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Urban Meteorology

# A numerical study on the effects of natural ventilation on summer nighttime indoor temperatures in an urban area

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**Abstract**

Natural ventilation is a simple and efficient method for nighttime passive cooling of buildings to improve residents' comfort and reduce air conditioning. The effectiveness of ventilative cooling depends on the number and arrangement of the openings and local wind and temperature difference between indoor and outdoor. However, natural ventilation works only if cool air is available in the surrounding of a building and when this cool air finds a way to infiltrate indoors. In this paper, numerical models are used to simulate the penetration depths of cool air from the rural countryside into a residential area and to estimate the local cooling potential for an indoor environment of buildings. The results demonstrate that the country breeze is an important process to transport cool air during the night, but, due to the limitations in strength and depth, it is only efficient in the first 100–200 m of the outskirts. Based on numerical experiments for a standard room with two windows, an empirical relation was derived to estimate indoor cooling depending on local wind speed and local temperature difference. This relation was used to calculate individual nighttime room temperatures of all buildings in a residential area. It was found that indoor temperature follows the ambient temperature with a delay and cooling is only half as great as outside the building. In addition, the models are used to demonstrate the cooling effect of the country breeze by calculating for a decade the number of days in the summer months when nocturnal minimum room temperatures are below a given threshold.

**Keywords:** numerical model, country breeze, natural ventilation, indoor temperature

## 1 Introduction

People frequently work and live in a relatively warm environment, not only in tropical or subtropical regions but also in a moderate climate. Reasons for this are a general global warming, a local temperature increase within an urban heat island, and an individual heat load within unfavourably tempered rooms and facilities. An uncomfortable thermal environment with high temperatures during the night prevents the recovery of the residents. During daytime, the heat load is not only unfavourable even for healthy people but may also be a danger for elderly and hospitalised people.

Many people in modern society spend approximately 90 % of their time indoors (WHO, 2013). While during night people spend nearly all the time at their home (Kunze, 2019), during daytime they move to their workplaces, schools, or other public spaces. A comfortable indoor thermal environment in these places can be ensured by using air-conditioning systems. However, such a cooling technology is associated with a strong increase of $CO_2$ emissions (Isaac and van Vuuren, 2009) and therefore counteracts the efforts to reduce this greenhouse gas. Consequently, in order to reduce especially the high daytime temperatures in the summer months, sustainable and environmentally friendly measures like additional shadow or urban green are to be preferred (Gill et al., 2007). However, during the night, these measures are not helpful or effective. After sunset, the urban temperature decreases because of the negative radiation budget, but this cooling often is not sufficient to achieve thermal comfort in the living environment of residents. The only available natural ventilation process is the advection of cooler air from parks or the rural surrounding into the urban residential area (Shreffler, 1978; Goldreich and Surridge, 1988; Barlag and Kuttler, 1990).

The German Meteorological Service DWD has established a heat warning system on the scale of a county to alert the population routinely in case of unfavourable or dangerous heat load conditions (Rosenfelder et al., 2016). Based on the weather forecast, an indoor model for a standard room is used (Pfafferott and Becker, 2008) in combination with a procedure to estimate human thermal comfort (Fanger, 1972) to calculate the heat load of people who stay permanently inside. Beside effects caused by an individual behaviour, the influence of ventilation on indoor heat load by operating windows is also considered. However, for practical use of this warning system, the effect of ventilation is greatly simplified and does not depend on the outside temperature.

Especially regarding this last aspect, numerous experimental and numerical studies have been published

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that demonstrate the wide variety of external and internal factors on ventilation through windows and openings. External factors are related to wind speed in front of the window and temperature difference between indoor and outdoor, while internal factors are usually related to the user behaviour like opening configuration (e.g., top-hinged, bottom-hinged, or side-hung windows) or opening times (Santamouris et al., 2010; Gao and Lee, 2011; Sacht and Lukiantchuki, 2017; Rijal et al., 2018). Results of these studies suggest that especially nighttime ventilation, when the outdoor air temperature is lower than the indoor air temperature through openings arranged with different orientations, is the best strategy to optimise natural ventilation capability.

While the heat warning system of the DWD is focused on the scale of a county, the experimental and numerical studies deal with different aspects of the natural ventilation of a single room or apartment. However, for urban planning, the scale in the middle of those two approaches is of high relevance, where local meteorological information within a complex urban environment is used to estimate the potential of natural ventilation of residential areas. In this study, a numerical method is described to bridge this gap between the scales mentioned above. The study is restricted to the nighttime of the summer season, when passive natural cooling is particularly desirable. Also, an outlook is given on how to use the presented method for longer periods.

## 2 The model system

Natural ventilation of a room depends on the temperature gradient between the indoor situation and the properties of the outside air in the immediate vicinity. However, the outside urban atmosphere itself is strongly influenced by the interaction of areas with different land use within the city and with the rural surrounding. These two different scales, relevant for ventilation, are treated by numerical models applicable for the neighbourhood-scale and the building-scale. Numerical models are widely used to study, in particular, the building-scale problem of ventilation of a room through windows of different configuration (Alloca et al., 2003; Bangalee et al., 2012; Caciolo et al., 2012), but few authors consider the individual situation of such a room within a complex urban environment (Liu and Chen, 2019).

The neighbourhood-scale model used here (Gross, 1993, 2019a) is based on the Navier–Stokes equations, the continuity equation, the first law of thermodynamics, and an equation for specific humidity. These equations are Reynolds averaged, and the resulting correlations of fluctuating quantities are parameterised by flux–gradient relationships. The eddy exchange coefficient introduced by this approach has been calculated using the Prandtl–Kolmogorov relation via the turbulence kinetic energy, which is estimated by an additional prognostic equation. Buildings are introduced into the model by a porosity concept with impermeable grid volumes, while an additional drag is used in the momentum equation to represent the effects of trees on airflow (Gross, 1993).

