Generating future-urban weather files for building performance simulations: case studies in London

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Abstract

Many methods to generate future weather files to run building performance simulations have been proposed. However, future weather files do not account for local urban climate modifications, such as urban heat island and may not be representative of urban buildings' climate conditions. This study describes a methodology to include urban effects in future weather files using multiple tools: the EURO-CORDEX regional climate model data, Urban Weather Generator, the URBVENT canyon wind models and EnergyPlus. Residential buildings located in different areas of London are used to test the methodology. The results confirm the significant impact of urban context on future-urban climate conditions and urban building thermal response.

Key Innovations

- A method to include site-specific urban climate effects in future weather files for use in building performance simulations
- Simulating the performance of different building conditions under future scenarios, considering changes in types, location across a city (i.e. urban geometry) and floors

Practical Implications

Considering site-specific urban heat island, wind speed reduction and solar access is crucial for a correct assessment of building thermal response to climate change. Including urban climate boundary conditions determines significant variations on indoor operative temperatures under future climate scenarios

Introduction

The indoor environmental quality of buildings may be significantly compromised in the next decades due to the overlapping effects of climate change and urban warming. Climate change will determine an increase of air temperature which will be amplified in cities, due to the urban heat island effect and the reduced wind speed in urban fabric. Considering that urban population and population ageing are increasing, the ability to predict the thermal behaviour of buildings under future-urban weather conditions is crucial to prevent serious health risks to the most vulnerable population groups due to building overheating.

According to the last report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), global temperatures will continue to rise over the 21th century and it is very likely that heat waves will become more frequent, long and intense under all assessed emission scenarios (IPCC Intergovernmental panel on climate change, 2014). The global temperature increase is estimated to have significant impact on the building heating and cooling demands (Ciancio et al., 2020) .

In addition to climate change, urban environments experience a local increase of air temperature due to the Urban Heat Island (UHI) effect (Oke, 1987; Oke et al., 2017). The UHI intensity is defined as the air temperature difference between an urban location and surrounding rural areas. The urban temperature increase is caused by the enhanced absorption of solar radiation and heat storage by urban structures compared to open, vegetated rural areas. The UHI intensity varies across a city depending on building density, thermal capacity and optical properties of materials, surface permeability and anthropogenic heat generation from vehicles and HVAC systems (Maria Kolokotroni & Giridharan, 2008; Salvati, Monti, et al., 2019; Stewart & Oke, 2012). Because of the local UHI intensity, the impact of climate change on building energy performance and heat-related health risks are amplified in cities (Lemonsu et al., 2015; Li and Bou-Zeid, 2013; Zinzi et al., 2020).

Furthermore, other climate phenomena that occur in urban areas influence building thermal behaviour.

Urban environments have a huge impact on the air flow around buildings. The roughness of the urban surface decreases the wind speed and increases the turbulence intensity when moving from the countryside to the city. The building shape and the geometry of street canyons (i.e. the ratio of the width and the length of the street to the height of the surrounding buildings) modify the airflow around urban buildings, reducing the potential for natural ventilation (Ghiaus et al., 2004; Xie et al., 2020). The combination of higher temperatures and reduced wind speed significantly increase the cooling loads and overheating risk of urban buildings (Kolokotroni et al., 2012; Salvati et al., 2020).

A further effect that needs to be included in the energy simulation of urban buildings is the shadows from surrounding buildings. Buildings located in dense urban areas receive less radiation on the facades. As opposite to the other urban effects, urban shadows can reduce the cooling load of buildings, by reducing solar gains and surface temperatures of external walls (Salvati et al., 2017, 2020). It is thus very important to include all the local and microscale climate modifications to accurately model urban buildings energy performance (Lauzet et al., 2019).

This means that urban context should be considered also when assessing the thermal response of buildings under climate change scenarios. This is crucial to avoid overestimations or underestimations of the impact depending on the location of the building across a city.

