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ORIGINAL PAPER

Modeling of changes in thermal bioclimate: examples based on urban spaces in Freiburg, Germany

Dominik Fröhlich · Andreas Matzarakis

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Abstract The Place of the Old Synagogue is a popular place in the city center of Freiburg, a medium-sized city in southwest Germany. It is going to be redesigned soon. In this paper the impact of urban street design and surface material on human thermal comfort is analyzed using the example of the Place of the Old Synagogue. The models SkyHelios, RayMan, and ENVI-met were applied to quantify and qualify the changes. All three models are freely available. Their combination allows analysis of development in long-term conditions, as well as changes in spatial distribution of thermal comfort, as well as of heat stress in summer. Results show that the models can provide valuable information. About the Place of the Old Synagogue, quantitative results show that the period with heat stress will become longer, while the intensity of heat stress increases. The spatial results show that the most significant changes are due to changes in shading. Nevertheless, an increase in thermal stress up to 10 °C is calculated for areas, where ground coverage changes from grass to pavement.

1 Introduction

Thermal bioclimate strongly influences comfort, productivity and human health (Mayer 1989; Nastos and Matzarakis 2006, 2008; Mayer et al. 2008). While the so-called ideal urban climate (Mayer 1989) can provide, among others, "a possibly wide range of atmospheric conditions avoiding extremes" (Mayer 1989). The thermal bioclimate of human beings depends on several meteorological and nonmeteorological parameters (Mayer and Höppe 1987). According to Mayer (1993), some of these parameters are strongly influenced by the surroundings [e.g., wind speed and the different radiation fluxes that strongly influence thermal bioclimate (Matzarakis 2001)]. Resort places in urban areas can therefore be designed/redesigned in view of maximum possible thermal comfort to humans. One of this popular urban places in Freiburg is the Place of the Old Synagogue. In the summer month, the place is usually overcrowded. As it is going to be redesigned soon, an analysis of the changes in thermal comfort caused by the modification could be prior performed.

Freiburg, a town of about 220,000 inhabitants located in southwest Germany, is the warmest city in Germany (Nübler 1979; Rudloff 1993). Its inhabitants are thus already familiar with heat stress in summer. Latest studies indicate that heat stress will occur even more often in the future due to global climate change (Matzarakis and Endler 2009, 2010). Local thermal bioclimate can easily be modified by the design of a place (Matzarakis and Herrmann 2010), e.g., by changes in ground coverage and shading (Lin et al. 2010a, b; Asaeda and Ca 2000; Dimoudi and Nikolopoulou 2003). At the Place of the Old Synagogue, both ground coverage as well as shading will, among others, be affected by the redesign. So significant influence on thermal comfort can be expected.

The aim of the study is to select and apply appropriate models that are freely available and can deliver results that can be applied in planning purposes. The Place of the Old Synagogue has been selected because of the frequent use of this place and the political importance in a medium-sized city with long tradition in climate-oriented urban planning (Matzarakis et al. 2008). The novelty of research here is that it is relying not only on a case study but also on a combination of a quantification of the basic elements and parameters. For

D. Fröhlich · A. Matzarakis (✉)
Meteorological Institute, Albert-Ludwigs-University Freiburg,
Werthmannstrasse 10,
79085, Freiburg, Germany
e-mail: andreas.matzarakis@meteo.uni-freiburg.de

instance, the calculation of the sky view factor (SVF) for the different planning opportunities, the combination of high temporal resolution based on hourly data of more than 10 years and the quantification of the recent and expected conditions in terms of the changes. The methodology of this study is prepared to assist model users dealing with questions of thermal comfort. Therefore, a method is described which delivers detailed quantified changes. These descriptions are also presented graphically in a way that can be easily understood.

2 Methodology and data

2.1 Area of interest

Since the City of Freiburg is the warmest city in Germany (Nübler 1979; Rudloff 1993), there is a strong need for reduction of heat stress particularly in the summer months. Additionally, the city government of Freiburg claims for itself leadership in environmental and climate issues among the cities in Germany, calling Freiburg a "green city." This makes Freiburg a perfect location for that kind of studies. Westward from the inner city of Freiburg between the main university buildings I and II (KG1 and KG2), the old university library and the theater, there is a large open space called Place of the Old Synagogue (Figs. 1 and 2). As the city wants it to be redesigned, it perfectly suits as an area of interest for this case study.

The Place of the Old Synagogue is currently divided into four sections by two roads crossing it. The larger one, the "Rotteckring" crossing from north to south, is an asphalt covered major road claiming more than a third of the place's area. The other one is the "Bertholdstraße" crossing from northwest to the east. It is sealed by a pavement. The two remaining areas are a smaller one in front of the theater and a larger one in front of KG2. The smaller one is covered half by lawn and half by pavement. The larger one is covered mostly by lawn. All in all, there are currently 22 trees of different sizes spread over the place. As they are deciduous trees, they provide shade in summer and let shafts of sunlight pass in winter, which makes them particularly important for local thermal bioclimate (Fig. 1).

After the redesign, according to current planning, the place will be sealed completely by large light-colored stone plates in the center, framed by small-pebble pavement. Both of the streets, the "Roteckring" as well as the "Bertholdstraße" will become pedestrian precinct and will be integrated in one single place area. Only a small section in front of the theater will be separated by a different, darker pavement. In front of the theater and in the southeast of the place, there will be narrow water basins. Many of the trees are planned to be removed. Instead, some small crowned deciduous trees will be added in the south and east of the place (Fig. 1).