Boundary conditions for wind at the ground are zero, and turbulence kinetic energy is proportional to local friction velocity squared. Temperatures at the ground are calculated by an energy budget (Gross, 2019a, 2019b), which includes short-wave radiation, long-wave radiation, heat flux into the soil, and sensible and latent heat flux. At the upper boundary, an undisturbed situation is adopted with given values for all meteorological variables.

The building-scale model used (Gross, 2014, 2018) is based on the same set of model equations like the neighbourhood-scale model. Also, similar boundary conditions for the different variables are used except for temperature, where fixed values are prescribed at the inner and the outer walls of the room and building.

A grid resolution of 10 m in both horizontal directions is used for the neighbourhood-scale simulations. In the vertical, a 2-m grid resolution is adopted from the surface up to 30 m height, with an expanded resolution up to the upper boundary at a height of 2000 m. For the building-scale model, the grid resolution in all three directions was 0.25 m. This grid spacing was adopted in the lowest 30 m and expanded above up to a height of 100 m.

The equations are solved on a numerical staggered grid where all scalar quantities are arranged in the centre of the grid volume, while velocity components are defined at the corresponding side walls. The pressure disturbance is calculated by solving a three-dimensional discrete Poisson equation directly by Gaussian elimination in the vertical and fast Fourier transforms in the horizontal directions. The model equations are integrated forward in time with a time step satisfying the CFL criterion.

## 3 Input data

For an application in a real complex environment, a typical suburban region close to Hannover with different land use in a confined space is adopted (Fig. 1). Open fields are located close to residential and industrial areas. While the residential area is a mix of mainly two-storey houses, green spaces, and garden, the industrial zone is characterised by 18-m-high buildings and extensive paved surfaces in between. The rural surrounding consists of an open field with short vegetation, some trees, and small water bodies.

The study is restricted to a summer day with large diurnal temperature amplitude and calm wind. For such a meteorological situation passive natural cooling is particularly desirable in order to reduce nocturnal temperatures in urban areas. Using a threshold for temperature amplitude of more than 12 K and an associated nighttime mean wind below 2 m s$^{-1}$, the situation adopted in

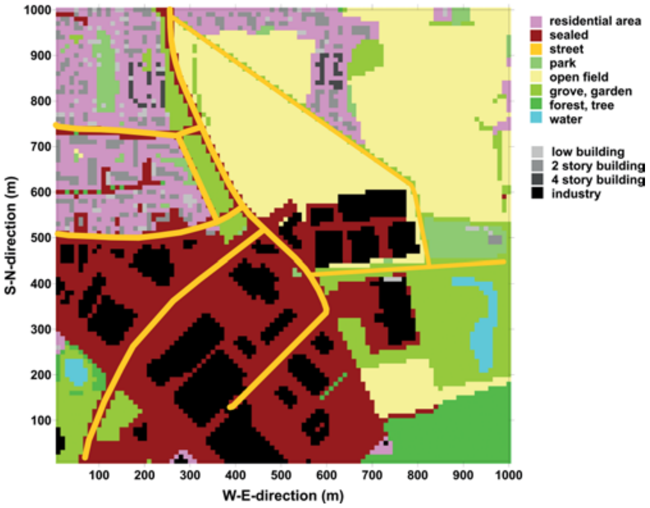


**Figure 1:** Areal distribution of land use in the simulation domain.

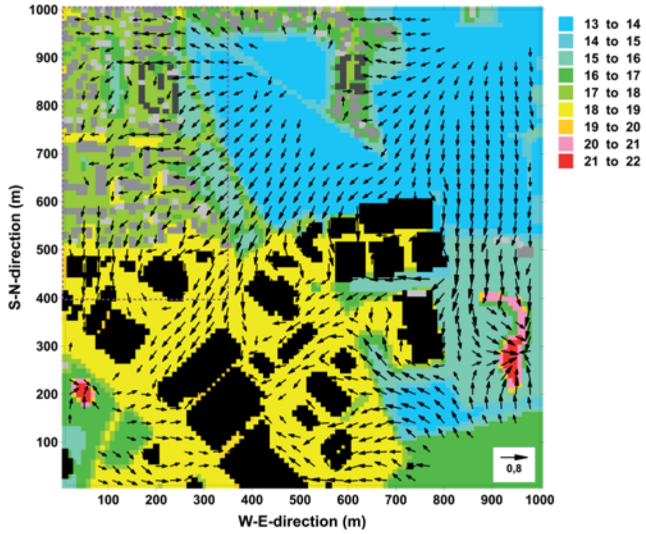


**Figure 3:** Simulated temperatures (colours, in °C) and horizontal wind speed at 2 m height (arrows) at 5 a.m.

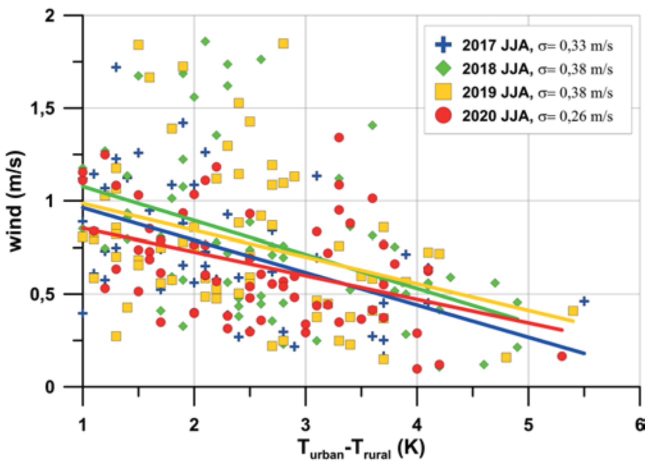


**Figure 2:** Observed summer urban-rural temperature difference around sunrise and corresponding nocturnal wind (mean 21 h–05 h). Solid lines are mean wind for 0.5 K intervalls for each year. Observations from DWD-stations Weidendamm (urban) and airport (rural).

this study is representative for nearly 20 % of the summer nights in Hannover in the period 1990–2020. For such calm nighttime synoptic conditions, a weak local wind system can be established, resulting in nocturnal ventilation of the outskirts. This air movement is caused by the temperature difference $\Delta T$ between the warmer urban heat island and the much cooler rural environment. The German Meteorological Service DWD operates a monitoring system in Hannover (DWD, 2018), and the observations show the relation between $\Delta T$ and the resulting wind. During the summer months JJA 2017–2020, the urban–rural temperature difference has reached values of more than 5 K (Fig. 2). However, larger values of $\Delta T$ are always associated with a low wind speed of a typical order of less than 1 m s$^{-1}$.