Different methodologies have been proposed to generate future weather files for building performance simulations, based on statistical or dynamic downscaling of global climate models projections (Herrera et al., 2017; Machard et al., 2020; Troup et al., 2019). Also, many urban climate models and coupling methodologies have been developed to include urban microclimate in dynamic thermal simulations (Lauzet et al., 2019).

Instead, very few attempts have been done to generate future weather files that also include urban effects (CIBSE, 2014; Mauree et al., 2018).

This study contributes to fill this gap, by testing a methodology to include global and local climate modifications in weather files for urban building energy simulations. London is used as a case study to demonstrate the impact of future climate scenarios on the overheating risk of buildings in different locations across the city.

Methods

This study uses EnergyPlus to simulate the dynamic thermal response of residential buildings under varying weather conditions that capture the impact of climate change and urban context. The analysis is carried out for the summer period.

Generation of future weather files

Typical Meteorological Years (TMYs) weather files representative of contemporary and future periods for London are generated based on the methodology provided by A. Machard et al. (2020). The methodology uses open-source dynamically downscaled regional climate multi-year projections from the European Coordinated Regional Downscaling Experiment (EURO-CORDEX) and the EN ISO 15927-4:2005 for assembling the TMY from 20-year long hourly climate data. The climate projections used in this study correspond to the worst case scenario RCP8.5 of the 5th IPCC Assessment Report (IPCC Intergovernmental panel on climate change, 2014). The downscaling method and driving model are REMO 2015 and MPI-M-MPI-ESM-LR, respectively. The climate projections were bias-corrected by using 20 year-long climate observations from the London Heathrow Airport weather station and multivariate bias correction method (Cannon, 2016). Three TMYs were generated from the multi-year EURO-CORDEX data: one contemporary TMY named “2010s” (based on the period 2001- 2020), one future mid-term TMY named “2050s” (based on the period 2041-2060) and one future-long term TMY named “2090s” (based on the period 2081 - 2100).

Including urban effects in future weather files

The climate modifications determined by the local-scale characteristic of the urban fabric are included in the TMYs by using the Urban Weather Generator (UWG) and the URBVENT wind models. An overview of the methodology is reported in Figure 1.

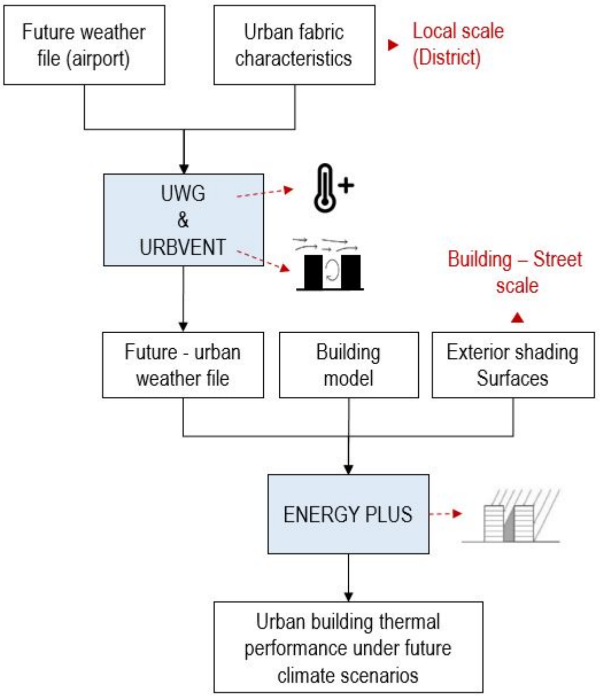

Figure 1 Overview of the steps, scales and models included in the methodology

The TMYs are used as weather data input to the UWG model (Bueno et al., 2013) along with the average characteristics of the urban fabric where the building is located. In this way, the site-specific hourly UHI intensity can be included in the contemporary and future weather files. The methodology was applied to three different urban areas of London: 1) the mixed-use and dense city centre, 2) a typical urban residential area and 3) a sub-urban low-density area. The urban morphology of the three urban areas is represented in Figure 2.

