Architectural Engineering and Design Management

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/taem20

Resilient cooling of the Mediterranean office spaces under climate change

Günsu Merin Abbas, Çağla Meral Akgül & Ipek Gursel Dino

To cite this article: Günsu Merin Abbas, Çağla Meral Akgül & Ipek Gursel Dino (17 Sep 2024): Resilient cooling of the Mediterranean office spaces under climate change, Architectural Engineering and Design Management, DOI: 10.1080/17452007.2024.2400577

To link to this article: https://doi.org/10.1080/17452007.2024.2400577

Published online: 17 Sep 2024.

ARCHITECTURAL ENGINEERING AND DESIGN MANAGEMENT
https://doi.org/10.1080/17452007.2024.2400577

Resilient cooling of the Mediterranean office spaces under climate change

Günsu Merin Abbas [a,b,c], Çağla Meral Akgül [d] and Ipek Gursel Dino [a]

[a]Department of Architecture, Middle East Technical University, Ankara, Turkey; [b]Department of Built Environment, Eindhoven University of Technology, Eindhoven, The Netherlands; [c]Department of Architecture, TOBB University of Economics and Technology, Ankara, Turkey; [d]Department of Civil Engineering, Middle East Technical University, Ankara, Turkey

ABSTRACT

Resilient cooling strategies can minimize overheating risks by reducing energy demands and providing healthy indoor environments. Envelope-based resilient cooling strategies are particularly crucial for limiting external heat gain through conduction, convection, and radiation. This paper examines the impact of these strategies on the indoor environment under climate change. Using a case study approach, we simulate various scenarios for single and combined envelope-based resilient cooling strategies in a hypothetical, free-running office building located in the Mediterranean across five Köppen-Geiger climate zones (BSh, BSk, BWh, Csa, and Cfa) for both historical and 2050 weather data. We calculate indoor overheating degree and evaluate occupants' adaptive comfort. The findings suggest that combining envelope-based resilient cooling strategies significantly reduces indoor overheating risks, particularly in Southern European and North-Western African cities. Strategies that effectively control solar exposure are more influential in mitigating these risks. Among the strategies examined, a ventilated double skin with low-SHGC or chromogenic glazing is the most climate-change-resilient. This study contributes to the field by assessing the effectiveness of envelope-based resilient cooling strategies and providing recommendations for their application in the Mediterranean climate. It also evaluates how climate change may impact the performance of these strategies, offering insights for design and policymaking.

ARTICLE HISTORY
Received 9 December 2023
Accepted 28 August 2024

KEYWORDS
Resilient cooling; indoor overheating; climate change; solar shading; chromogenic glazing technologies; cool envelope materials; ventilated façades; IOD

Introduction

Climate change (CC) has many consequences, such as rising sea levels and extreme weather events such as flooding, severe heatwaves, wildfires, and drought (European Comission, 2022). The past eight years have been recorded as the warmest period since 1880 (NASA, 2022). Towards the end of the twenty-first century, higher temperature levels and extreme heat stress conditions are expected (IPCC, 2021). It is also projected that if GHG emissions continue as today, an increase of 4.4°C in temperature is anticipated worldwide (UN Climate Action, 2022).

The built environment is one of the high-risk areas under CC impacts due to the complex balance to be maintained with its environment and occupants. In the future, temperatures are expected to

CONTACT Günsu Merin Abbas g.m.abbas@tue.nl Department of Architecture, Middle East Technical University, Ankara, 06800 Turkey Department of Built Environment, Eindhoven University of Technology, Eindhoven, 5600 MB The Netherlands Department of Architecture, TOBB University of Economics and Technology, Ankara, 06510 Turkey
This article has been corrected with minor changes. These changes do not impact the academic content of the article.

increase in parallel with the building-related CO_2 emissions. The increasing temperatures are expected to give rise to increased overheating problems, necessitating air conditioning systems with high cooling energy demand. While air conditioning is an effective CC adaptation strategy to provide comfortable thermal conditions, however, it also contributes to global warming due to the associated greenhouse gas emissions (Akkose, Meral Akgul, & Dino, 2021). Moreover, air-conditioning systems may fail to meet the cooling demands and result in power outages when used during extended overheating periods (Miller et al., 2021). On the other hand, buildings without active cooling systems (i.e. naturally ventilated buildings) are highly vulnerable to overheating, especially in hot and humid climates such as the Mediterranean region. Buildings that rely solely on natural ventilation for cooling which constitute the majority of buildings in the Mediterranean region will deteriorate indoor environmental quality and affect occupants' thermal comfort. The Mediterranean basin is particularly at high risk of overheating, where drastic climate variability over recent years with severe heat waves is observed (IPCC, 2021). By the end of the twenty-first century, mean air temperatures in Mediterranean regions are expected to gradually increase between 1-5°C, reaching up to 7°C during summer (Todaro, Oria, Secci, Zanini, & Tanda, 2022). Particularly, decreasing trends in both precipitation and the number of frost days are expected in the Mediterranean, combined with a steady increase in the frequency and magnitude of heatwaves (Dino & Meral Akgül, 2019; Giorgi & Lionello, 2008; Kuglitsch et al., 2010).

