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A multi-scale and GIS-based investigation of climate change effects on urban climate and building energy demand for the city of Stuttgart

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Abstract. This paper presents a multi-scale and GIS-based investigation approach whose goal is to quantify the consequences of a climate change scenario (2041-2050) on the energy demand of buildings by comparison to a past scenario (1991-2000) applied to the city of Stuttgart. Energy simulations are made at building scale while taking into account the surrounding urban microclimates. The investigation method combines 1) numerical modelling using TEB and TRNSYS, 2) design of experiments (DOE) statistical analysis for data pre- and post-processing, and 3) GIS techniques. The outcome of the study is the heating and cooling energy demands summed up at city block level and displayed in 2D GIS maps. The results reveal that i) warmer urban microclimates occur, ii) with less heating and more cooling of buildings required if future versus past reference climate data are used. Spatial differences in the results within the city are found depending on the geometrical and thermal characteristics of the individual city blocks and buildings.

1. Introduction

The three-dimensional nature of urban structures plays a crucial role in the energy balance of a city alongside harmful gas emissions and heat release from buildings, transport and other urban activities. These features lead to the formation of urban climates, mostly characterized by urban heat islands (UHI) as well as standalone microclimates in the close vicinity of buildings. Moreover, that modified climate represents a new boundary condition for buildings, hence standard climate data for building energy analyses is no longer representative. The overarching changing global climate adds to the complexity of the issue. Due to this close loop *indoor – urban – global climate(s)* affecting building – street – city scales all together, it is of primary importance to design energy-efficient buildings under real climate background, thereby breaking this vicious circle by preventing further global warming.

This paper is focused on climate change effects on the thermal and energetic conditions of urban areas and buildings and shows the applicability of a downscaling method on a real case study (see [1] and [2] for the full research, and also [3]). The focus of this work is put on high temporal and spatial level of detail based on real data for the city of Stuttgart. The partial availability of city and building data as well as the tools-related computational complexity and limitations add to the challenge.

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The study allows checking and assessing the suitability of the proposed holistic method in the treatment of spatially differentiated and scale-related thermal interactions in practice. It also provides prognostics on heating and cooling energy demands under cumulated global and local (urban) warming conditions. This work provides a different handling of the subject with respect to the method, scope and targeted outcomes than other complementary published works, e.g. [4], [5], [6] and [7].

2. Data pre- and post-processing

Manifold information about the boundary climate and the city is required, including i) long-term past observed and ii) future prognosticated weather data, iii) digital 2D and 3D city maps in high spatial resolution, and iv) statistical data about buildings, traffic, people, etc.

First, the weather data for the decade 1991 - 2000 (past scenario) and 2041 - 2050 (future forecast), available at the resolution of $2.8 \times 2.8 \text{ km}^2$ [8, 9], are spatially interpolated into the resolution of 1 km^2 with the help of measured weather data for the period of 2003 - 2012 provided by the LARSIM database [10, 11], see figure 1 for the two resolution grids. Second, these two sets of weather data are further corrected by means of the town energy balance model TEB [12] as described in [3] in order to take into account the microclimatic effects of the various urban structures (including urban density, traffic and industry heat release, etc.). Third, a generic characterisation of the urban and building parameters is undertaken in order to simplify their real physical description while considering all thermally-relevant features which are sufficiently well documented. These include urban density (height-to-width ratio H/W, plan density), building size and compactness, thermal insulation, building use, window ratio, etc. This step is processed at building-level and city block and scaled with GIS. Fourth, dynamic building energy simulations are run in TRNSYS based on a 3-steps parametric design of experiment plan (DOE) covering, in a matrix, the whole range of urban typologies and buildings occurring in Stuttgart. Fifth, the TRNSYS (release 17) results are then post-processed statistically by regression. The advantage of this procedure is to cope with the large amounts of data while systematically identifying the main effects and two-way interactions of all involved variables, hence, mathematical models can be derived for the targeted useful heating and cooling energy demands for each building and city block. Finally, these building energy attributes for heating and cooling are displayed in form of GIS-based spatial maps for the entire study area of Stuttgart. The data processing, numerical modelling (in TEB and TRNSYS) and the overall analysis are made at fine-scale building level. Yet, the outcome GIS maps are reported at city block level in respect of data privacy necessity.

