Urban context and climate change impact on the thermal performance and ventilation of residential buildings: a case-study in Athens

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ABSTRACT

Urban settings and climate change both impact energy use, thermal comfort and ventilation of buildings. This is more noticeable in hot urban areas where the urban heat island effect is more pronounced; also, in densely built urban areas where thermal comfort in naturally ventilated buildings is affected by changes in natural ventilation rates because of surrounding obstructions. In some cases, overshadowing might alleviate the impact. This paper presents a study of changes in energy demand in residential buildings considering the overlapping effect of climate change and urban heat island intensity in Athens representing a hot European climate and a dense urban setting. The case study building is a real residential building in an urban canyon in central Athens with data obtained from the PRELUDE H2020 project. The impact of urban parameters on air temperature wind speed and solar overshadowing was considered. Urban air temperature was calculated by using the Urban Weather Generator which includes a number of indices such as site coverage, façade to site ratio and average building height; it also considers the building construction materials as well as anthropogenic heat emissions by the operation of the buildings. Urban wind speed was modified using the URBVENT urban canyon model for the computation of wind speed; this model was validated by its proposers in 2005 by measurements in Athens. Solar overshadowing was calculated for the case-study building considering the surrounding buildings. Current-urban and future-urban weather files were generated, and simulations were run considering energy demand and indoor thermal comfort. The thermal simulation results show that in the hot European climate of Athens with densely built urban areas and for a building within an urban canyon, current weather files which include overshadowing, urban heat island and canyon wind will increase the cooling demand by 24% in comparison to using a typical current weather file. However total energy demand (heating and cooling) increased only 3% for lower floors and 12% for higher floors due to the reduction of heating demand. Simulations using future weather files indicated a 66% increase of cooling demand in comparison to using a typical weather file. Future total energy demand increased by 32% for higher floors and 13% for lower floors. If the building is free floating an adaptive thermal comfort analysis indicated that only 25% of the summertime will be comfortable in comparison to the 50% prediction by the current typical weather file. Therefore, the use a suitable weather file to include urban external conditions in thermal simulations is essential for more accurate predictions of energy demand and internal avoidance of overheating in free-floating buildings.

KEYWORDS

Microclimate, climate change, urban heat island, ventilation, thermal comfort, energy use

1 INTRODUCTION

As reported by (Salvati and Kolokotroni, 2022) ‘in thermal simulations studies of buildings, ambient conditions are accounted for by using weather files of the building’s location, providing hourly values of typical ambient conditions: temperature, humidity, solar radiation and wind. Weather files are built using historical observational data usually over 30 years; they are based on measurements at meteorological stations usually at airports. Therefore, weather files do not account for characteristics of the urban environment which modify climatic conditions, especially those of air temperature and wind. In addition, buildings designed and built today, will last for many years. Therefore, future climate projections should be used to predict how our buildings will perform in 30 or 50 years. Using such climate projections can ensure that energy and comfort performance simulations can more realistically predict future performance.’

(Salvati and Kolokotroni, 2022) presented to the AIVC Conference in 2022, proposed a methodology based on the use of urban climate models (Urban Weather Generator -UWG) and detailed microclimate models (ENVImet) for urban microclimate simulation, in order to investigate the overlapping effects of climate change and urban effects on the future performance of urban buildings. This was applied to two case study buildings in London, UK and Cadiz, Spain.

The present paper is developed along the same methodology using the UWG (Bueno et al, 2013) to obtain modified urban temperatures, overshadowing calculations to consider restrictions in impending solar radiation by adjacent buildings and URBVENT (Ghiaus and Roulet, 2004) models to obtain modified wind speeds in an urban canyon. The case-study building is located in an urban canyon in Athens, Greece and its data were obtained from the PRELUDE H2020 (PRELUDE, 2023) project.

The paper presents the urban climate modifications – both for ambient temperature and urban canyon wind by generating site-specific urban weather files for the location of the case-study in Athens; section 2. The weather files are generated for both current and future urban weather scenarios and are used for EnergyPlus (DesignBuilder, 2023) energy and thermal simulations which include the effect of urban overshadowing; section 3. The results of simulations (energy and comfort) are presented in section 4.