# 4 Results

## 4.1 Results for the neighbourhood-scale

Simulations for Julian day 172 start at 20 h, shortly before sunset, and run till sunrise of the next morning. The initial 2-m temperature was prescribed with a value of 23 °C, with a weak stably stratified atmosphere above ($\partial\theta/\partial z = 0.2$ K/100 m; $\theta$ is potential temperature). During the evening hours and the night, a different cooling of the various land uses is calculated, also resulting in temperature differences between the surrounding and the urban areas. For the synoptic situation adopted here, temperature in the open field decreases to 13–14 °C around sunrise, while the urban areas and the water bodies are much warmer (Fig. 3). The temperature difference between the rural and the residential areas is around 4 K and therefore in a comparable order like the observations.

The coexistence of warmer and cooler air masses causes a country breeze, a relatively weak thermally induced local wind system (Barlag and Kuttler, 1990). In Fig. 3, the resulting horizontal near surface wind in the morning hours is given by wind vectors, where for clarity only every 10$^{\text{th}}$ information is displayed. From the rural environment, the country breeze advects cooler air into the warmer building area to reduce the temperature contrast. This weak wind is strongly affected by the urban obstacles, resulting in a channeling in streets, airflow around buildings, and recirculation areas behind the houses.

Although the country breeze is a weak wind system, a certain degree of effectiveness is evident. To demonstrate the importance of cold air advection by the country breeze, an additional simulation was performed, where horizontal and vertical advections are excluded. By comparing the results of these two simulations, the pure effect of the local wind system can

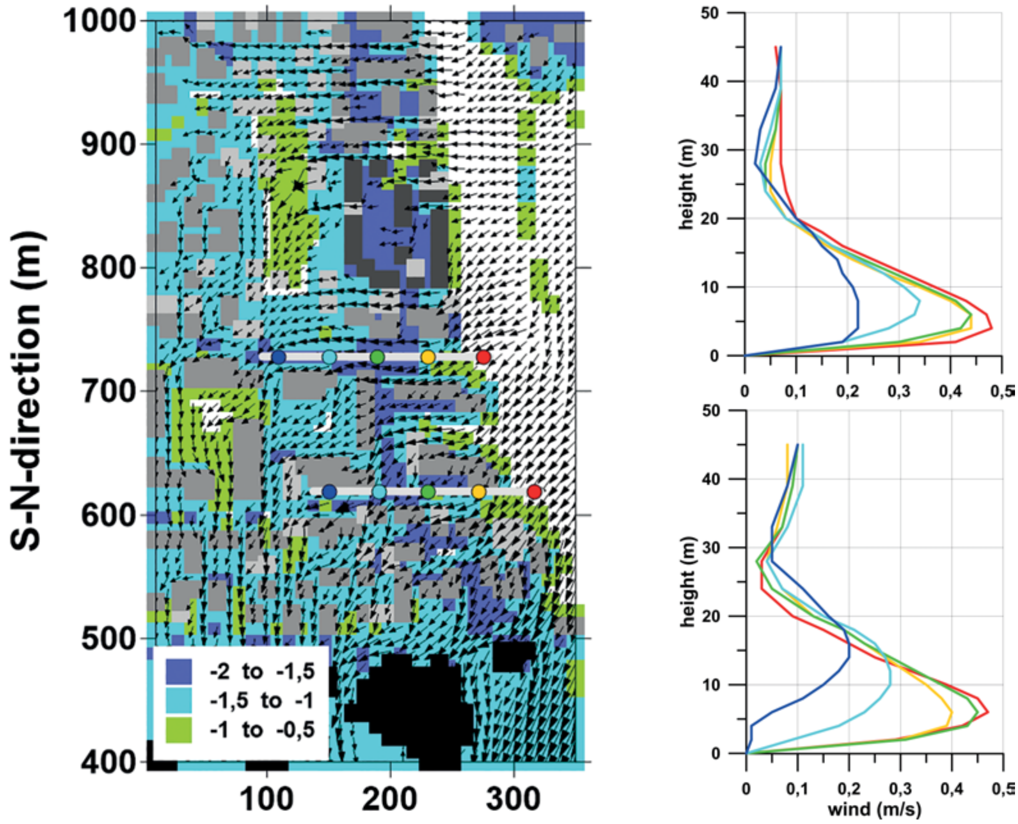


**Figure 4:** Left: 2-m temperature difference in K with-without advection at 05 hours and wind vectors at a height of 8 m (= height of the wind speed maximum of the country breeze). Right: Vertical wind profiles at different positions (colour dots) along the streets.