3. Simulation plan and settings

The calculation time initially required in TEB and TRNSYS was considerable owing the fine spatial and temporal resolution used over a large study area. In order to cope with that, the study area was limited to the densely occupied built-up core area of Stuttgart instead of the entire metropolitan area (36 from 340 cells) as shown in figure 1. The calculations were conducted at hourly basis for ten past years (1991-2000) and ten future years (2041-2050) over 36 km^2 with 1 km^2 resolution in TEB and at building level in TRNSYS. Each square kilometre was differentiated, where applicable, in loose, medium and tight urban typology according to building density, which resulted in 99 climate data sets.

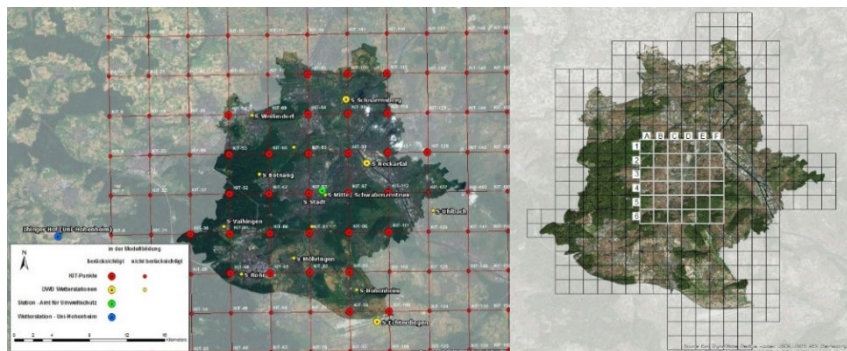


Figure 1. KIT weather data (red points) at $2.8 \times 2.8 \text{ km}^2$ (left) and the study area of $6 \times 6 \text{ km}^2$ within a 1 km^2 resolution grid (right)

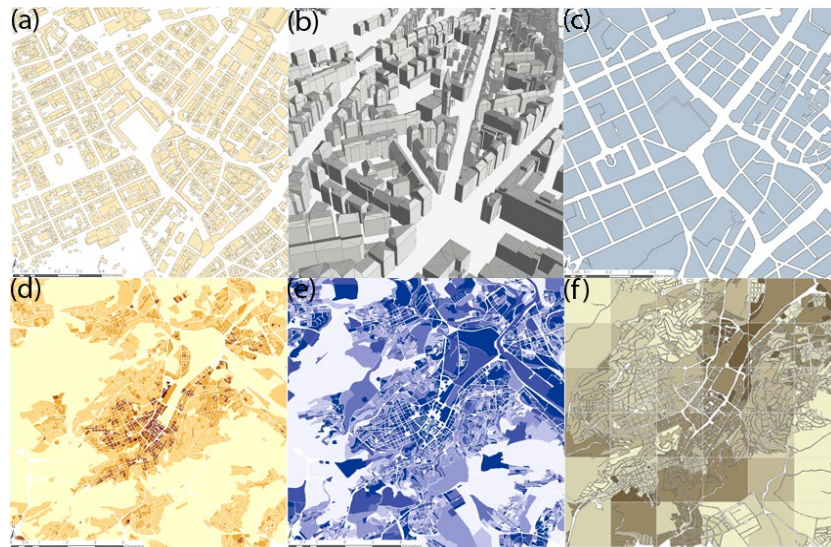


Figure 2. Examples of data sources used and generic urban and building characterisation in Stuttgart city : (a) and (b) digital 2D and 3D building maps, (c) simplified city block map, (d) aspect ratio H/W GIS map, (e) shape coefficient (compactness) GIS map, (f) traffic heat release (CO₂) GIS map

