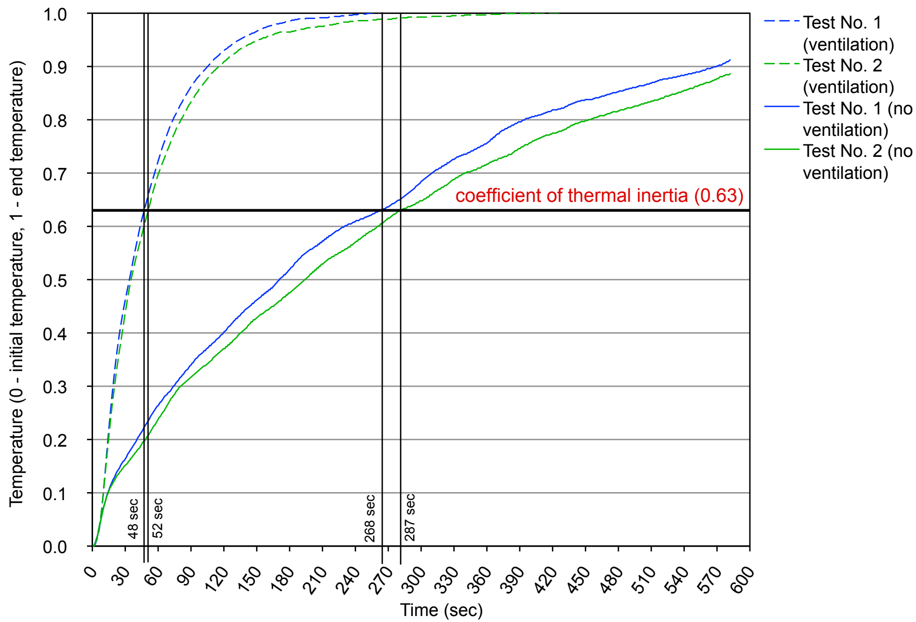

Fig. 4. Temperature adaptability of ventilated (5 ms^{-1}) and non-ventilated sensors.

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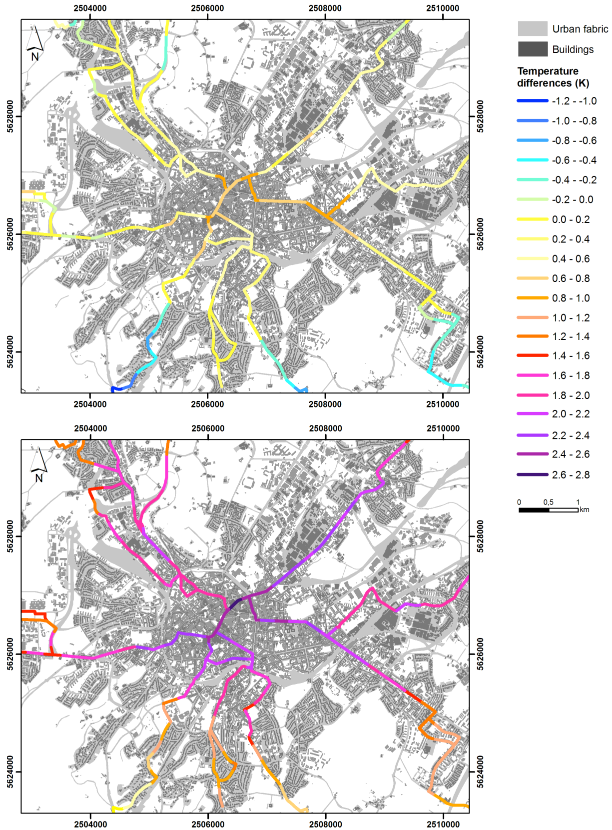

Fig. 5. Average temperature differences between mobile measurements and suburban WS Aachen-Hörn during **(a)** the period of temperature maximum (12:30 p.m.–05:30 p.m.) and **(b)** the evening cooling phase (05:30 p.m.–10:30 p.m.).

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