The Matlab version of UWG 4.1 was used in this study (Mao, 2018). The accuracy of UWG estimations and the calibration of the most sensible meteorological parameters was done by comparing the simulated urban temperatures to urban air temperature measurements taken in the urban residential area (Salvati & Kolokotroni, 2019). The performance of the model was assessed over the period June-August 2020.

The calibrated UWG models were then used to include the urban heat island in the three TMYs, using these as input rural weather files to the simulation.

UWG modifies the weather files hourly air temperature and relative humidity, but does not change the wind speed. The hourly wind speed values in the future-urban weather files have been adjusted following the approach developed by the URBVENT project (Ghiaus et al., 2004). The URBVENT project proposed an algorithm to calculate hourly urban wind attenuation in urban canyons from undisturbed values above roof level for a better assessment of the natural ventilation potential of urban buildings. The calculations are based on empirical models, which apply to different urban situations depending on the geometry and orientation of the canyon and the wind speed and direction at the meteorological station outside the city. A detailed explanation of the models can be found in (Salvati et al., 2020).

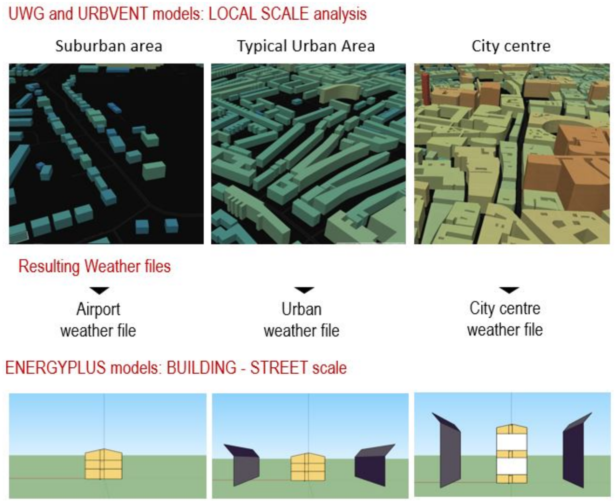

Figure 2: Graphical representation of the three urban areas and scales of analysis used in the study. The characteristic of the urban fabric at the local scale are used to run the UWG and URBVENT models. The typical geometry of the urban canyon in each area is used to define the reference building height and the external shading surfaces in EnergyPlus.

Energy plus models

The urban and non-urban TMYs were used to simulate the indoor operative temperature of naturally ventilated residential buildings using EnergyPlus.

The reference building typology is a terraced house. External shading surfaces were modelled to reproduce the street geometry of the three sites, as represented in Figure 2. The building height was modified accordingly, to match the average height of buildings in the three areas. Simulations were run for two bedrooms apartments located at the ground floor, middle floor and top floor. The average windows-to-wall ratio is 26%. Internal gains and occupancy schedules are set according to the BS EN 16798-1:2019 for residential apartment. The fabric construction and thermal performance was set according to typical values for existing buildings (CIBSE, 2015): solid brick external walls (U-value 2.18 W/m^{2}K), double glazing (U-value 2.95 W/m^{2}K), pitched insulated roof (U-value 0.48 W/m^{2}K) and solid floor with 50mm XPS insulation for the ground floor (U-value of 0.47 W/m^{2}K). For the building located in the “city centre” area, the middle floor is modelled with adiabatic floor and ceiling surfaces. Internal blinds with solar transmittance coefficient of 0.4 are used as shading systems, assuming they are closed when the incident solar radiation rate on the window exceeds 350 W/m^2.