Climate-resilient cooling strategies

Climate-resilient passive cooling strategies have a high potential to reduce operational CO_2 emissions and provide comfortable thermal conditions for occupants. International Energy Agency Energy in Buildings and Communities Programme (IEA-EBC) Annex 80 introduced 'resilient cooling strategies', which are low energy and low carbon cooling methods to improve the capability of the occupants and the built environment to resist the negative impacts of global and local climate (Attia et al., 2021).

IEA-EBC Annex 80 has identified several resilient cooling technologies, that are (A) reducing externally induced heat gain, (B) removing sensible heat, (C) enhancing personal comfort, and (D) removing latent heat (Figure 1) (Rahif et al., 2021). A is considered as the fundamental strategy to reduce overheating, as the building envelope plays a critical role in controlling the external heat gain in buildings (Kirimtat, Kundakci, & Chatzikonstantinou, 2016). Categories B, C, and D are secondary, as they are used to cool an already overheated building.

The envelope-related cooling strategies involve various building components and measures. The use of solar shadings and low SHGC glazing can effectively control/reduce heat gain by blocking

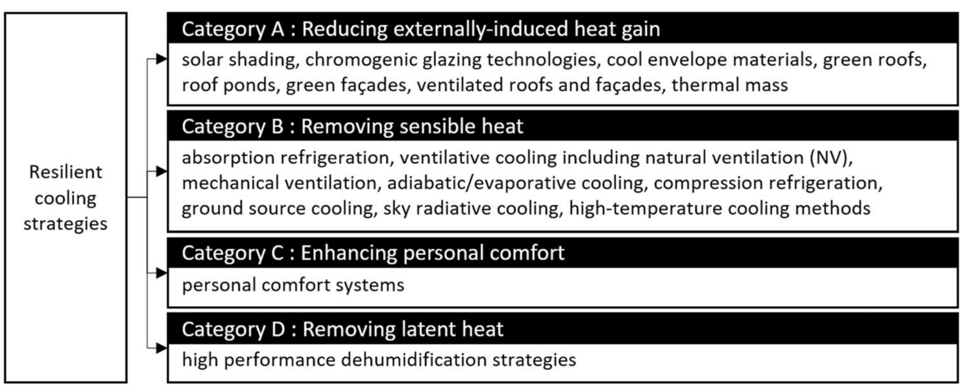

Figure 1. Resilient cooling strategies of IEA-EBC Annex 80.

excessive solar exposure (Kirimtat et al., 2016). Similarly, using chromogenic glass with an optically changeable/switchable technology such as photochromic (surface color changes with UV exposure) or thermochromic (surface color changes with temperature) reduces heat gain (Lampert, 2004). Cool envelope materials (CEM) with reflective surfaces reduce radiative heat gain by reflecting incident solar radiation (Revel, Martarelli, Emiliani, Celotti et al., 2014; Zhang et al., 2021). CEM are promising in mitigating urban heat islands, reducing cooling loads, and therefore improving indoor comfort (Lucero-Álvarez & Martín-Domínguez, 2019; Rosso, Pisello, Castaldo, Ferrero, & Cotana, 2017). Ventilated double-skin façades reduce heat gain by acting as a thermal buffer preventing overheating during sunny days (GhaffarianHoseini et al., 2016; Zhang et al., 2021). The combined use of these resilient cooling strategies can reduce indoor overheating risks and improve thermal comfort (Akkose et al., 2021; Attia et al., 2021; Rahif et al., 2021; Zhang et al., 2021).