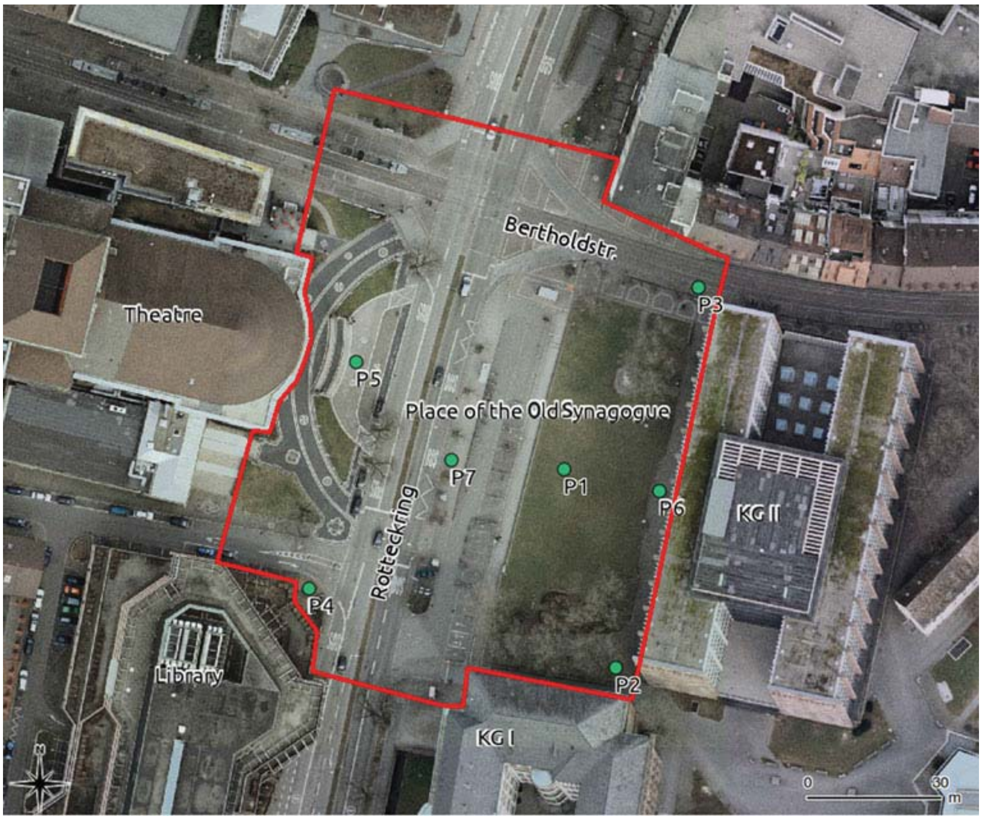

Fig. 1 The Place of the Old Synagogue before the redesign. Aerial imagery provided by the City of Freiburg

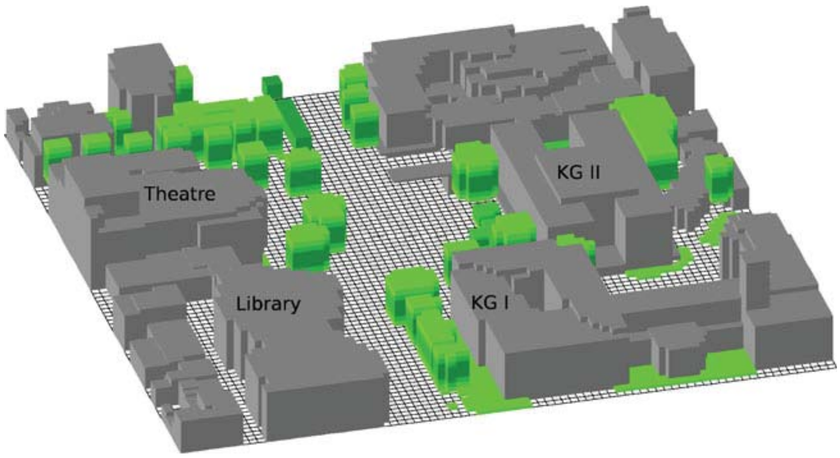

Fig. 2 The Place of the Old Synagogue in Freiburg after the redesign as an ENVI-met surface model viewed from South West. Data source: "iMA Richter & Röckle GmbH und Co. KG." Image created with Leonardo

Additionally, a new building is planned to be set up in the northern part of the place.

2.2 Physiologically equivalent temperature

As an index for the assessment of the changes in thermal bioclimate, the physiological equivalent temperature (PET) was used. It is defined "as the air temperature at which, in a typical indoor setting (without wind and solar radiation), the energy budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed" (Höppe 1999). It is one of the most commonly used indices for thermal bioclimate, so results can be easily compared to those from other studies (Matzarakis and Endler 2009; Lin et al. 2010a, b; Lopes et al. 2011). Another big advantage of PET is the use of °C as unit, making results more easy to be interpreted by people without knowledge in the field of human biometeorology. As the case with many other thermal bioclimatic indices, PET also base on a human energy balance model. For the case of PET, the Munich Energy Balance Model for Individuals (MEMI, Höppe 1984), is used. One of the most important determining factors for PET is the mean radiant temperature, T_{mrt}. T_{mrt} is defined as the temperature of a perfectly black and equal surrounding environment that leads to the same energy balance as the current environment (VDI 1998; Fanger 1972).

2.3 Applied models

For analyzing the changes in thermal stress on humans at the Place of the Old Synagogue, a combination of three models were used. SkyHelios (Matzarakis and Matuschek 2010) was used for a quick overview and data preparation, while quantitative changes have been calculated in RayMan (Matzarakis et al. 2007, 2010; Matzarakis and Rutz 2010) and the spatial distribution of changes were analyzed in ENVI-met (Bruse 1999).

2.3.1 SkyHelios

SkyHelios is a new tool for the rapid estimation of the SVF which is the free portion of the upper hemisphere. It was used for a quick overview over the changes in SVF. Additionally, SkyHelios is able to combine source data of different types and to create input data for the use in RayMan. RayMan itself is only able to import a textfile containing raster data or a RayMan obstacle file. The obstacle files are not very common and normally have to be produced manually using the RayMan editor. SkyHelios, in contrary, is able to deal with several different input files at the same time, that can be of many commonly used formats. In this case, a textfile containing an elevation raster, an ESRI® shapefile containing the surrounding buildings, and a RayMan object file containing the trees were imported. Both the shapefile as well as the elevation raster have been directly extracted from data provided by the City of Freiburg using common GIS software. After importing the input data, seven points were selected and two fisheye images were saved for each of them (one for the current situation and one for the planned place) in preparation for the calculations with RayMan.