The AirFlow Network (AFN) model of EnergyPlus was used to simulate the ventilation rate due to wind pressure, windows opening, and multi-zone airflows linkage. The ventilation rate is controlled at zone level assuming that windows are open if the indoor temperature is higher than 22 ºC and higher than the outdoor temperature.

The simulations were run in free-running mode for the three summer months (June to August) using the TMYs corresponding to the three periods (2010s, 2050s and 2090s) in the three reference locations: sub-urban, urban and city centre.

The relative impact of the different weather and urban conditions is assessed in terms of change in the percentage of hours that the indoor operative temperature is beyond the adaptive thermal comfort limits (Nicol and Humphreys, 2010).

Results

UWG calibration

The comparison between hourly UWG calculations and measured urban air temperature in the typical urban area is reported in Figure 3. The monthly UHI intensity as measured and simulated by UWG is reported in Table 1.

The comparison shows a good agreement between UWG predictions and measured values and that UWG can accurately simulate the night-time UHI intensity in the urban area in comparison to the airport weather data.

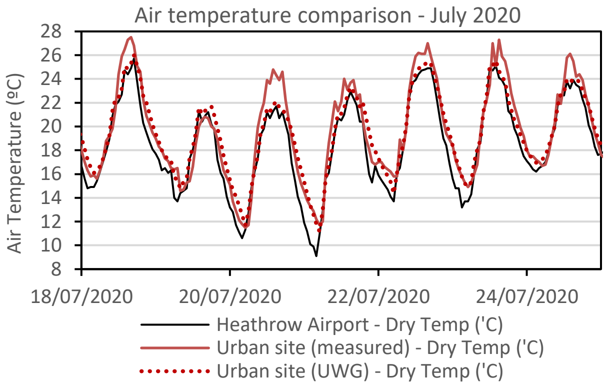

Figure 3 Hourly urban air temperature over one week in July 2020: comparison of measured data and UWG simulation

Table 1 Monthly UHI intensity measured and simulated by UWG.

	Measured	**UWG**
Average UHI (ºC)	0.8 (June) 0.9 (July) 0.7 (August)	0.9 (June) 0.8 (July) 0.8 (August)

The model performance was evaluated in terms of average hourly root mean square error (RMSE) and mean bias error (MBE) for the three months of measurements, as reported in Figure 4. The trend of the MBE shows that UWG tends to underestimate urban air temperature during daytime. The highest values of RMSE are also found for the daytime estimations, meaning that the maximum absolute error of UWG is the underestimation of daytime urban air temperature in comparison to measurements, as similarly found also for other cities (Salvati et al., 2019).

The monthly average RMSE is always below the acceptable threshold of 1 ºC, namely 0.9 ºC for June and July and 0.8 ºC for August.

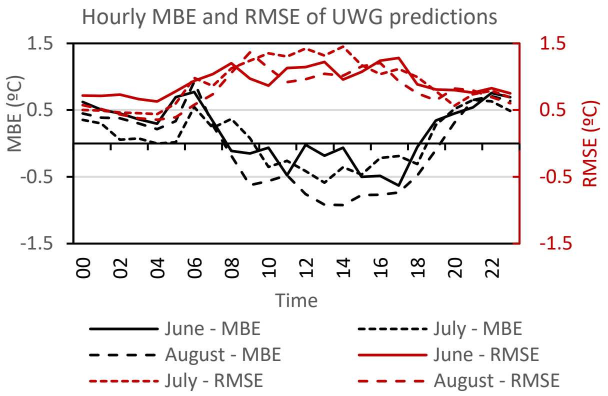

Figure 4 hourly MBE and RMSE or UWG estimations in comparison to urban air temperature measurements