be demonstrated. In Fig. 4, the resulting 2-m temperature difference for the early morning hours is given for the box highlighted in Fig. 3. The residential area benefits from the transport of air from the surrounding open fields, resulting in a near surface cooling effect of 1–2 K. However, a significant effect is mostly restricted to the first 100 m at the edge of the urban area except for locations in small distances where the thermally induced wind finds a way through streets or above the roofs. Further downstream the impacts are much smaller. This is because of the shallow thickness and the low wind speed of the country breeze, demonstrated by vertical profiles along two streets from the outskirts to the inner residential area (Fig. 4). All profiles show a similar structure with a maximum wind speed near the ground at a height of 4–6 m and a vertical depth of 20 m or less. The northern street is relatively broad, with no disturbances, and the country breeze that transports cooler air can easily penetrate the built-up area. Towards the end of the street, the wind speed is slowed down and the country breeze almost disappears. Along the southern road with isolated trees and narrow buildings, airflow is strongly slowed down, and the maximum is shifted to a higher elevation, typically above the roof top of the residential two-storey buildings. Because of the larger temperature contrast between the industrial zone and the rural area and the larger open spaces between the individual buildings, a more pronounced country breeze was simulated in this part with a maximum wind speed up to 0.8 m s$^{-1}$. Temperature effects in the vertical along the streets are restricted to the lowest 20 m and show a continuous temperature increase from the rural into the urban area.

## 4.2 Results for the building-scale

The cooler air, transported by the country breeze from the rural environment into the residential area, has the potential to reduce the nocturnal heat load of the residents. However, during nighttime, people are usually inside their apartments and the cooler air is only of advantage for thermal comfort if infiltration into the rooms is possible. The air exchange between indoor and outdoor depends on existing openings, temperature difference, and wind. To determine empirical relations for practical use between air exchange and meteorological conditions, a number of numerical simulations were performed for a standard room, comparable to the approach of the DWD (Pfafferott and Becker, 2008). This standard room size of 5 m × 2.5 m × 2.5 m has two adjacent windows of 1 m$^2$ each, and three of them are arranged above a solid ground floor, resulting in a four-storey building (Fig. 5).

Rooms were filled with warmer air, and it was studied how this warmer inside temperature changes by mixing with an outside air mass of 21 °C for different wind conditions. The bandwidth of the temperature excess was 0–10 K, and undisturbed windspeed at 10 m height was set to 0, 0.5, and 1.5 m s$^{-1}$, which is approximately

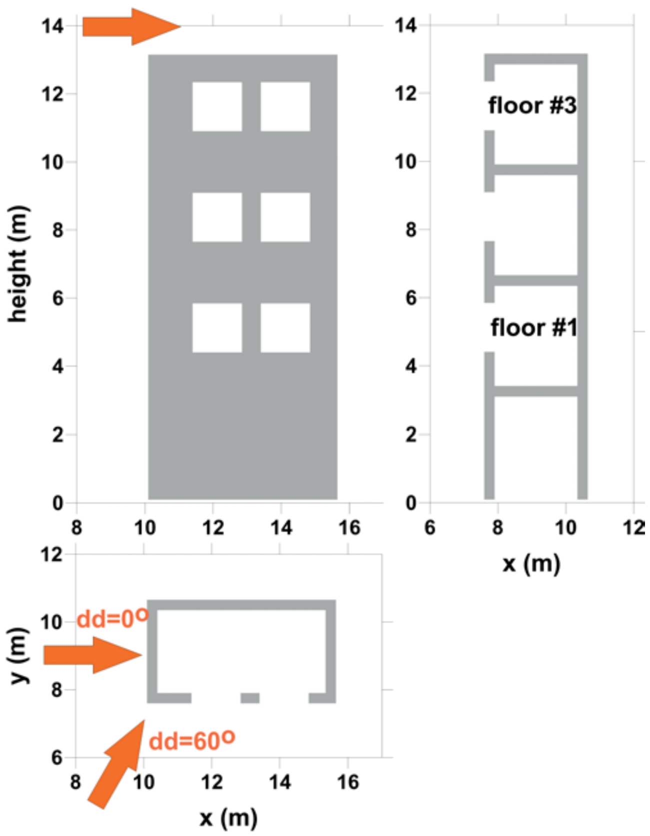


**Figure 5:** Schematic view of the standard room and the building used. Arrows are indicating superimposed wind direction.

the range of the country breeze. Studies were performed for an airflow parallel to the windows ($dd = 0°$) and towards the windows ($dd = 60°$).

For a temperature difference inside–outside of 2 K and an undisturbed wind speed of 1.5 m $s^{-1}$ at 10 m, wind and temperature distributions in the lower part and in the upper half of the windows of floor #1 are given in Fig. 6. Here the results after 300 s real time are presented when a quasi-stationary situation was established.

For a calm situation with no superimposed wind, a small-scale local circulation transports cooler air from outside in the lower part of the window into the room, while in the upper part a reverse flow from inside to outside was simulated. Such a flow pattern has been observed, for example, by Caciolo et al. (2012). For an airflow parallel to the windows, vortices were developed at the lower edges of the two windows, causing effective intrusion of cooler air into the room. Because of mass conservation, in the upper part of the opening, an outflow was simulated. A completely different wind pattern is obvious for a wind direction of $dd = 60°$. Now the outside air enters the room through the complete area of the first window, and the outflow is through the second opening behind. Estimated air exchange rates result in 7–10 $h^{-1}$ with slightly higher values for $dd = 0°$ which is in good agreement with results of Caciolo et al. (2012) and Sacht and Lukiantchuki (2017).

For each simulation, the mean temperature changes of the entire room at different floors caused by mixing with the outer cooler air was calculated. The results are given in Fig. 7. Only the results for $dd = 0°$ are used for further analysis and applications since the effects for $dd = 60°$ are smaller. For an increasing temperature difference inside–outside, $\Delta T_{io}$, a stronger cooling was simulated. However, this cooling is different for different floors and depends on wind speed. A higher wind speed is associated with a stronger cooling, and this is also the reason for a larger decrease of indoor temperatures at the upper floors. Indoor cooling depends not on the undisturbed wind far away from the building but on local wind speed close to the window. This point is of particular importance for application in a real built-up area, where wind speed mainly depends on the direct surrounding. Therefore, wind speed $U_{window}$ along the façade, averaged over a 1-m thick layer in front of the windows, is calculated, which is, as a first approximation, a comparable value provided by the neighbourhood-scale model. The simulated indoor cooling (in K) given in Fig. 7 can be approximated by a regression curve

$$cooling = a\Delta T_{io} + b\Delta T_{io}^2, \qquad (4.1)$$

with factors $a$ and $b$ listed in Table 1.