2.3.2 RayMan

For analyzing the long-term changes in thermal bioclimate due to the redesign of the place, the RayMan model was applied. RayMan is a numerical MODEL developed by the Meteorological Institute of the Albert-Ludwigs University Freiburg to calculate radiation fluxes in simple and complex environments (Matzarakis et al. 2007, 2010; Matzarakis and Rutz 2010; Röckle et al. 2010). This allows the calculation of T_{mrt} which is used to calculate thermal bioclimatic indices, e.g., PET. The idea was thus to calculate PET twice for each of the seven points using the same meteorological data as input. During the first run, the fisheye image for the current place was used. During the second, the image of the redesigned place was used. Afterward, results were classified into nine classes of thermal stress (Table 1; Matzarakis and Mayer 1996) and compared. As the fisheye images as well as Bowen ratio and albedo, which had to be adjusted due to a change in ground coverage, are the only difference between the results of the two runs, the differences in results show the absolute changes in PET caused by the redesign.

Input data for the RayMan calculations In order to get representative, basic and comprehensive results, meteorological data of a 10-year period from Sept. 1st, 1999 to April 30th, 2010 in hourly resolution provided by the urban climate station of the Meteorological Institute Freiburg (Matzarakis et al. 2000; Matzarakis and Mayer 2008) was used. As the urban climate station is located quite close to the area of interest, its data is particularly suited for this study. The only adaption that had to take place was an altitude correction of air temperature, T_a, and wind speed, v. T_a was approximated by applying a factor of 0.6 K/100 m. For approximation of wind speed in 1.1 m above ground level, an approach from Matzarakis and Mayer (1996) was used, applying the following formula:

$$WS_{1,1} = WS_h*(1.1/h)^a \qquad (1)$$

where: a=0.12z_0+0.18, $WS_{1.1}$ is the wind speed in 1.1 m above ground, WS_h* is the wind speed in measuring altitude, 1.1 is the target altitude in meters above ground, h is the original measuring altitude and z_0 is roughness length.

2.3.3 ENVI-met

The spatial distribution of changes in thermal bioclimate was analyzed with ENVI-met. ENVI-met is a three-dimensional, prognostic, microscale model for the calculation of meteorological conditions and distribution of air pollutants (Bruse 1999). It consists of an atmosphere model, a soil model and a vegetation model. Spatially, ENVI-met divides into a model core, containing the three-dimensional area of interest as a raster of cells and a surrounding border cell. Although it is highly complex, the version 3.1 of ENVI-met used is not able to calculate PET itself. Only another index PMV is supported. Though the model delivers all the necessary parameters, PET can be calculated using an additional program called CalcPET. This method was also used for this analysis.

Table 1 Thermal stress classes for human beings [with an internal heat production of 80 W and a heat transfer resistance of the clothing of 0.9 clo (clothing index)] modified after Matzarakis and Mayer (1996)

PET	Thermal perception	Grade of physical stress	Combined classes
<4	Very cold	Extreme cold stress	Cold
4–8	Cold	Strong cold stress	Cold
8–13	Cool	Moderate cold stress	Cold
13–18	Slightly cool	Slight cold stress	Comfortable
18–23	Comfortable	No thermal stress	Comfortable
23–29	Slightly warm	Slight heat stress	Comfortable
29–35	Warm	Moderate heat stress	Hot
35–41	Hot	Strong heat stress	Hot
>41	Very hot	Extreme heat stress	Hot

Input data for the ENVI-met calculations As ENVI-met is a prognostic model, it only requires initial values to run. As initial conditions, meteorological data of the urban climate station Freiburg was used. Starting from Sept. 4th, 2003, the first day of a heat wave in 2003, a 7-day period, was calculated for the current place as well as for the planned one. These conditions have been chosen as initial values because they cause highest possible heat load for humans and thus represent meteorological conditions of highest importance for the reduction of thermal stress on humans (Mayer 1989). Results of the run before and after the redesign were compared to analyze the changes. However, it was more complicated to get the spatial input. As the ENVI-met editor "Eddi" does not support any common input except a background image, the whole model area was to be rebuild manually. As ENVI-met model areas are very complex, this takes lot of time. Fortunately for this study, the model area had already been created for another study (Röckle et al. 2010) and was provided by the urban climate consulting company "iMA Richter & Röckle GmbH und Co. KG."

3 Results

The results are presented as follows: (a) changes in the SVFs in order to know about the changes of the fundamental conditions about radiation possibilities, (b) changes on thermal comfort classes based on long-term data sets and with application of an appropriate human bioclimate model and (c) spatial analysis of thermal comfort issues during a specific episode in order to quantify the areas with highest heat load for humans.

3.1 Changes in SVF

By the reconstruction of the Place of the Old Synagogue, the SVF, which is the visible fraction of the sky, will be changed (Fig. 3). This influences thermal bioclimate by affecting T_{mrt}. While during times with cold stress, especially in the winter time, a higher SVF could cause an increase in thermal bioclimate due

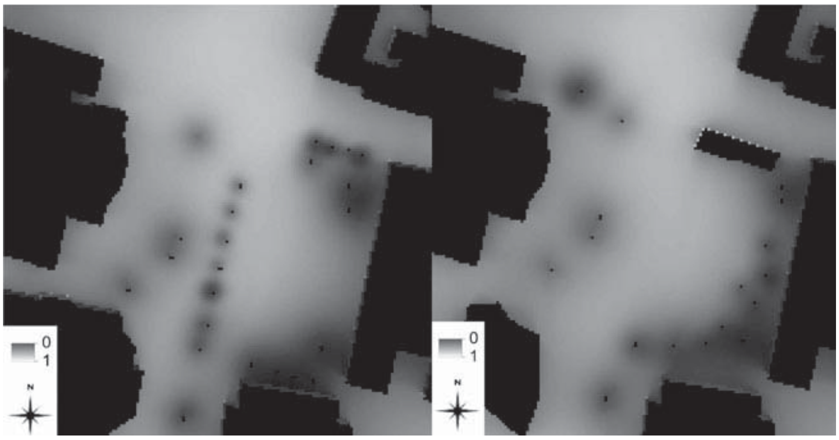

Fig. 3 Sky view factor in the Place of the Old Synagogue as calculated by SkyHelios before (*left*) and after (*right*) the redesign

to rise of hours with direct sunlight, the same effect would cause a decrease of hours with thermally comfortable conditions by increasing heat stress in the summer time. Especially the centers of large urban places often show this effect, as most of them are sparsely shaded. Results of the calculations show that the current place as well as the planned one are missing shading in their central area. While the trees along the Rotteckring will be removed during the redesign, which enlarges the central area with high SVF, SVF will be reduced by the new small trees in front of the KG2. All in all, this central area is thus only little expanded, but rather moved westward.