2 CASE STUDY LOCATION AND BUILDING DESCRIPTION

2.1 Climate of case-study location

The Mediterranean climate of Athens (Köppen climate classification: Csa) represents a dominant alternation between prolonged hot and dry summers and mild, wet winters with moderate rainfall. July and August are the driest months for Athens with the highest outdoor dry bulb temperatures, and diurnal variations in outdoor temperatures are notable (Figure 1). The dominant southwest wind comes with higher wind speeds to Athens throughout the year (Figure 2). The heating degree days and cooling degree days for the current climate of Athens showed that the buildings in Athens need both heating and cooling for comfort (Figure 2).

The building in Athens is located in a very dense urban texture within a well-defined urban canyon street and in a climate region with high solar radiation and summer air temperatures, where the urban heat island (UHI) intensity has the highest negative impact.

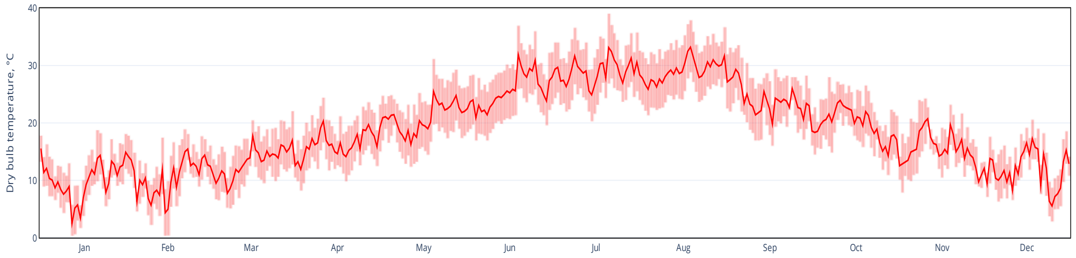

Figure 1: Daily outdoor dry bulb temperature profiles of Athens

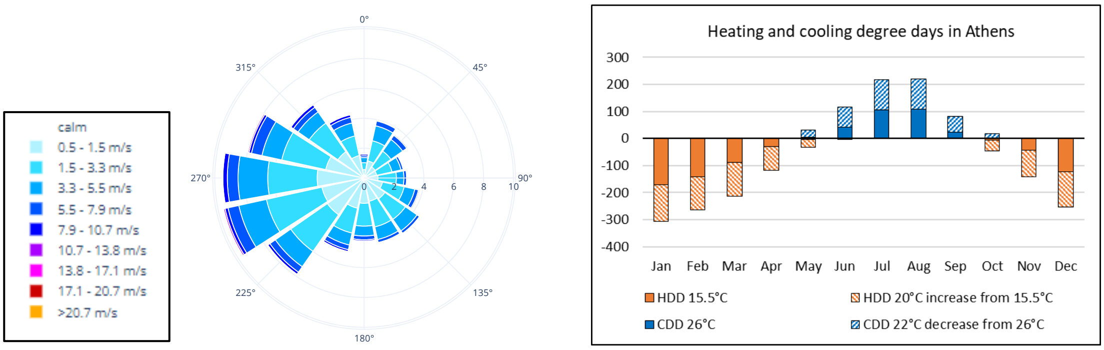

Figure 2: A wind rose, heating degree day and cooling degree day profiles of Athens

2.2 Case-study building description

The case-study building is a five-storey residential building in Athens. It is highly representative of low-rise multi-apartment buildings that were built during the 1930s. It was renovated in 2005 by adding rooftop insulation, installation of double aluminium windows to minimise thermal losses, replacement of outdated lighting with LED lamps etc. It is used as a hostel for the homeless and houses support staff with maximum capacity of 60 occupants. The total floor area is 1080 m2 and it has a ground-floor, 5-storeys and a basement. It is located in Patission Street which is a long street surrounded by similar in-height buildings starting from the centre of Athens and extending to the north. The building is located about 3 km from the centre of Athens (Omonia Square). A typical floor plan and an external view of the building are presented in Figure 3. The heating and hot water system operates with natural gas, the lamps are LED and all windows are double-glazed aluminium. The apartments of the tenants are hotel-like rooms including a room and bathroom with TV and fan, heating & cooling thermostat. The thermal properties of the external envelope are presented in Table 1.

For this paper, two “intermediate levels” – level 2 (above the ground floor) and level 4 (below the top floor) were chosen. Each floor consists of 6 rooms – three single rooms (SR) and three twin rooms (TR). The single room (SR) is for one occupant and the twin room (TR) is for two occupants. Each room has one bath and there is a balcony with one window/door on either the east or west side. The communal areas, which include the kitchen, lift and stair core, are located in the middle of the building.