The urban climate and building energy simulations use generic indicators which express, in simplified form, thermally-relevant attributes of the urban fabric and buildings and hence dispenses with unrealistic modelling of all urban and buildings geometries and constructions while keeping good accuracy. These indicators used in TEB and TRNSYS include, at urban level, the street aspect ratio (H/W), built density (roof plan density), and traffic heat release (based on CO₂) and at building level the shape coefficient (building compactness), building volume, thermal insulation (estimated from building age), window ratio (estimated from building typology), and building use (residential or not, special use). The 3-steps values range of each indicator is set based on real minima and maxima occurring for city blocks and buildings in Stuttgart. The accuracy of the indicators depends on data availability for the investigated city area and for which the spatial resolution needs to be high enough. The data sources and some of these indicators are exemplarily shown in figure 2 (see [1] and [2] for more details). Partial factorial design of experiments plans reduce the DOE matrix to one third. Thus, the entire simulation set in TEB accounts 243 cases (instead of 729) and 4374 cases in TRNSYS.

4. Discussion of the results

The following figures report on i) the results of the urban microclimates prediction by means of the Town Energy Balance model TEB for determining the thermal changes within the urban atmosphere, as well as ii) the resulting useful heating and cooling energy demands predicted subsequently by the dynamic thermal building simulation with TRNSYS 17.

4.1. The results about the urban climate

In the following, the city climate effects calculated by TEB are presented and interpreted. The results displayed refer to in-canyon air at 2 m height. Figure 3 (left) shows the mean strength of the warming of the urban air for the period 1991 - 2000. This corresponds to the air temperature difference between the calculated value from TEB (T_{can}) and the reference input air temperature (T_{ref}) at the same height (2 m) above street level $\Delta(T_{\text{can}} - T_{\text{ref}})$. The canyon can heat up to an average value of 0.87 K, while the highest warming value is 2.64 K. In fact, the spatial differentiation of the warming effect depends strongly on the density of urban development. This is given by the street profile height-to-width ratio H/W. Another contributing factor is the transport of waste heat (cf. figure 2). The higher the H/W ratio, the more pronounced the warming of the street air due to more heat storage or later heat release during warm weather, but also a certain slowdown in the daylight hours, where shading occurs. Report to [3] for details on the urban microclimate causal effects and processes.

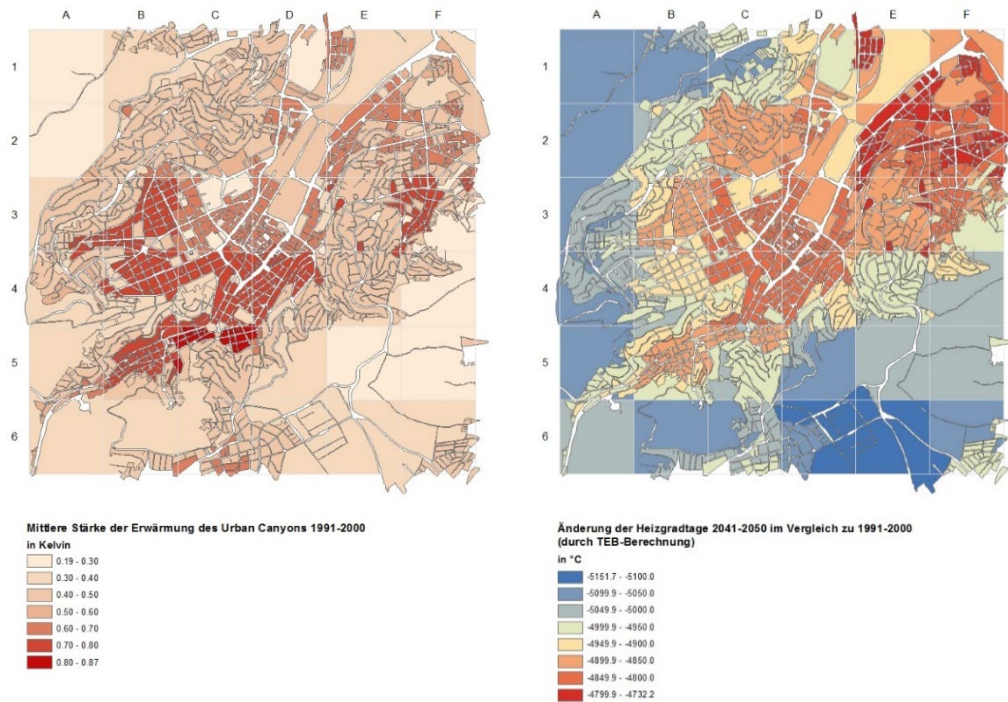


Figure 3. Mean strength of in-canyon air warming for the past decade (1991 – 2000) based on TEB calculations (left) and the heating degree days deviation Δ HDD (degrees sum) between future decade (2041-2050) and past decade (right)