## 4.3 Indoor cooling in the urban area

For all grid points of the suburban region that are defined as 'buildings' and have external walls to the atmosphere, the nocturnal cooling is calculated. It is assumed that each of these grid points represents the standard room introduced above, and indoor cooling can be approximated by Equation 4.1. The necessary input data, temperature, and wind of the direct surrounding are provided by the results of the neighbourhood-scale simulation.

In the evening hours of a sunny day, outdoor temperatures drop fast, and after a certain time, the indoor temperature is equal to this outer value (e.g., Peuportier et al., 2013; Hamdani et al., 2018). Here it is assumed that this situation can be found around 21 h, and a cooling of the room by mixing with the ambient air occurs in the subsequent period. Starting at time $t = 21$ h, the indoor temperature $T_{room}$ is calculated according to

$$T_{room}^{t+1\,h} = T_{room}^{t} + cooling\left(\Delta T_{io}^{t+1\,h}, U_{window}^{t+1\,h}, floor\#\right) \qquad (4.2)$$

$T_{room}$ at 21 hours is equal to the local outside atmospheric value. Temperature as well as wind of the surrounding are updated every hour from the neighbourhood-scale simulation. Calculation will continue in steps of one hour till 5 hours of the next morning. Feedback on the outside temperature is not considered here.

A threshold of 20 °C is used in this study because of the definition of a tropical night by this value and also because higher nighttime ambient temperatures

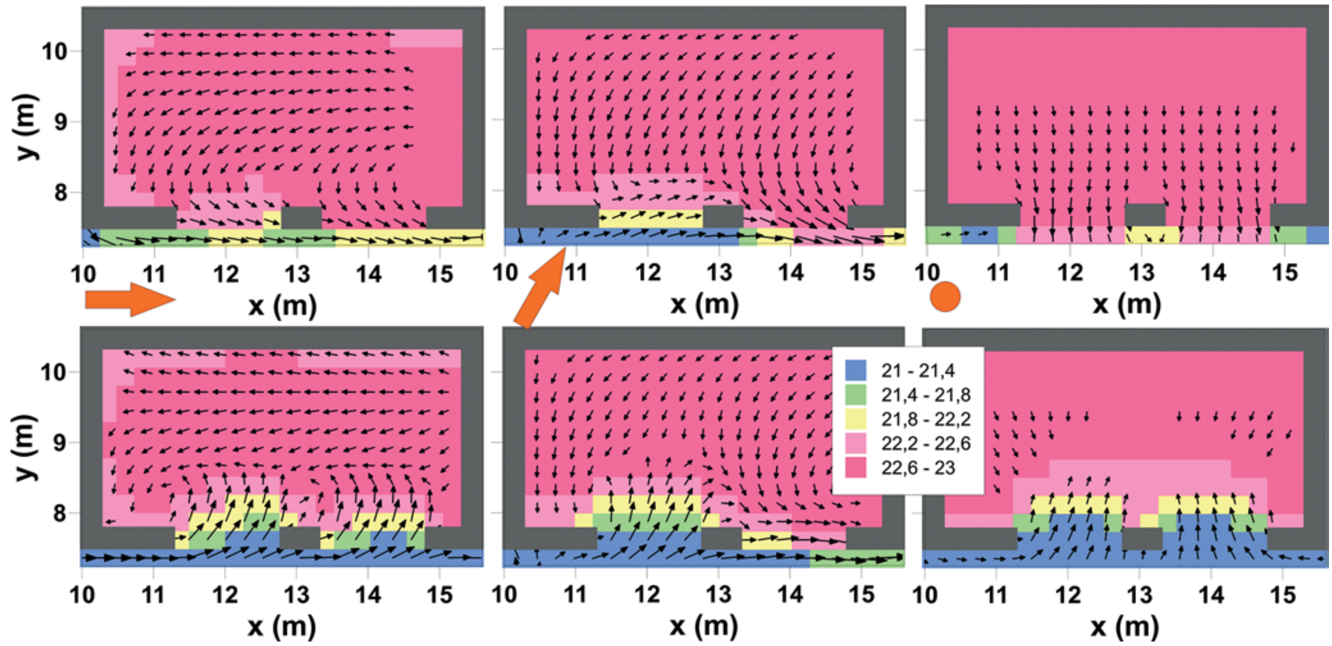


**Figure 6:** Horizontal cross sections of wind and temperature in the lower (bottom) and the upper (top) part of the windows in floor#1 for a direction of the oncoming wind of $dd$ = 0° (left), $dd$ = 60° (middle) and for a calm situation (right).

**Table 1:** Factors to calculate indoor cooling of the standard room for $dd$ = 0°.

| | $U_{10\,m}$ = 1.5 m s | | | $U_{10\,m}$ = 0.5 m s | | |
|---|---|---|---|---|---|---|
| | floor #1 | floor #2 | floor #3 | floor #1 | floor #2 | floor #3 |
| $U_{window}$ (m s$^{-1}$) | 0.32 | 0.37 | 0.57 | 0.13 | 0.16 | 0.18 |
| a | −0.19 | −0.22 | −0.31 | −0.16 | −0.18 | −0.21 |
| b | −0.005 | −0.006 | −0.011 | −0.005 | −0.004 | −0.005 |