Table 1: Thermal properties of the building envelope

Building envelope	Thermal transmittance (W/m^{2}K)
External wall	1.739
Party wall	2.038
Ground floor	1.834
Internal floor	0.788
Roof	0.639
Internal door	2.672
Window	2.5 (light transmission 0.78)

Figure 3: External view and typical floor plan of the case-study building.

3 METHODOLOGY FOR GENERATING URBAN WEATHER FILES

The methodology for generating urban weather files to be used in thermal simulations is presented in Figure 4. Two rural weather files (current and future) from Meteonorm were used (Meteotest, 2020) as the starting point. The future weather was considered for the RCP8.5 scenario which is the worst-case, high-emissions scenario for the year 2050 caused by "business as usual" without efforts to cut greenhouse gas emissions (IPPC, 2014).

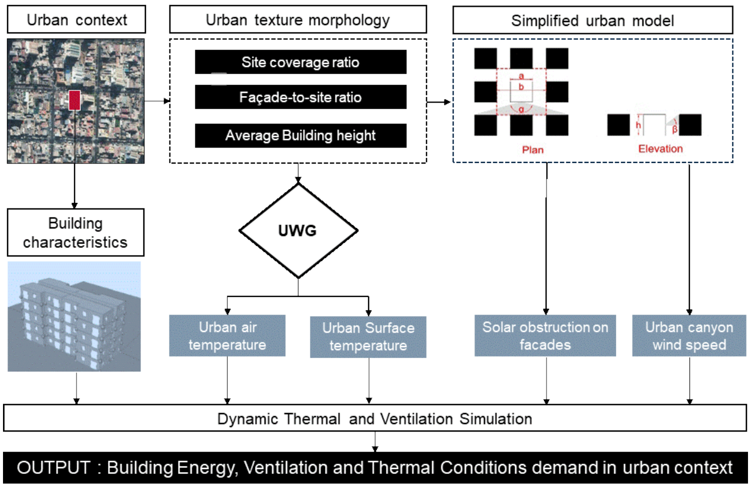

Figure 4: Urban considerations in building simulation (adapted from Salvati et al, 2020)

Autodesk *Revit* was used to generate the required building information for the UWG program. The 3D model was computed over an area of about 250m in length, as suggested for local urban climate studies (Salvati *et al.,* 2016) (Stewart and Oke, 2012). The case studied building is located on the road (yellow arrow shown in Figure 5) where the urban canyon wind was to be calculated. The topography of the site was modelled according to its location above sea level; the south is lower than the north. The buildings were represented in the Revit massing models that allow calculating the façade and floor areas of the site, and average building height for the UWG program. The building types were defined for each 3D model that allows calculating the energy consumption for residential, primary and secondary schools, retail shops, hotels, restaurants, supermarkets etc. The building density, urban buildings' vertical-to-horizontal ratio and green area coverage are then calculated through the Revit area scheme. Evergreen trees were considered for the vegetation growing seasons. The massing models of urban buildings for the selected site are shown in Figure 5. After the UWG's .xlsm files and other source files are co-simulated using Matlab, two urban weather files for current and future scenarios were obtained. Table 2 presents the input values calculated.

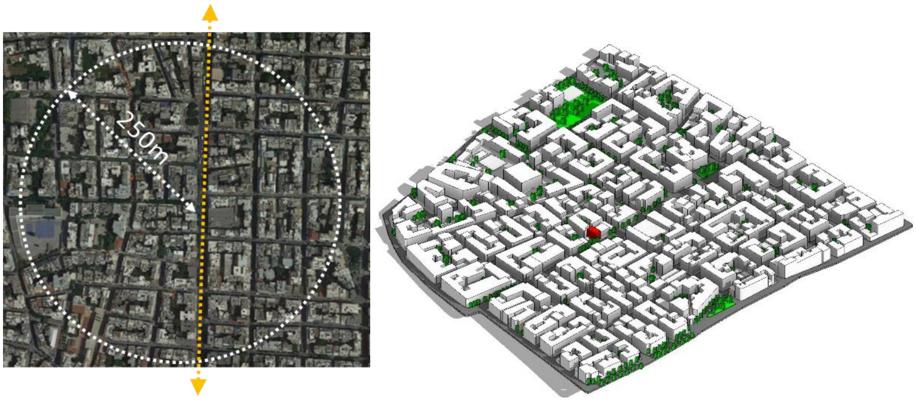

Figure 5: Site plan and 3D massing model of the case study location (Case study building is shown in red colour)