3.2 Changes on thermal comfort classes based on long-term data sets

The changes in thermal stress on human beings at the Place of the Old Synagogue due to the redesign is calculated to be very different at various points, so presenting all of them would be to much for one paper. Only point 7 is thus presented here as an example. It is located closest to the center of the place and shows a typical and clear view of development.

Comparing the plotted frequency of the occurrence of the different thermal stress classes (cf. Table 1) at point 7 before (Fig. 4) and after (Fig. 5) the redesign, this development is

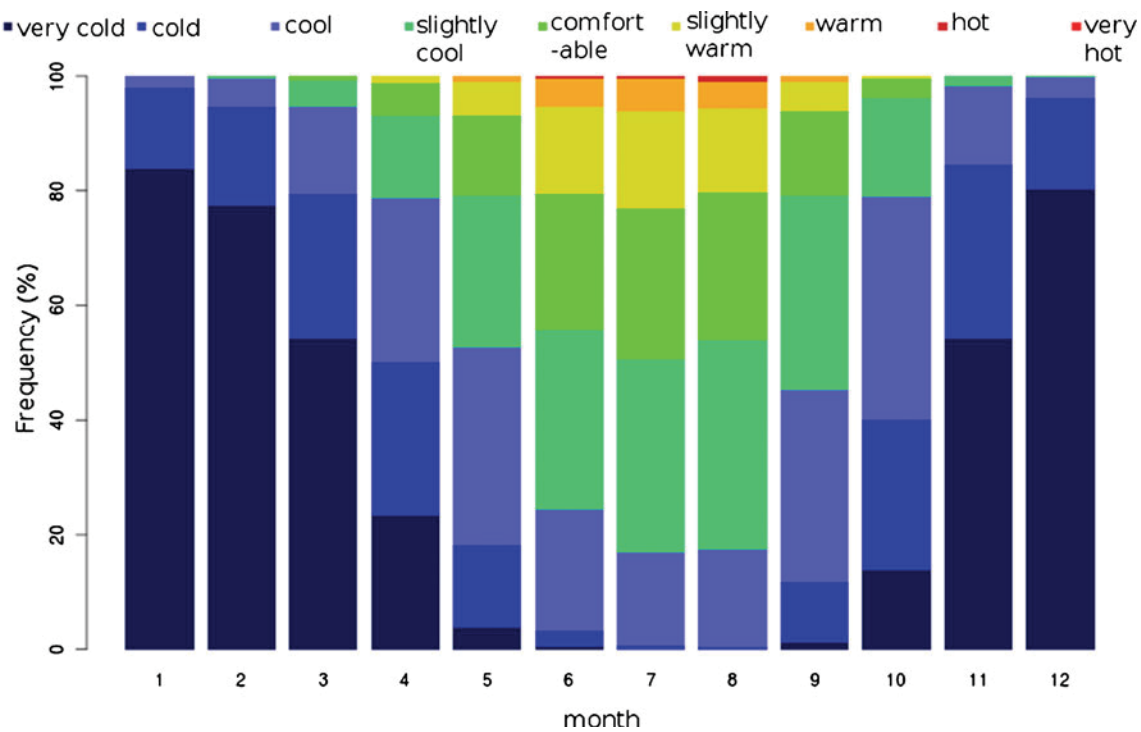

Fig. 4 Frequency of the different PET-classes at point 7 (located in the center of the place) on the current place

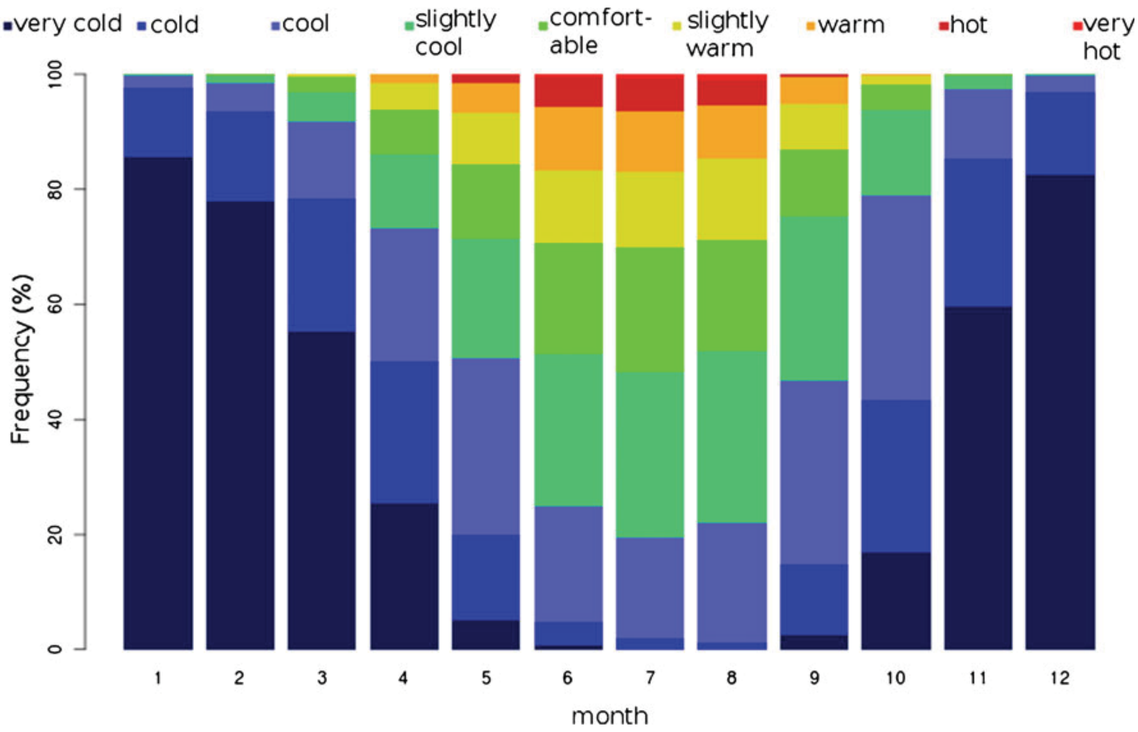

Fig. 5 Frequency of the different PET-classes at point 7 (located in the center of the place) on the redesigned place

obvious: While there is heat stress (represented by the classes "hot" and "very hot") only to be found in June to August before the redesign, heat stress is expected to occur from May to September on the redesigned place. Also the frequency of its occurrence is significantly increased. While heat stress appears from June to August with a frequency of around 1 % before the redesign, its frequency rises to about 5 % in July onward. For June and August, a frequency of some 5 % is calculated. Besides the quantitative change, a qualitative development is shown by the comparison. While for the current place, the class "very hot," standing for PET of about 41 °C and thus extreme heat stress, is not calculated to occur at all, it is showing up from May to August at point 7 on the new place.