Table 2 UWG input parameters for the two reference sites: urban and city centre

	Urban	**City**
Microclimate Parameters;		
Urban Boundary Layer Height: Day (m)	1000	1000
Urban Boundary Layer Height: Night (m)	50	50
Inversion Height (m)	50	50
UCM-UBL Exchange Coefficient	0.6	0.6
Urban fabric characteristics		
Average Building Height (m)	8.6	24.5
Building Density (m2/m2)	0.33	0.6
Vertical to Horizontal Ratio (m2/m2)	0.72	0.99
Sensible Anthropogenic Heat (W/m2)	8	22
Latent Anthropogenic Heat (W/m2)	2	2
Building types		
Midrise Apartment (%)	100	16.5
Restaurant (%)	0	8.5
Office (%)	0	66.5
Strip Mall (%)	0	8.5

Table 2 reports the values of the most sensible parameters used to run UWG for the urban and city centre areas. The values for the microclimate parameters were calibrated through the comparison with the air temperature measurements in the urban site. The same values have been used for the city centre simulation. The urban fabric morphology parameters and building types percentages have been calculated over an area of approximately 500m diameter in order to represent the average characteristics of the two urban areas at the local scale, in accordance with UWG model calculation approach (Bueno et al., 2013).

Urban and non-urban TMYs: comparison

The average dry bulb temperature over the three summer months for the three time periods - 2010s, 2050s and 2090s - and the three locations is compared in Figure 5. The graph shows that climate change will increase the average summer temperatures at the airport site in London by 0.9 ºC in 2050 and 2.2 ºC in 2090. The graphs also show a similar relative increase in the typical urban area and the city centre area. This means that, according to UWG estimations, the UHI intensity will not increase in future climate scenarios. Instead, it seems to be slightly mitigated in the typical urban area. This can be seen also from the average daily cycle of UHI intensity reported in Figure 6.

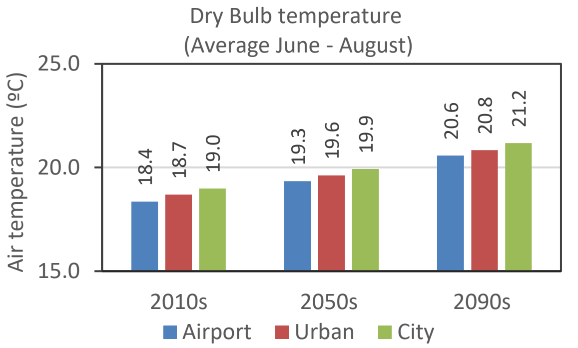

Figure 5 Average dry bulb temperature over the summer months for the three time periods and the three areas of London

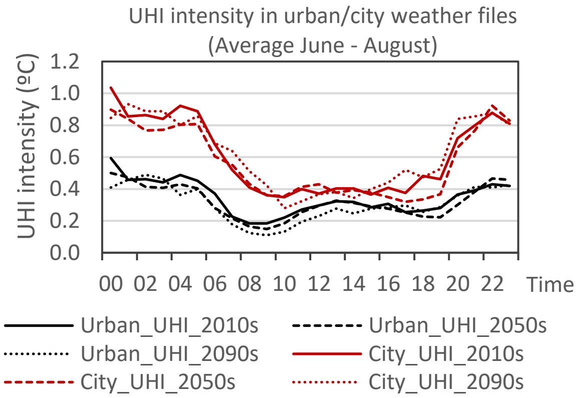

Figure 6 Average hourly UHI intensity in the urban and city centre TMYs in comparison to the airport TMYs for the three periods: 2010, 2050s and 2090s.

This result can be explained considering the predicted change in solar radiation in the two future periods. Figure 7 shows that global horizontal radiation will diminish in 2050s and 2090s in London. This result is common to other world regions and it is explained by higher concentration of aerosols and water vapour in the atmosphere (Liu et al., 2019). The absorption of solar radiation and heat storage by solid urban structures is one the main causes of the UHI phenomenon. Therefore, diminished solar irradiance levels may entail a reduction in the heat absorbed and stored in urban areas, and thus a decrease in UHI intensity in the future.