In order to compare the future scenario (2041 – 2050) with the past climate situation (1991 – 2000), the change in the heating degree days Δ HDD (base temperature set at 18 °C) is mapped in figure 3 (right). TEB-calculated urban microclimates being included, the climate change effects are hence isolated. The future climate is forecasted to be generally warmer, so that fewer heating degree days are the result. The magnitude of change in the dense built-up valley is lower than the remaining higher-lying urban area. The comparison map in figure 3 (right) shows a similar trend towards increasing warming in the future, albeit with a clearly identifiable urban structure, if the city climate effects are taken into account. In general, the change in the Δ HDD in the city centre due to climate change is lower than in rural areas, because the denser the city, the better it can smooth the climatic changes.

4.2. Building heating and cooling energy demand for the past climate (1991 – 2000)

Figure 4 (left) shows the specific useful energy demand for heating for the decade 1991 - 2000. The useful energy can reach 413 kWh/m²a for a few houses on the outskirts due to poor insulation, otherwise the heating is between 44 - 163 kWh/m²a for about 80% of the total city blocks. Heating demand is lowest for large buildings with very good thermally insulated building envelope predominantly for inner urban areas. Residential areas on the slopes have more heating demand on account of their poor heat transfer coefficient, which is estimated based on building age.

Figure 4 (right) depicts a reverse situation, where the residential areas have low need for cooling by the fact that the building space undergoes much transmission heat loss through the poorly insulated building envelope. By contrast, the inner city buildings have more need for cooling because they are better insulated and hence thermally separated from outdoors. An amplifying reason for increased cooling energy requirements is the large proportion of window area. Urban climate effects could also have played a role here, for example, in the case of a high building density (cf. (d) and (e) in figure 2).

4.3. Heating and cooling energy demand for the forecasted future climate (2041 – 2050)

The impact of climate change on heating and cooling building energy demand for the period (2041 – 2050) is illustrated in figure 5, as a difference to the energy demands for the past period (1991 - 2000).

Logically, this comparison is theoretical, because thermally-relevant information about the buildings in 2041 is not known. In view of the continuous tightening of the thermal regulation EnEV in Germany, it is expected that building envelopes will be appropriately insulated (cf. [6]). Nevertheless, this comparison makes it possible to make a general statement about the impact of global warming.

In figure 5 (left) it becomes clear that the demand for heating energy will be lower in the future. The inner-city areas are experiencing less reduction in heating energy demand, as the microclimate is more strongly influenced by climate change. Conversely, the heating energy demand in the outskirts areas is clearly lower, because of less insulated and compact buildings within a warmer environment. For cooling (figure 5 right), the situation is reversed. The city centre needs more cooling due to higher air temperatures, while the surrounding residential areas must be cooled yet to a much lesser extent.