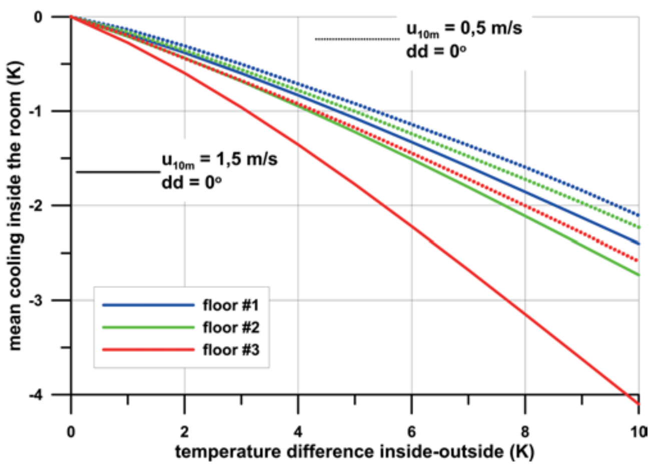


**Figure 7:** Simulated mean indoor cooling for different floors depending on temperature difference inside-outside and wind speed in front of the windows $U_{windows}$.

may have adverse effects on quality of sleep and health (Franco et al., 2000). Such a minimum nighttime indoor temperature of 20 °C will be achieved in some areas of the simulation region but may be exceeded in other parts (Fig. 8). Especially in the industrial zone located in the south-western part, the urban atmosphere is relatively warm, and cooling of the standard room located at the outer walls is reduced. However, the industrial zone in the middle is strongly affected by a well-developed country breeze, and indoor temperatures drop significantly till the morning hours. Also, the residential area in the north-west is under the influence of the thermally induced local circulation. While the advection of cooler air from the rural area causes a reduction of the indoor temperature below the prescribed comfort threshold in the outskirts, the inner residential area does not benefit in the same order. For the scenario adopted here, it takes 7–8 hours, which means nearly till the end of the night, to reach the specified threshold in the outskirts. At the elevated floor #3, the situation is slightly different due to two competing processes. While the higher wind speed at this height would cause a stronger cooling, the advection of warmer air, resulting from the inversion developed in the rural area, counters this effect.

The time evolution of mean indoor temperature, calculated for all rooms in the residential area, is given together with the simulated range in Fig. 9. At the start of the simulation at 21 h, local indoor temperature is

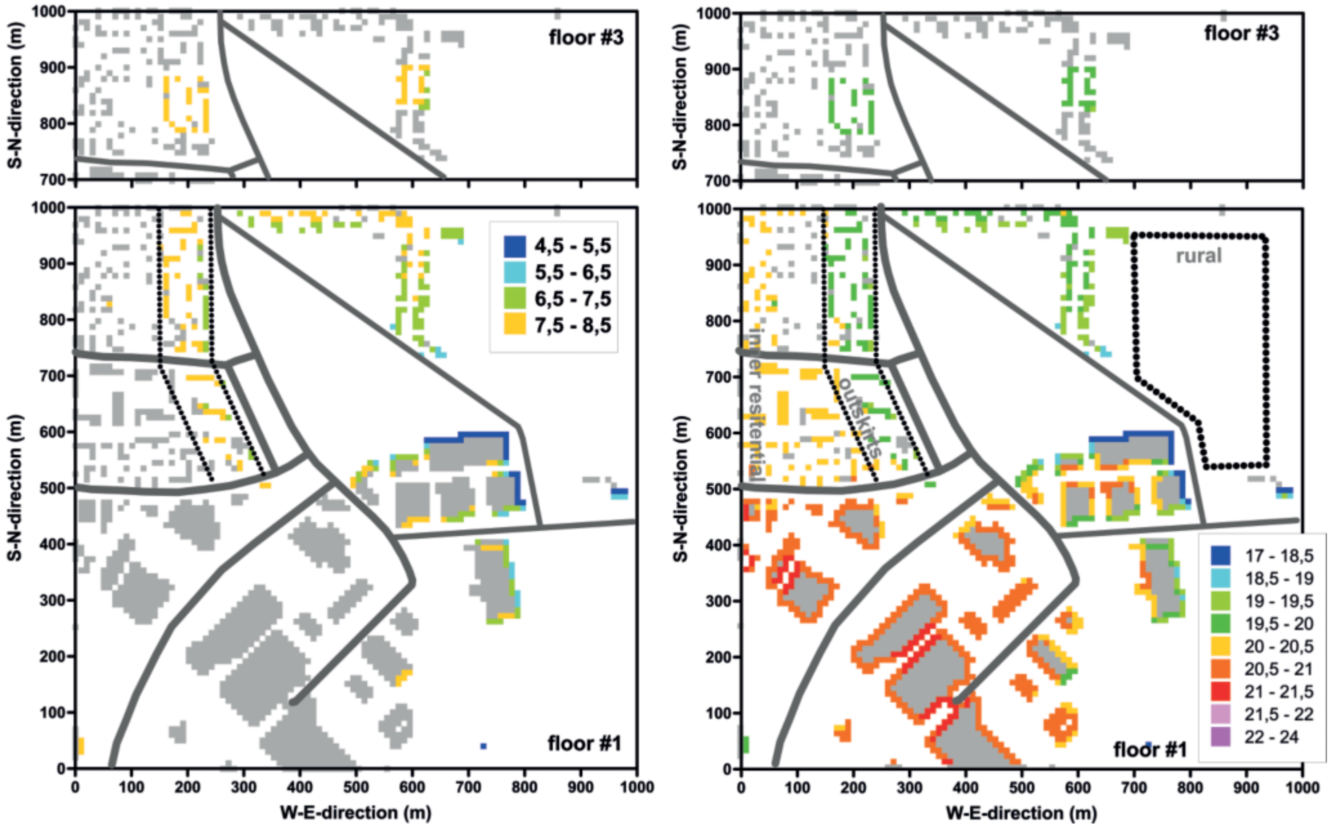


**Figure 8:** right: Areal distribution of the estimated room temperature at 05 h for floor#1 and floor#3. left: Duration in hours to reach a threshold indoor temperature of 20 °C.