The potential impact of urban areas on solar radiation was not investigated in this study; for this reason, the TMYs for the three areas show the same average values (Figure 7). However, the different street geometry of the three locations do affect the solar access of the building facades. The sub-urban building is not located in an urban canyon, and thus receives the maximum incident solar radiation on the façade. Conversely, the typical urban area and city centre areas have street geometries with average aspect ratios (i.e. ratio of buildings height to street width) of 0.54 and 1.24 respectively. Therefore, the street geometry reduces the incident solar radiation at the different floors as reported in Table 3.

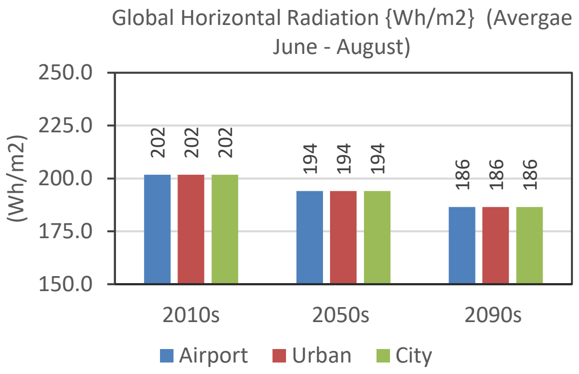

Figure 7 Average Global Horizontal Radiation over the summer months for the three time periods and the three areas of London

Table 3 reduction of the incident Solar Radiation Rate per Area [W/m2] on the façade in the urban models with respect to the model without external shading surfaces

	Urban MODEL	**City**
Ground floor	-37%	-60%
Middle floor	-21%	-36%
Top floor	-11%	-6%

Finally, Figure 8 shows the comparison of the average wind speed in the different TMYs. The graphs show that wind speed is reduced in the London's 2090s TMY compared to 2010s and 2050s TMYs. As a consequence, the relative impact of urban context on wind speed reduction will be mitigated in the future-long term scenario, given the lower undisturbed wind speed. Instead, the reduction of the average wind speed in the typical urban area and the city centre area is clear for the time periods 2010s and 2050s. The reduction of wind speed is higher in the city centre, due to the narrower geometry of the average urban canyon in comparison to the typical urban area (as represented in Figure 2).

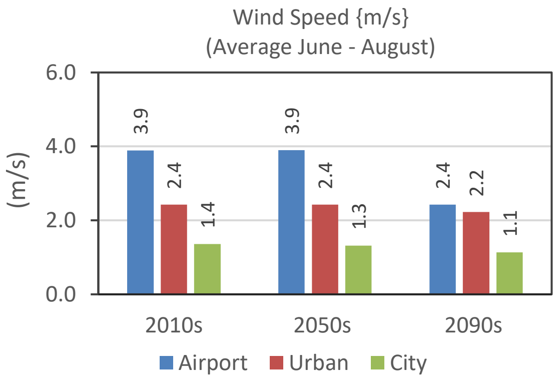

Figure 8 Average summer wind speed in the three TMYs for the three areas of London

Impact of future weather files and urban context on building indoor discomfort hours in summer

The impact of the overlapping effects of climate change and urban context on summer discomfort hours for the simulated residential buildings is reported in Figure 9. The three graphs show that the relative impact of urban context on the building overheating risk varies depending on the floor analysed.