To assess the development for the place as a whole, however, all points have to be considered together. Therefore, average changes for all the points have been calculated. To facilitate interpretation of the results even more, they have been divided by the input time period to get monthly results of an average year. These monthly averages show a lot of differences in the frequency of occurrence for the different classes of thermal stress between those for the old and the redesigned place. To facilitate again the interpretation, the nine classes have been joined to form a "cold" class with cold stress, a "comfortable" class with thermally comfortable conditions and a "hot" class with heat stress (compare to Table 1). The new class "cold" thereby contains the former classes "very cold," "cold" and "cool," "comfortable" contains the thermal classes with relatively comfortable thermal conditions ("slightly cool," "comfortable" and "slightly warm") and "hot" consists of the classes with heat stress ("warm," "hot" and "very hot"). For each of the new classes, a comparison between the old and the redesigned place has been made. Results of the run before the redesign were subtracted from those created by the run after the redesign. Results of the subtraction show the changes due to the redesign.

The class of cold stress (Fig. 6) shows a decrease of hours with cold stress during the seasons spring and fall. During the winter months, a very light decrease of approximately 0.2 h/month is shown, while cold stress was calculated to be increased during the summer month by up to 3 h/month. In detail, a decrease of hours with cold stress is calculated for the months January to May and September to December. While this decrease is very small for the months January, September and December with less than 0.1 h/month, there is a strong decrease calculated for the months March to May with up to 7 h/month in April. Another medium decrease of around 1.5 h/month was calculated for the months October and November. Referring to the ideal urban climate (Mayer 1989), this can be considered positively, as thermal stress is reduced. In contrary, for the months of June to August, an increase of hours with cold stress was calculated. This increase is very small in June with less than 0.2 h, but raises up to about 3 h in August. This is, according to the ideal urban climate (Mayer 1989), to be considered a negative development. The decrease of hours with cold stress during

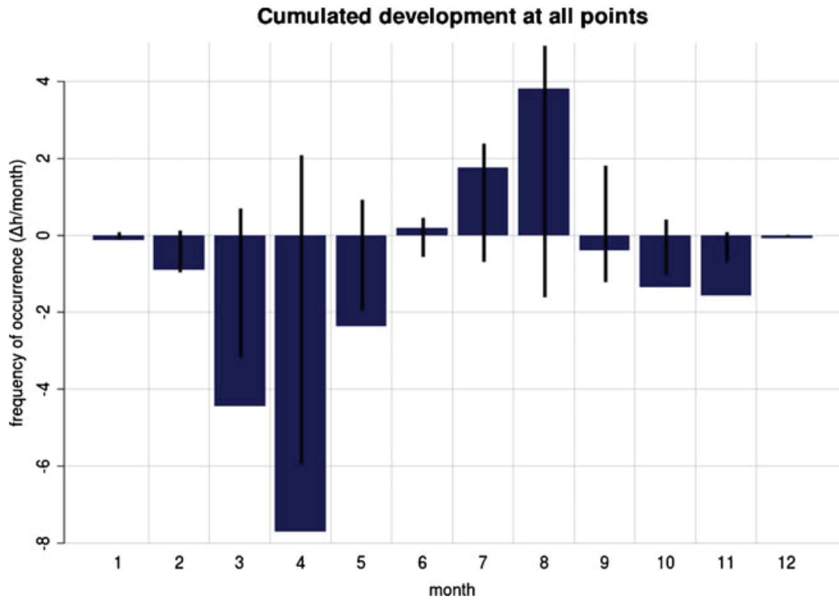

Fig. 6 Cumulated change in the frequency of occurrence of classes with cold stress (Table 1) due to the redesign in hours per month. The *black lines* indicate the range of the development at single points

spring and fall, as well as the increase of hours with cold stress in summer, can be explained by reduced shading. This causes warmer conditions during daytime in spring and fall by increased hours of direct solar radiation to the points. At nighttime, reduced shading causes cooler conditions due to an increase in net longwave radiation at nighttime.

Looking at the classes of thermal comfort (Fig. 7), a similar development can be seen. While hours with thermal comfort are occurring more often after the redesign in spring and, by a much smaller amount, in fall, they are significantly reduced in the summer months. In reference to the ideal urban climate (Mayer 1989), this again means an advantage during spring and fall, but a great disadvantage in summer. In detail, there is nearly no change in hours with thermal comfort calculated for the months January, May and December (less than 0.1 h/month). From February to April, they are increasing from about 1 h in February to up to about 6 h in April. From June to September, the hours with relative thermal comfort are strongly reduced. Starting with about 6 h in June, the reduction increases to about 12 h in August. In September, a smaller reduction of about 8 h is calculated. October and November again show a slight increase of hours with thermal comfort of around 2 h/month. As for the changes in classes of cold stress, reduced shading can be seen as a major cause of this development.

Most important for this study have been, however, the classes of heat stress (Fig. 8). Their development exclusively shows an increase in their frequency of occurrence. A decrease of probability for hours with heat stress is not even calculated for one single month. This increase is calculated