Table 2: Input data used in UWG's .xlsm file

Urban Characteristics	**Input data**	**Vegetation Parameters**	**Input data**
Average Building Height	15.78	Urban Area Veg Coverage	0.0157
Fraction of waste heat into the canyon	1	Urban Area Tree Coverage	0.0245
Building Density	0.473	Veg Start Month	1
Vertical to Horizontal Ratio	1.078	Veg End Month	12
Urban Area Characteristic Length	250	Vegetation Albedo	0.25
Max Dx	62.5	Latent Fraction of Grass	0.5
Road Albedo	0.1	Latent Fraction of Tree	0.5
Pavement Thickness	0.5	Rural Road Vegetation Coverage	0.8
Sensible Anthropogenic Heat (Peak)	20		
Latent Anthropogenic Heat (Peak)	2		

The hourly wind speed was calculated using the algorithms of (Ghiaus et al 2005) as presented by (Salvati *et al.*, 2020). The terrain type with a roughness of 5.0 was assumed for the urban area. The average urban height, building density and vertical-to-horizontal building area ratio were considered referring to the data generated for the UWG program. The length-to-width ratio of the road is more than 20 hence, the canyon height-to-width ratio was checked, and it was identified that the case study building is exposed to the urban canyon wind. The case studied building has five stories; the urban canyon wind was therefore required to calculate from its relative building height above the ground level. It was considered 7m above street level for level 2 and 15m height for level 4 r. Hourly wind speed values of canyon wind were calculated for the undisturbed wind and wind direction values found in the rural weather files. The urban canyon wind speed values were then replaced with the urban weather files generated from the UWG program.

4 RESULTS AND DISCUSSION

EnergyPlus simulations were carried out using the generated weather files and overshadowing effect as presented in Figure 6. Data obtained from the building were used to define inputs such as construction, schedules and internal heat gains, supplemented by values from (BS EN 16798-1, 2019) where data were not available.

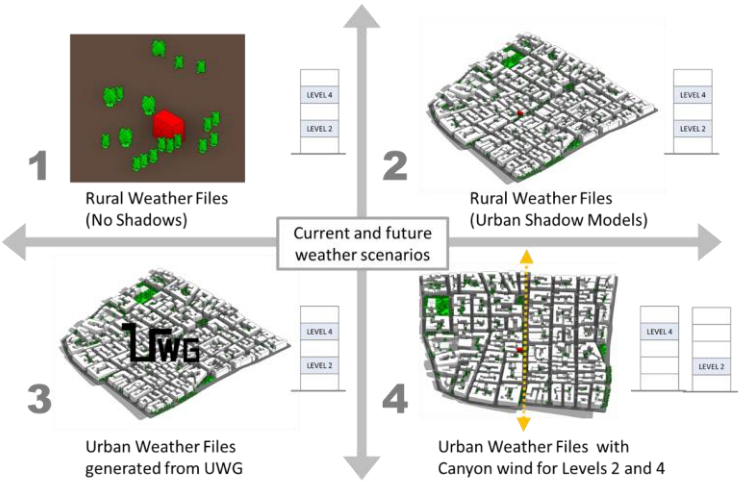

Figure 6: Tested cases for current and future weather scenarios

4.1 Comparison of weather files

The differences between different weather files are compared in Figure 7. As expected, higher temperature values were found in the urban weather files compared to the rural weather file. It can also be seen that the temperature values were increased in future weather conditions, but the annual mean temperatures were lower than 21°C in all scenarios. However, when the temperature values were assessed for the summer period only, a significant temperature increment could be observed in future weather conditions, reaching its summer average temperature above 31°C. On the other hand, significantly lower wind speed values were found in the urban weather file with the urban canyon wind modification. The average urban canyon wind speed, generated for level 4 rooms which are located at 15m height above the ground level, was as low as 1.5m/s and mostly still throughout the year. That implies decreasing natural ventilation efficacy in urban areas overshadowed.