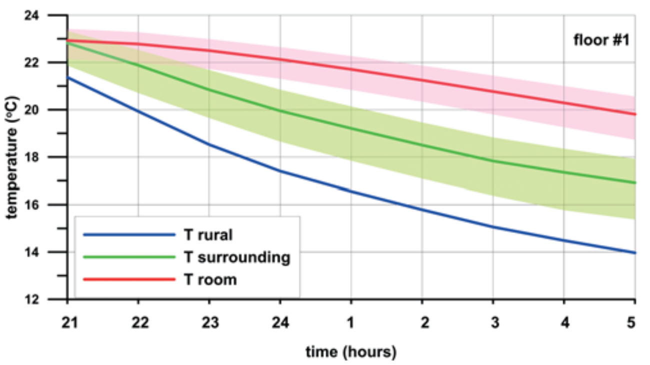


**Figure 9:** Time evolution of mean temperatures for room, surrounding and rural environment together with the simulated ranges.

by definition equal to the temperature of the direct surrounding, while the rural environment is much cooler. For the weather situation considered here, temperatures in the open field decrease by around 7 K during the night, in the urban surrounding by 5–7 K (on a higher level), and in the room by only 3 K. The relation of the nocturnal cooling of a room with open windows compared with the surrounding of 0.5 was also found by Peuportier et al. (2013) and Hamdani et al. (2018).

## 4.4 A climatological extension

An attempt is made in this study to estimate the nocturnal indoor temperatures for varying atmospheric conditions of the environment for longer periods. Especially during the summer months when wind is calm and the evening temperature is high, a warm nighttime urban atmosphere can be observed (Gross, 2019b). For such a synoptic condition, the areal distribution of temperature is not affected by larger scale advection but nearly completely determined by the local site parameter causing the urban heat island. For different initial temperatures in the evening, the areal temperature distribution will be similar during nighttime, but on a different level. This statement is supported to a great extent by the observations at the urban station Weidendamm of the DWD monitoring system for the summer months JJA of the period 2017–2020. For the following analysis, similarity is assumed, which means that the simulated early morning temperature distribution shown in Fig. 3 as well as the temporal development till sunrise will be representative for other calm weather situations. For an adaptation to the actual situation, the temperature level will be adjusted, while the areal distribution remains unchanged. Wind is not modified because the developing country breeze only depends on the temperature gradient, which is not changed at all by this procedure.

**Table 2:** Simulated and observed number of tropical nights per year for the urban and rural areas.

| Year | Observation Hannover-Langenhagen | 'Rural' simulation | Observation Weidendamm | 'Inner residental' simulation |
|---|---|---|---|---|
| 2017 | 0 | 0 | 2 | 0 |
| 2018 | 5 | 3 | 8 | 9 |
| 2019 | 3 | 2 | 12 | 11 |
| 2020 | 2 | 3 | 12 | 9 |

For a practical application of the proposed approach to estimate indoor temperatures using neighbourhood-scale results, the input data must be available for a longer time like the routine observations of a weather station. Here the observations at the DWD airport station Hannover-Langenhagen for the summer months JJA of the years 2011–2020 are used to demonstrate the potential applicability. Simulated 21-hour temperatures of the open field, calculated as a mean for the rural area shown in Fig. 8, are compared with the observed 21-hour temperatures at the airport station. The difference of these two values is used to increase or decrease the simulated temperatures to adjust the numerical results to the actual situation. As an indicator to prove this approach, the numbers of observed and simulated tropical nights with a minimum temperature above 20 °C are calculated and compared. For this comparison, the observations of the summer months JJA of the years 2017–2020 are used because this is the period where data of the urban DWD station Weidendamm were available (Table 2).

Comparing the results for the rural environment, the order is captured by the model quite well. The number of tropical nights at the urban location is much higher than for the rural surrounding in the observations as well as in the simulation for the 'inner residential' area. The larger amount of green spaces in the inner residential area of the simulation is higher than in the surrounding of the observation site Weidendamm, which might be the reason for the systematically lower values. However, again the order is captured reasonably.

Encouraged by these findings, an attempt is made to use the numerical results for a longer term, climatological extension. For all days of the summer months JJA of the years 2011–2020, the nighttime neighbourhood-scale temperature was adopted to the actual weather situation by raising or lowering the overall level at all grid points. For this thermal environment, local cooling of the standard rooms according to the procedure described above is calculated for each night till sunrise. It should be noted that this is only a rough approximation and a first attempt to describe the cooling effect by natural ventilation in a quantitative manner. For situations with a higher wind speed, which are also included in the data, the country breeze will not be so well developed as described in this paper. However, in 40 % of the nights of the selected period observed nocturnal 10-m wind at the open landscape of the airport are below 2 m $s^{-1}$ and in 70 % below 3 m $s^{-1}$.