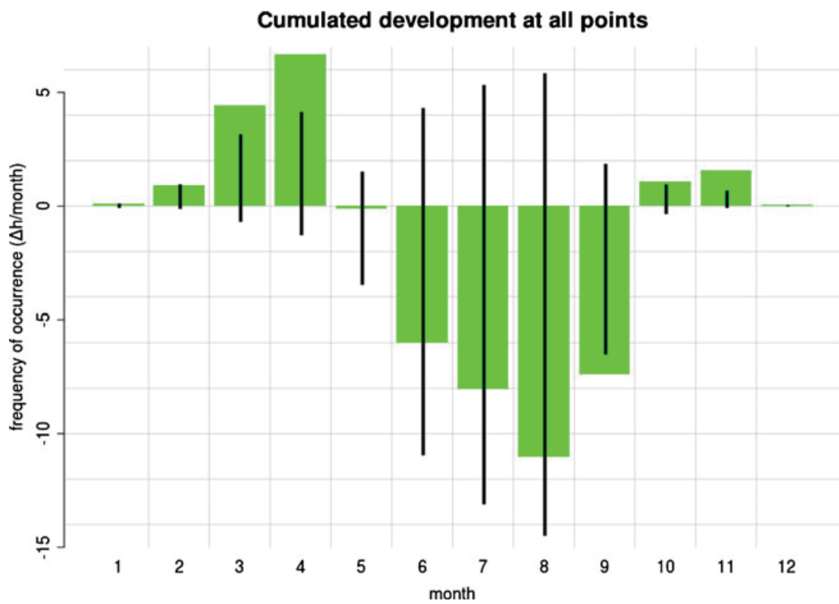

Fig. 7 Cumulated change in the frequency of occurrence of classes with thermally comfortable conditions (Table 1) due to the redesign in hours per month. The *black lines* indicate the range of the development at single points

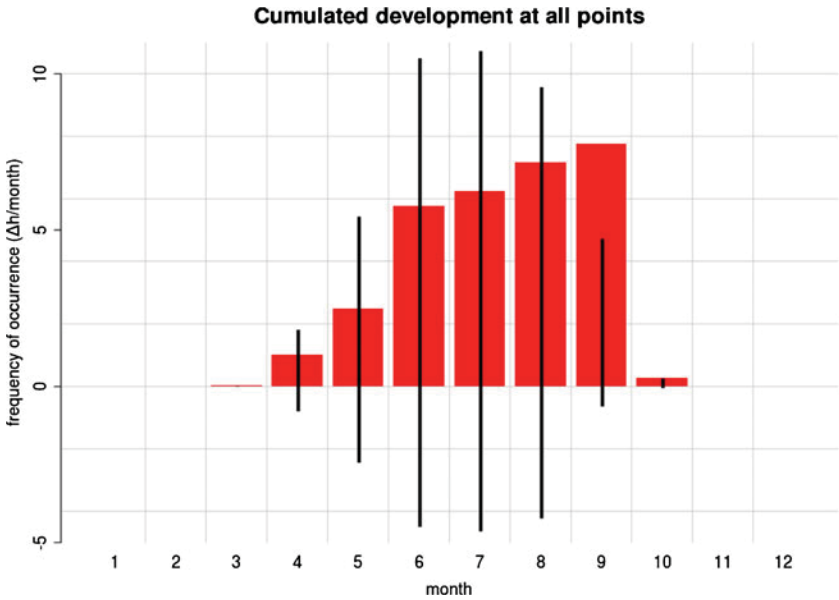

Fig. 8 Cumulated change in the frequency of occurrence of classes with heat stress (Table 1) due to the redesign in hours per month. The *black lines* indicate the range of the development at single points

not only for the summer months but also for spring and fall. For winter, no change for the classes of heat stress was calculated. While the increase is calculated to be small in March and October with up to 0.3 h/month, it already raises about 1 h in April. In May, the increase exceeds 2.5 h. The strongest increase in hours with heat stress is calculated for the months June to September. It raises from about 5.5 h in June to nearly 8 h in September. According to the ideal urban climate (Mayer 1989), this is to be seen as strong disadvantage. Again the development is mostly caused by the reduced shading in the place, which causes hours with exposure to direct solar radiation to become more often.

3.3 Changes in spatial distribution of thermal stress

The spatial distribution of thermal stress was calculated by ENVI-met. For both the current and the redesigned place, a 7-day period using the same meteorological input was calculated. As there is only a few more developments between days 3 and 7, but the uncertainties are increased as ENVI-met is a prognostic model, only day 3 is presented here. Summing up ENVI-met calculates the following differences between the run for the current and the run for the redesigned place in the spatial distribution of thermal bioclimate (compare Figs. 9 and 10). On one hand, there is a reduction of heat stress by up to 18 °C due to the redesign in locations that offer shading on the redesigned place and that have been exposed to direct solar radiation on the current place. Most of these locations can be found not only under new trees but also in the shade of the new building. On the other hand, there is an increase of heat stress in locations that have been shaded by trees that will be removed due to the redesign at the same scale. A reduction can be also found in locations where the new water basins are going to be built. In front of the theater, where two new water basins will replace lawn, a reduction of PET of approximately 4–6 °C is calculated by ENVI-met. In the south of the place, where a new water basin will replace asphalt as ground coverage, an even stronger reduction of approximately 8 °C is calculated. Important for the assessment of these reductions is that they are limited to the locations of the water basins themselves. Results do not show any influence of the water basins on PET beyond their borders.

Generally, there are two major changes in ground coverage caused by the redesign that cause different changes in thermal comfort. First, there is the replacement of asphalt on the current place by huge natural stone plates of the planned one. This causes a light increase in heat stress for locations that are exposed to direct solar radiation. For locations with shading, a reduction of heat stress by the replacement is calculated. Larger in scale are changes that result from the replacement of lawn by natural stone plates. This leads to a severe increase in PET of up to 10 °C. Though this effect decreases over the time of the calculated 7 days, there is still a difference of approximately 1 °C PET on the seventh day. As the calculated week is part of a heat wave, this decrease is most likely due to drying out of the lawn. Thus its positive effects on PET could be preserved by irrigation of the lawn.

All in all, the analysis of results of the calculations with ENVI-met shows an increase in heat stress caused by the changes in ground coverage. Referring to the ideal urban climate (Mayer 1989), this has to be assessed as a disadvantage.

4 Discussion

In the course of this study, several methods of applied urban climatology have been used. Each of them bears its specific advantages and disadvantages.