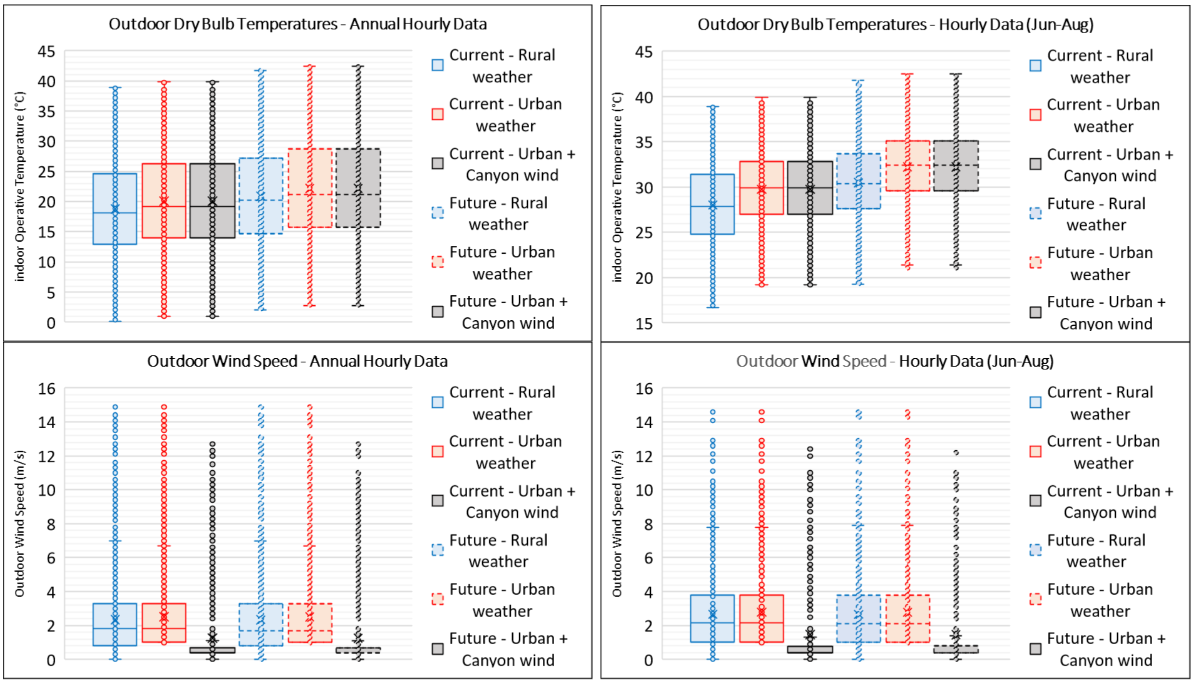

Figure 7: Comparison of outdoor dry bulb temperature and wind speed in different weather files

4.2 Energy use results

4.2.1 Annual energy demand

The annual heating and cooling demand for current and future weather conditions are presented in Figure 8 and Table 3 for a lower floor (L2) and higher floor (L4) of the building; on all cases overshadowing has been considered. The impacts of building height and building density on energy demand were noted due to its exposure to the Urban Heat Island, overshadowing by surrounding buildings and lower urban canyon wind resulting to higher cooling demand and lower heating demand. A higher floor would demand more cooling and less heating compared to a lower floor due to lower wind speeds near the ground reducing infiltration and ventilation losses. As expected, future weather will demand higher cooling and lower heating because of an increase in external temperature. The highest total energy demand would be for higher floors in the future.

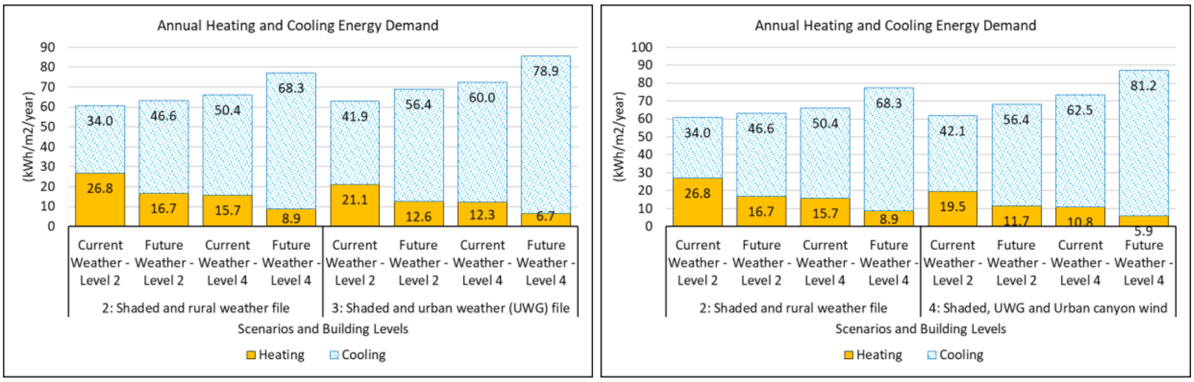

Figure 8. Annual heating and cooling demand of level 2 and level 4 rooms for scenarios 2 and 4.