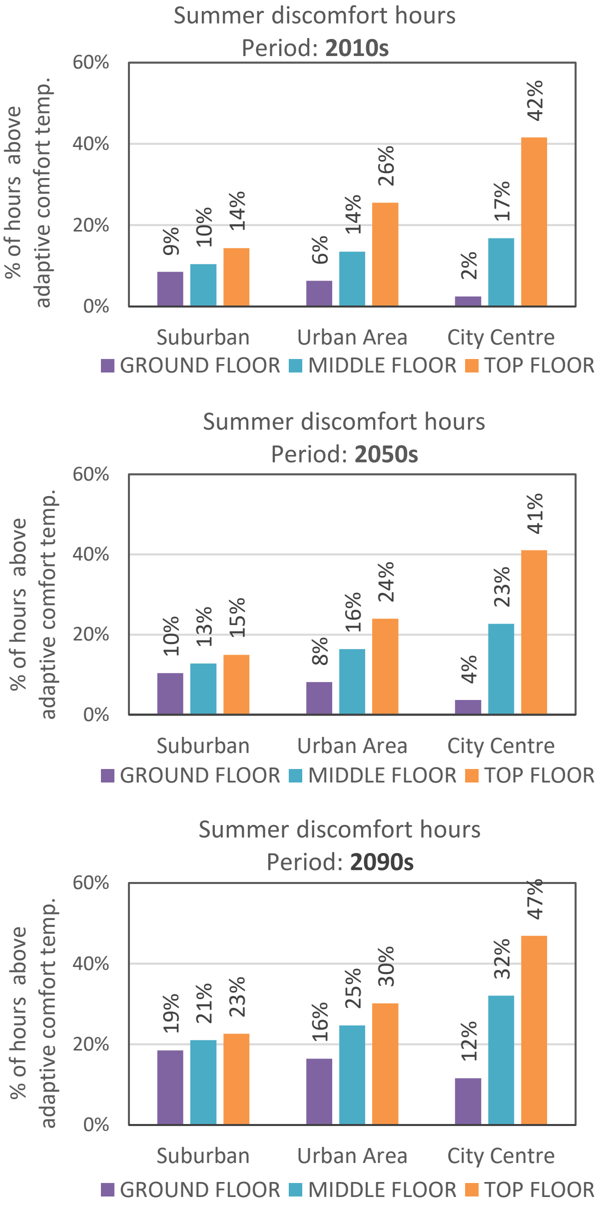

Figure 9 Percentage of time that the indoor operative temperature is above the adaptive thermal comfort temperature in the three summer months in present (top), future mid-term (middle) and long-term (bottom) climate scenarios for a residential building located in a sub-urban location, typical urban area and city centre in London

In all the three scenarios, the urban context increases the percentage of overheating hours in comparison to sub-urban locations for the middle and top floors, while it reduces the discomfort hours in the ground floor apartment. The urban context has a positive impact on indoor thermal conditions of ground floor apartments in summer, thanks to the beneficial effect of reduced solar radiation incident on the façade. Conversely, the urban context determines an increase in overheating hours for both the middle and top floor locations because the beneficial effect of shadows is reduced at these floors and thus the impact of UHI intensity and reduced urban wind speed prevail.

The varying impact of urban context affect the relative impact of climate change on each floor and location. For ground floor apartments, climate change will determine an increse in discomfort hours by +1-2% in 2050 and +10% in 2090, pretty much consistently in the three locations. For the middle floor apartments, the discomfot hours increase by 2-6% in 2050 and by 11-15% in 2090, with higher impact in the city centre than urban and sub-urban locations. For the top floor apartments, the discomfort hours vary between -2% and +1% in 2050 and increase by +5-9% in 2090, with higher impact in the sub-urban location. These results confirm the need to include all urban effects when assessing the impact of climate change on building thermal performance.

Considerations on the models used in the study

All the methods used in this study are subject to uncertainties and the results must be interpreted considering their limitations.

The EURO-CORDEX climate projections are based on the last IPCC Assessment Report (2014), which will be updated by 2022. More accurate climate projections will be available after that, but it is unlikely that the new scenarios will be more optimistic.

The standard ISO 15927-4:2005 to assemble TMYs from multi-years data is based on a ranking procedure based primarly on air temperature, humidity and solar radiation, giving secondary importance to wind speed. This means that the actual change in wind speed in the three TMYs may be less well represented compared to the other three variables. In fact, the average wind speed in the three periods 2001-2020, 2041-2060 and 2080-2100 are 3.8, 3.6 and 3.5 m/s respectively, which is different from what resulted by comparing the three TMYs.