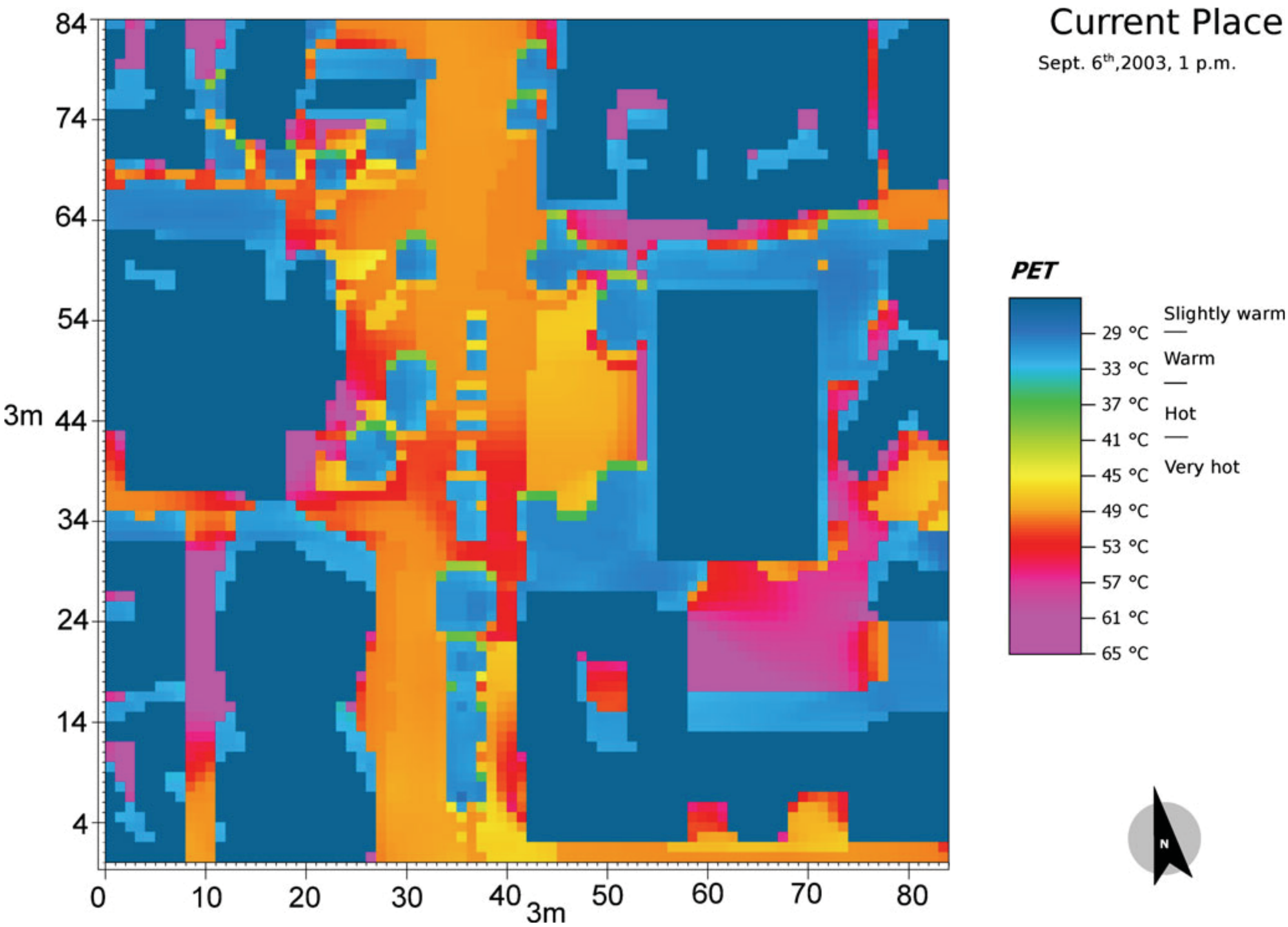

Fig. 9 Thermal bioclimatic conditions on the current Place of the Old Synagogue as calculated by ENVI-met for the third day of a hot and dry period

4.1 SkyHelios

The advantage of calculating SVF using SkyHelios is that it can be done very quickly and that it is good for a first overview over possible changes. The disadvantage is that thermal bioclimate depends also on many other parameters (e.g., shading) that show even stronger influences. So conclusions cannot be drawn by looking at this parameter only. For this study, they are mainly based on results of the models RayMan and ENVI-met, which respect many more parameters during their calculations.

4.2 RayMan

As the most important model for this study, the RayMan model was used. The decision to use RayMan is based on several advantages of the model. First, RayMan is a very fast model. While other models require a lot of time for computation, what limits the possible dimensions for calculated timespan, RayMan is able to calculate very long and thus more representative periods. As RayMan also accepts real meteorological data as input, the usage of data recorded by the urban climate station Freiburg covering a 10-year period became possible.

As all other models too, the RayMan model includes simplifications that may lead to inaccuracy in results. As RayMan is a very common and often used model, severe unknown model errors are unlikely. Furthermore, RayMan is well validated by several former studies (e.g., Matzarakis et al. 2007, 2010; Matzarakis and Rutz 2010; Gulyás et al. 2006; Hämmerle et al. 2011a, b) that attest RayMan's very good accuracy.

4.3 Modification of the input data for the use with RayMan

Using data recorded by the urban climate station Freiburg data, however, causes some impreciseness that has to be considered. First, the data had to be altitude-corrected. As the urban climate station Freiburg is recording on top of a high-rise building at a height of approximately 53 m