Table 3: Heating, Cooling and Total energy demand for the various weather scenarios

Weather file	Heating	Change ratio	Cooling	Change ratio	Total	Change ratio
Overshadowing included in simulations						
Building Level 4	**kWh/m2/year**		**kWh/m2/year**		**kWh/m2/year**	
Current Weather	15.7		50.4		66.1	
Current Urban Weather (UWG)	12.3	0.78	60	1.19	73.1	1.11
Current UWG, Urban canyon Wind	10.8	0.69	62.5	1.24	74.0	1.12
Future Weather	8.9	0.57	68.3	1.36	77.8	1.18
Future Urban Weather (UWG)	6.7	0.43	78.9	1.57	86.0	1.30
Future UWG, Urban canyon Wind	5.9	0.38	81.2	1.61	87.5	1.32
Building Level 2						
Current Weather	26.8		34		60.8	
Current Urban Weather (UWG)	21.1	0.79	41.9	1.23	63.8	1.05
Current UWG, Urban canyon Wind	19.5	0.73	42.1	1.24	62.3	1.03
Future Weather	16.7	0.62	46.6	1.37	63.9	1.05
Future Urban Weather (UWG)	12.6	0.47	56.4	1.66	69.5	1.14
Future UWG, Urban canyon Wind	11.7	0.44	56.4	1.66	68.5	1.13

4.2.2 Monthly energy demand

The impacts of weather and microclimatic conditions on monthly heating and cooling demand are presented in Figure 9, considering the difference between rural and urban weather files, and the overshadowing and urban canyon wind effects on urban buildings; a higher floor (L4) is presented as it was shown to perform worse than lower floors. The overshadowing impact is included in the results presented.

Figure 9 shows that heating demand is mainly from December to March due to the cold season in Athens. The heating demand of a single building exposed to the open terrain was less than the urban building as the urban building could be shaded by surrounding buildings limiting useful solar gains. Overshadowing considerations are important as would affect (increase) the heating demand significantly in all cases. As expected, using urban temperatures and future weather would reduce heating demand because of the increase in outdoor air temperatures. Because of the urban canyon wind, the heating demand could reduce.

Figure 9 also shows that cooling demand which is mainly during the summer months of June to September. As expected, the cooling demand of a single building exposed to the open terrain was higher than the urban building due to its exposure to solar radiation. Overshadowing considerations are important and would reduce the prediction of cooling demand. As expected, using urban temperatures and future weather would increase the cooling demand. Urban canyon wind, does not seem to impact monthly cooling demand significantly.