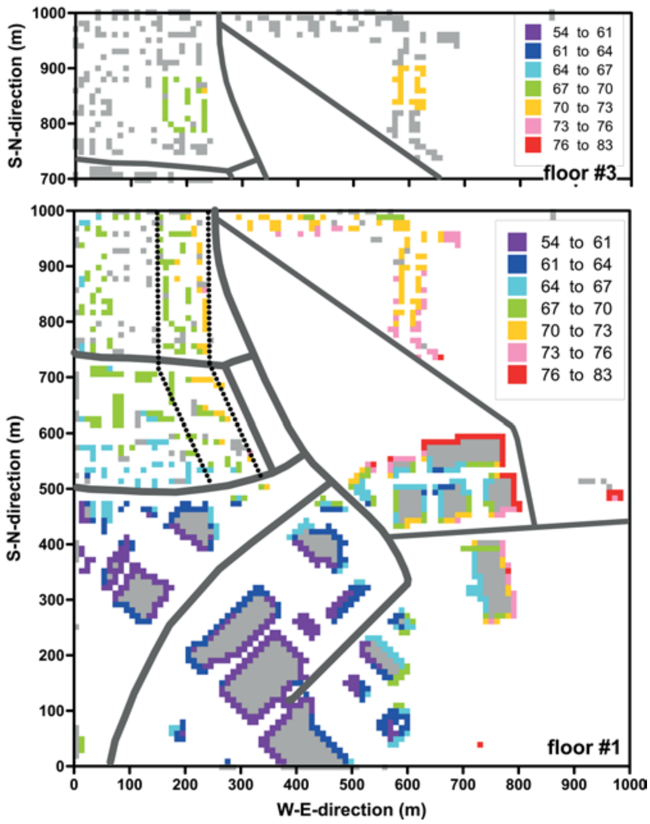


**Figure 10:** Number of days per year for the summer months JJA for the period 2011–2020 where nocturnal minimum room temperature is below 20 °C for floor#1 (below) and floor#3 (above).

Adopting a minimum room temperature in the morning hours of 20 °C, there is a wide spread of days per year, depending on land use and proximity to the cooler rural environment, where this threshold is achieved (Fig. 10). Out of the 92 possible summer days of JJA, a minimum room temperature of 20 °C was not exceeded on 67–73 days in the outskirts and on 64–70 days in the inner residential area. This gradient from the edge of the town into the more urban-type spaces is caused by the country breeze and the advection of cooler air. This effect is even more pronounced in the narrow, finger-like residential area near $x = 600$ m and $y > 700$ m. Here the country breeze is well developed, and this zone is closer to the cooler environment, which together result in a higher value of 70–76 (locally even higher) days per year, where the minimum room temperature is below the prescribed threshold. In the elevated floor #3,

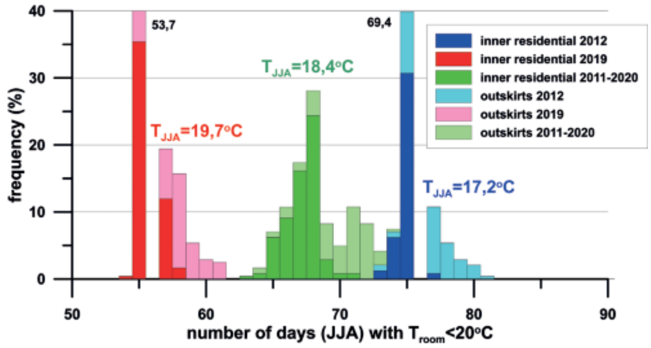


**Figure 11:** Frequency distribution of days with indoor temperatures below 20 °C for a cold year 2012, a warm year 2019 and the decadal mean for the inner residential area and the outskirts.

the number of days with a thermal load ($T_{room} > 20$ °C) is slightly higher than closer to the surface because relatively warm air is advected at this height from the surrounding caused by the nocturnal inversion.

Within this 10-year period (2011–2020), colder and warmer years can be observed, which modify the occurrence of days below the prescribed threshold significantly. By evaluating the simulated minimum room temperatures for all grid points defined as a standard room for different years, the frequency distribution given in Fig. 11 is calculated. Independent of the mean summer temperature of a particular year, the outskirts are notably preferred compared to the inner residential zone, with an excess of typically more than five days, where room temperature drops below the 20 °C limit. However, there is a difference of around 20 days (out of 92) between the hottest year (2019) and the coldest one (2012).

# 5 Conclusions

Urban residents often are exposed to a stronger heat load than their rural counterparts. Because of the urban heat island, nighttime temperatures in summer might be several degrees higher than in the surrounding countryside. In addition, expected future climate change will raise the overall level and contribute to an unfavourable thermal environment of city dwellers. Foresighted and sustainable urban planning opens the possibility to mitigate or even prevent adverse consequences for human health. In this study, an investigation for an outer city limit is chosen because this is typically the location of planned new developing areas. The advantage of an urban climate model is that not only the situation of today can be studied but also future scenarios with regard to a changed urban geometry.

The nocturnal urban heat excess can be reduced by the advection of cooler air. In this study, a numerical urban climate model is used to estimate the order and the significance of this process. It has been demonstrated that a country breeze, which develops due to the pressure gradient between the cooler surrounding and the warmer urban areas, has the potential to reduce the nighttime temperature in the outskirts by 1–2 K. The simulated country breeze with a vertical height of 10–20 m is a very shallow phenomenon and wind speeds are below 1 m s$^{-1}$. Therefore, the obstacles in the outskirts like buildings and trees reduce and slow down this wind system, and the penetration depth into the residential area is only 100–200 m. However, along wide openings and broad streets, the penetration of the country breeze associated with the advection of cooler air can be deeper.

This available cooler air has the potential to reduce the thermal load of humans, but only if it infiltrates rooms and apartments where humans stay nearly the whole night. Such a ventilative cooling depends on technical parameters like the number of windows and opening configuration, but also on meteorological parameters like wind speed in front of the windows and temperature difference between indoor and outdoor. Based on several numerical experiments, an empirical relation between ventilative cooling of a room and local meteorological conditions was derived. This relation was used to estimate the morning temperatures of all individual rooms in the residential area within the complex nighttime wind and temperature distribution calculated by the urban climate model.

Indoor temperatures follow the ambient temperature of the direct surrounding with a delay, and cooling inside is only around half as great as outside the building. The method presented in this study was used to calculate for a longer period of a decade the number of days in the summer months when nocturnal minimum temperatures are below a given threshold. An evaluation of the number of days with minimum indoor temperatures above 20 °C results in a significant difference up to 20 % between a cold year and a warm year.

The procedure described in this paper can be used in other urban climate models as well, e.g. PALM-4U (Maronga et al., 2019; Scherer et al., 2019), and is an additional contribution for urban planning to prepare our cities for climate warming and to protect the inhabitants from an unfavourable heat load.

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