Some considerations are needed also regarding the models used to include urban effects.

The selection of the UWG and the URBVENT models motivated by their suitability for the purpose and ease of use by building energy modellers. In fact, these models are designed to morph undisturbed hourly values of the meteorological variables into urban values, including the urban heat island intensity (UWG) and the urban wind speed attenuation (URBVENT models). Both methods use hourly weather data from a weather station located outside the city as input (i.e. the airport weather station) and a parametric description of the urban area. The input weather data can be observations of a specific period or TMY weather files, making it easy to appy also to future climate scenarios. Furthermore, the simulation is efficient and can be run for a year in few minutes.

Many urban canopy parametrisations have been developed to calculate urban energy fluxes and temperatures; some of them are more accurate than UWG in modelling the three-dimensional radiation exchange (Conigliaro et al., 2021) and the impact of trees and vegetation (Krayenhoff et al., 2020). However, they are also less practical for use by building modellers, because they are forced with meteorological variables on top of their domain, needing coupling with mesoscale models. To the knowledge of the authors, the UWG is the only stand-alone model able to calculate hourly urban meteorological variables considering the effects of urban geometry, trees, building energy and radiation exchanges without the need of mesoscale forcing. This is the main reason for standing-up as the best tool for use by building modellers. An improved version of the UWG has been published recently, called the Vertical City Weather Generator (VCWG). This model seems very promising as it also calculates the vertical profiles of air temperature, humidity and wind speed in urban canyons (Moradi et al., 2021) and could a be a valuable alternative to UWG.

Even if easy to use, performing UWG simulations requires some basic understanding of the interactions between the atmosphere and urban elements to set reasonable values to the input parameters. This is crucial especially for the most sensible parameters, such as the meteorological parameters and the geometric parameters of the urban area (Bueno et al., 2013; Mao et al., 2017; Salvati, Monti, et al., 2019).

Similar considerations have led to the identification of the URBVENT models to account for urban wind attenuation in urban canyons. The empirical models involved in the calculation allows a better estimation of the wind attenuation compared to the use of the terrain coefficients of EnergyPlus. The calculation algorithm has been run with a simple spreadsheet that is publicly available for applications in other studies (Salvati, Palme, et al., 2019). The VCWG could be an alternative to the URBVENT models that we intend to test in future studies.

Finally, other urban effects are more complex to model. For instance, the fact that the UHI intensity does not increase in the future holds true assuming no changes in the urban fabric. A more accurate estimation of the future UHI intensity would also include the foreseen changes in urban growth (i.e. change in land cover and building density).

Another aspect that was not investigated is the influence of urban areas on cloud cover. A recent observational study revealed that cloud cover is systematically enhanced in the afternoon in the urban core of London and Paris compared to the surrounding rural areas (Theeuwes et al., 2019). This may have a significant impact on the incoming solar radiation in central areas compared to sub-urban and rural areas.

Conclusion

This study described a methodology to include urban effects in future weather files for building performance simulation. The methodology was applied to assess the impact of climate change and urban context on the indoor operative temperature of residential buildings located in different locations across London. The results showed that the relative impact of climate change on building thermal performance may change depending on the urban context and building type. Depending on the density of the urban area and the street geometry, the average UHI intensity, wind speed and solar access of building façade may vary substantially. In some situations, urban context can have a mitigating effect on the building overheating risk associated with climate change. In others, it may amplify the negative impact of climate change by increasing the percentage of indoor discomfort hours.

These results indicate that a correct assessment of the impact of climate change on building thermal performance should also include site-specific climate modifications determined by urban context. The modelling procedure presented in this study is based on open-source climate projections and models that can be applied also to other cities and could be useful for a more accurate prediction of the impact of climate change on building in urban areas in different climate regions.

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