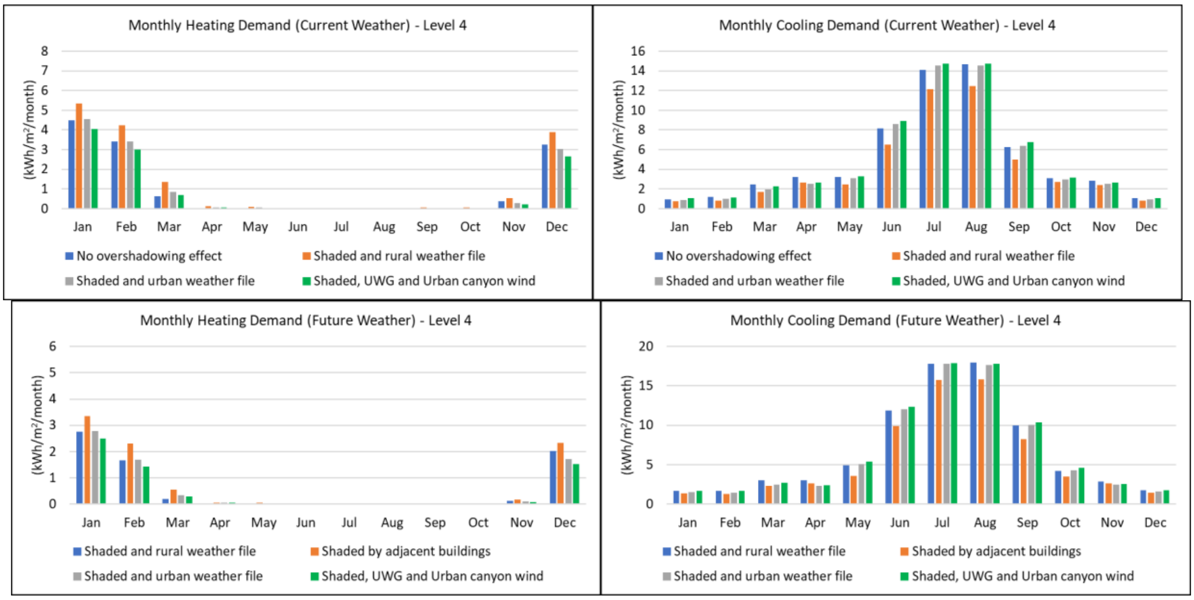

Figure 9: Monthly heating demand of level 4 rooms

4.3 Thermal comfort results

The impacts of weather and microclimatic condition on thermal comfort in the absence of air-conditioning are presented in Figure 10 as percentage of overheating hours during the summer (June to September). In calculating these, Category II (EN 16798-1-2019) limits were considered, hence, adaptive comfort temperature range can be expected by widening the upper limits to +3°C and lower limits to -4°C. Within these upper and lower limits of adaptive comfort, the temperature is assumed to be comfortable range, which is presented as yellow colour in Figure 10. If the indoor temperature is above the upper limits, it is the condition with overheating, which is presented as red colour for active cooling requirements. It can be seen that the overheating time was increased in the urban weather condition and future weather conditions. In the future weather condition with urban canyon wind, the SR2 room has less than 10% of summertime for adaptive comfort range, and more than 90% of summertime hours overheating.

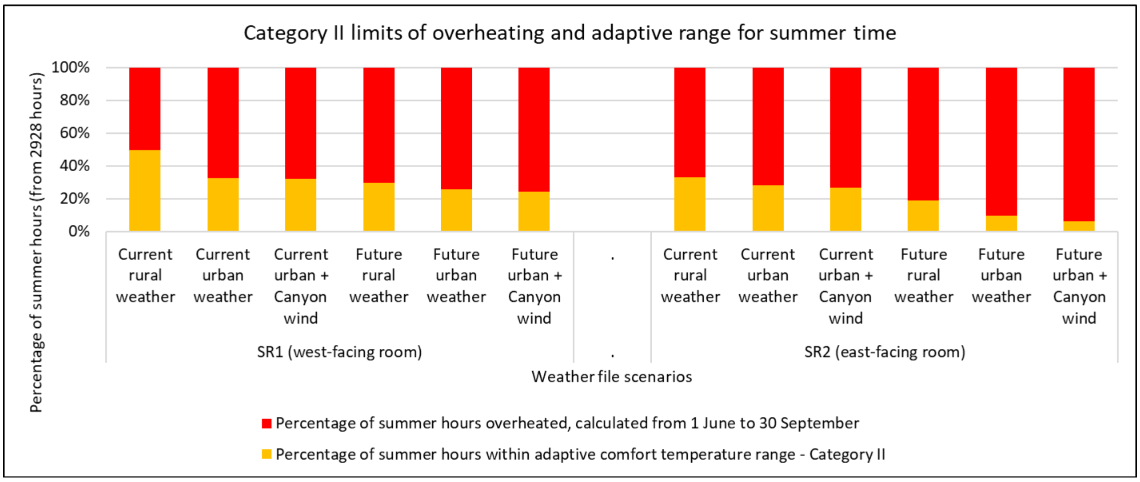

Figure 10. The percentage of summer hours for adaptive comfort and overheating time.

5 CONCLUSIONS

The confounding effects of urban density, urban textures and exposure to the wind, building design and human activities chemically and physically alter weather characteristics over and around urban areas. This paper aimed to identify the effects of changes in urban air temperatures and urban canyon wind on building energy performance and thermal comfort compared to rural conditions. Six weather files were generated from the UWG program and urban canyon wind calculation, and a total of eight weather files (two were the rural weather files generated from the Meteonorm) were used to compare how different weather impacts building performance. The overshadowing effects from the surrounding buildings were considered as it is relevant to an urban setting. The case study building is located in Athens within an urban canyon with data obtained from the PRELUDE H2020 project.