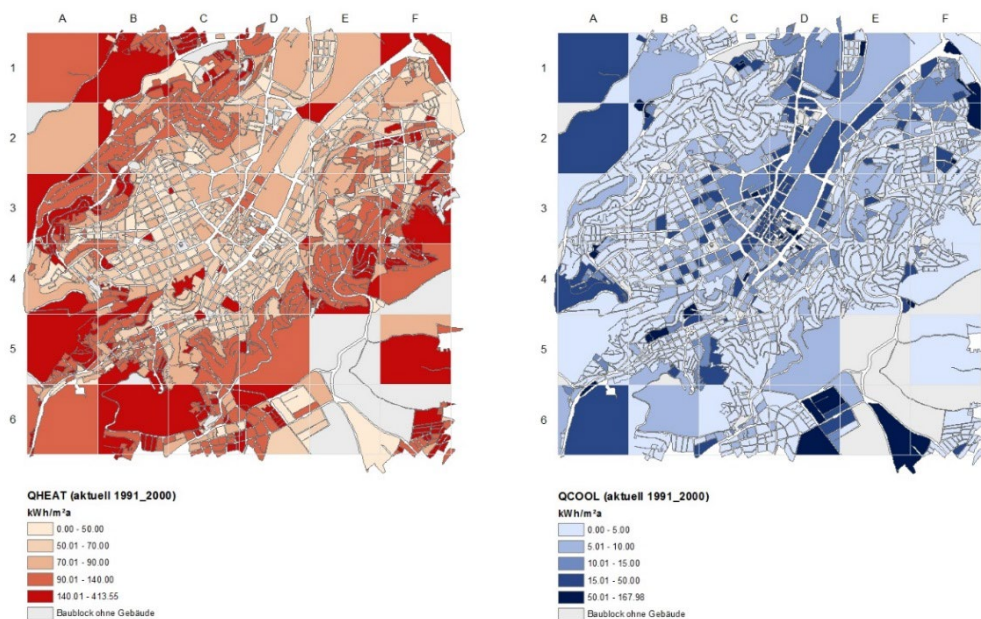


Figure 4. Useful energy for heating (left) and for cooling (right) computed with TRNSYS for Stuttgart city for the past climate (1991 – 2000)

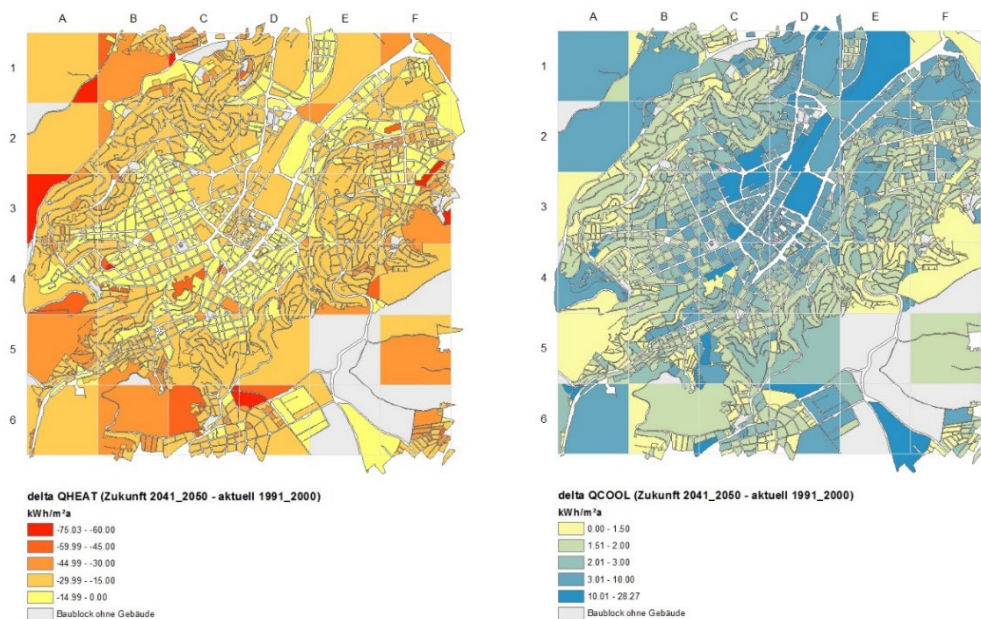


Figure 5. Difference in useful energy for heating (left) and for cooling (right) between future and past climate (2041 – 2050 versus 1991 – 2000) computed with TRNSYS for Stuttgart city

5. Conclusion

This project had methodological and substantive objectives. The overall research method combining GIS, TEB, TRNSYS, and DOE proved to be suitable for a multi-scale investigation with high spatial and temporal resolution applied on a practical object of study. However, using real data required some necessary estimates to cope with missing information. In regard to content, the effects of climate change could be demonstrated i) on the urban microclimates and ii) on the useful energy demands for heating and cooling in buildings. The forecasted global warming will lead to more heat islands, less indoor heating and more cooling energy demands unless strategies are implemented to mitigate that warming trend such as with energy-efficient buildings and sustainable urban development (e.g. [13]).

Acknowledgments

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