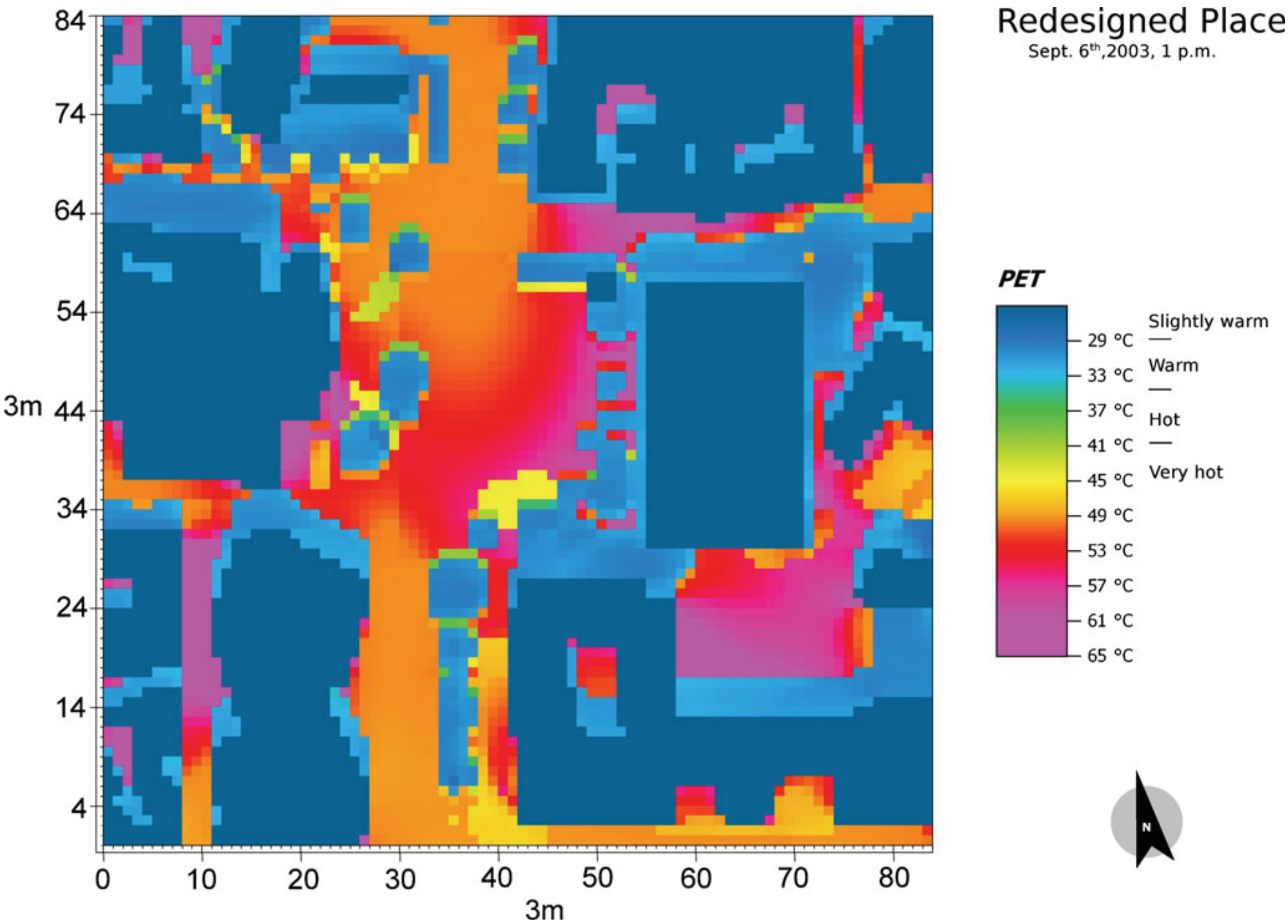

Fig. 10 Thermal bioclimatic conditions on the redesigned Place of the Old Synagogue as calculated by ENVI-met for the third day of a hot and dry period

aboveground, some formula for the transformation to the desired altitude of 1.1 m had to be applied. Most of this formula bear simplifications, so inaccuracy due to the altitude correction is likely. Another point is the horizontal distance of approximately 800 m between the measuring site and the area of interest. This may not bear difficulties referring to inert parameters like air temperature. Parameters that show strong spatial variability like wind velocity may include some uncertainties. But as this study deals with the comparison of two conditions using the same meteorological data, these uncertainties should not have much influence on results.

The spatial input for the RayMan calculations also contains uncertainties that have to be considered. The use of fisheye images as spatial input is actually a very precise method. But as the fisheye images used for the calculations are not photographs but by SkyHelios calculated images, the creation process is a potential source of inaccuracy. Of course, the spatial input for creating the fisheye images bear inaccuracies too.

4.4 ENVI-met

Other inaccuracy has to be respected concerning the calculations with ENVI-met (Kántor and Unger 2011). While RayMan is rather easy to use, the high complexity of ENVI-met increases probability of operating errors. Additionally, it makes the model very slow and limits the calculated timespan as well as the model resolution or the size of the area of interest. Of course, the calculations have been prepared very carefully to avoid operating errors. The imported model areas also should not contain severe inaccuracy as they have already been used for another study. However, the limitation to the resolution leads to inaccuracy that has to be mentioned. Due to the grids' resolution, all object shapes are cuboids of 3 by 3 m horizontally. While lager objects are composed by several cuboids, smaller objects cannot be included in the calculations at all. But the inaccuracy in the shape of objects leads to inaccuracy in the calculation of radiation fluxes and air flow. These inaccuracies are clearly seen in results and have to be recorded for the interpretation. For example, there is a strong overestimation of obstacles referring to air currents if objects that have gaps between them, in reality, grow together on the model grid. This happens very often to vegetation. In particular, the trees standing close together, in reality, become blocks that seriously decreases wind speed in their lee. As these locations are clearly seen in results, they can be easily excluded from the analysis.

5 Conclusions

All in all, results show strong modifications of the local thermal bioclimate by the redesign of the place. Referring to the ideal urban climate, the summarized changes are to be considered negative. This assessment is based not only on the increase in hours with heat stress, especially in spring, summer and fall, but also on the decreasing frequency of occurrence for hours with thermally comfortable conditions that mostly occur in summer. Comparing the development of the three combined classes of thermal stress, a trend toward warmer conditions can be seen. While this may be considered positively in winter, it strongly increases thermal stress in summer. Additionally, since most people are adapted to cold winter conditions, this puts the positive assessment of the development in winter into perspective. Although the trees on the current Place of the Old Synagogue are deciduous trees that have no leaves in winter, so the positive development in winter is likely to be overestimated as there is more direct solar radiation on the current place than calculated by the model. The increase in hours with heat stress in spring and fall is, in contrary, experienced stronger than calculated, as people are adapted to colder conditions. Nevertheless, the most severe changes are calculated for the summer months. While heat stress is already a problem in Freiburg, results show that it will be worsened by the project.

Spatial results of the ENVI-met calculations show that the water basins on the planned place, which are meant to reduce heat stress, do not have an improving effect on thermal comfort of the place as a whole. In contrary, a strong decreasing effect on heat stress is calculated for the meadows, as long as they are not too dry. The greatest reduction of heat stress can be achieved by shading. In particular, the shade provided by the trees appears to strongly influence thermal comfort. As many of the big trees on the current place are planned to be removed during the redesign, the areas with thermally comfortable conditions will be smaller on the new place. Though some new trees will be planted on the redesigned place, their impact is calculated to be quite small, as they will be of types with small treetops.

The present study has shown that combined methods (models) based on long-term basic analysis and specific spatial simulations can deliver helpful results for the assessment of thermal conditions in urban places.

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