The results of the simulation experiment showed that in hot European climate regions with densely built urban areas and for buildings within urban canyons, thermal simulation using current climate considering overshadowing, urban heat island and canyon wind will reduce the heating demand in future while the cooling demand could increase due to the increment in outdoor dry bulb temperature. The urban canyon wind caused lower wind speed which influences the efficacy of natural ventilation and energy consumption. The adaptive thermal comfort potential could reduce in the future while the overheating period could extend.

Specifically, for the case-study building in Athens the simulation results show an increase of the cooling demand by 24% in comparison to using a typical current weather file. However total energy demand (heating and cooling) increased only 3% for lower floors and 12% for higher floors due to the reduction of heating demand. Simulations using future weather files indicated a 66% increase in cooling demand in comparison to using a typical weather file. Future total energy demand increased by 32% for higher floors and 13% for lower floors. If the building is free floating an adaptive thermal comfort analysis indicated that only 25% of the summertime will be comfortable in comparison to 50% prediction by current typical weather.

Therefore, the use of a suitable weather file to include urban external conditions in thermal simulations is essential for more accurate predictions of energy demand and internal avoidance of overheating in free-floating buildings.

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7 REFERENCES

BS EN 16798-1 (2019) Energy performance of buildings. Ventilation for buildings. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. Module M1-6. UK: BSI.

Bueno, B., Norford, L., Hidalgo, J. and Pigeon, G. (2013) 'The urban weather generator', Journal of Building Performance Simulation, 6(4), pp. 269-281.

Design Builder software https://designbuilder.co.uk/ (assessed 23 June 2023)

IPCC. 2014. Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. edited by Core Writing Team, R. K. Pachauri, and L. A. Meyer. Geneva, Switzerland: IPCC.

Georgakis, C. and Santamouris, M. (2008) 'On the estimation of wind speed in urban canyons for ventilation purposes — Part 1: Coupling between the undisturbed wind speed and the canyon wind', Building and Environment, 43(2008), pp. 1404–1410.

Ghiaus, C., F. Allard, M. Santamouris, C. Georgakis, Ca Roulet, M. Germano, F. Tillenkamp, N. Heijmans, Jf Nicol, E. Maldonado, M. Almeida, G. Guarracino, and L. Roche. 2005. "Natural Ventilation of Urban Buildings - Summary of URBVENT Project." Pp. 29–33 in International Conference "Passive and Low Energy Cooling for the Built Environment." Santorini, Greece.

Meteotest. (2020) Meteonorm Available at: https://meteonorm.com/en/ (assessed 23 June 2023)

PRELUDE project, Prescient building Operation utilizing Real Time data for Energy Dynamic Optimization (https://prelude-project.eu) (assessed 23 June 2023)

Salvati A and Kolokotroni M (2022), Urban microclimate impact on ventilation and thermal performance of multi-family residential buildings: two case studies in different climates and urban settings, 42nd AIVC conference: Ventilation Challenges in a Changing World, 5-6 October 2022, Conference, Rotterdam, The Netherlands.

Salvati A, Palme M, Chiesa G, and Kolokotroni M (2020). Built form, urban climate and building energy modelling: case-studies in Rome and Antofagasta. Journal of Building Performance Simulation. https://www.tandfonline.com/doi/full/10.1080/19401493.2019.1707876

Salvati, A., Coch, H. and Cecere, C. (2016) 'Urban Heat Island Prediction in the Mediterranean Context: An Evaluation of the Urban Weather Generator Model', ACE: Architecture, City and Environment, Arquitectura, Ciudad y Entorno, 11(32), pp. 135–156. DOI: 10.5821/ace.11.32.4836.

Santamouris, M., Georgakis, C. and Niachou, A. (2008) 'On the estimation of wind speed in urban canyons for ventilation purposes — Part 2: Using of data driven techniques to calculate the more probable wind speed in urban canyons for low ambient wind speeds', Building and Environment, 43(2008), pp. 1411–1418.

Stewart, I.D. and Oke, T.R. (2012) 'Local Climate Zones for Urban Temperature Studies', Bulletin of the American Meteorological Society, 93(12), pp. 1879–1900. DOI: 10.1175/BAMS-D-11-00019.1.