Previous studies proposed different approaches for the assessment of buildings' and occupants' vulnerability to heat stress (Dino & Meral Akgül, 2019; Hamdy, Carlucci, Hoes, & Hensen, 2017; Miller et al., 2021; Mulville, Jones, & Huebner, 2014; Rahif, Amaripadath, & Attia, 2021). The impact of active cooling systems on indoor overheating and energy consumption is analyzed in (Attia & Gobin, 2020; Ciancio, Salata, Falasca, Curci, & Golasi, 2020; Engelmann, Kalz, & Salvalai, 2014; Figueiredo, Kämpf, & Vicente, 2016; Rahif et al., 2022; Sabunas & Kanapickas, 2017). Passive cooling strategies focused mainly on natural ventilation (Abbas, Gursel Dino, & Percin, 2023; Barbosa, Barták, Hensen, & Loomans, n.d.; Heracleous & Michael, 2018; Figueroa-Lopez, Arias, Oregi, & Rodríguez, 2021; Gamero-Salinas, Monge-Barrio, Kishnani, López-Fidalgo, & Sánchez-Ostiz, 2021; Gupta et al., 2021; Li, Taylor, & Symonds, 2019; Mohamed, Al-Khatri, Calautit, Omer, & Riffat, 2021; Sengupta, Steeman, & Breesch, 2020; Spentzou, Cook, & Emmitt, 2022), external shading (Figueroa-Lopez et al., 2021; Gupta et al., 2021; Li et al., 2019; Mohamed et al., 2021; Ozarisoy, 2022; Qadourah, 2023), wall and glazing properties (Gamero-Salinas et al., 2021; Gupta et al., 2021; Ozarisoy, 2022; Psomas, Heiselberg, Duer, & Bjørn, 2016), thermal mass (Brambilla, Bonvin, Flourentzou, & Jusselme, 2018; Kuczyński & Staszczuk, 2020), and construction materials (Hay & Ostertag, 2015; Rosso, Pisello, Castaldo, Cotana, & Ferrero, 2017; Sghiouri, Charai, Mezrhab, & Karkri, 2020). Other studies investigated systems such as windcatchers (Ozarisoy, 2022), passive walls, and evaporative cooling (Mohamed et al., 2021), and green roofs (Ascione, Bianco, de Masi, de Rossi, & Vanoli, 2015). However, systematic research focusing on the impact of the combined use of climate-resilient passive cooling strategies on indoor overheating under CC in the Mediterranean region is still lacking. Evaluating the effectiveness of cooling strategies, both individually and in combination, is crucial given the anticipated impact of CC on overheating risk.

Research approach and contribution

This study investigates the performance of resilient cooling strategies under CC effects across 15 Mediterranean cities selected from five Köppen-Geiger climate zones. Resilient cooling strategies are selected from IEA-EBC Annex 80 Category A. 20 scenarios are developed based on the single and combined use of the selected strategies. A hypothetical, naturally ventilated office zone in a medium-rise building is modeled, and hourly energy simulations are run for the Typical Meteorological Year (TMY) and 2050 weather. To calculate occupants' heat stress, indoor overheating degree (IOD) based on the adaptive comfort model is used. The comparative analyses allow the systematic evaluation of the impact of envelope-based resilient cooling strategies on overheating across different climate zones in the Mediterranean climate. These analyses can inform decision-making for design and policymaking processes. Moreover, the analysis pipeline that we use in this study can be used for the analysis of other climates and building typologies in the future.

This paper assesses the performance of single and combined use of several envelope-based resilient cooling strategies for Mediterranean cities. The change that can potentially occur in the performance of the resilient cooling strategies due to CC is also evaluated. Based on the results, it is concluded that the combined use of the strategies is capable of reducing IOD and summer discomfort. The coupled use is particularly critical and specifically recommended for Southern European and North West African cities. The strategies with effective solar exposure are more influential in controlling indoor overheating. Among the simulated strategies, the combined use of a ventilated double-skin façade with either low SHGC glazing or chromogenic glazing is the most resilient strategy to CC. On the other hand, cool envelope material is the least resilient strategy to CC.

The rest of this paper is structured as follows: Section 2 outlines the methodology and the case study. Section 3 presents the results of the simulations and indoor thermal comfort evaluation. Section 4 discusses the findings and Section 5 summarizes the main conclusions.

Methodology

This study adopts a simulation-based approach for the performance evaluation of the resilient cooling strategies under CC impacts. A parametric study is performed to simulate 20 resilient cooling scenarios in 15 Mediterranean cities for TMY (historical weather data) and 2050 weather files. The simulations are performed for a single-zone hypothetical office by using EnergyPlus operating through Ladybug Tools, environmental plug-ins for Grasshopper3D/Rhinoceros (Robert McNeel & Associates, 2020; Rutten, 2007) (Figure 2). Based on the indoor air temperature calculated during simulations, IOD is calculated using the adaptive comfort model.

Case-study

Building characteristics

The office zone is assumed to be in a medium-rise building (Figure 4). The zone dimensions are 10 × 10 m with a 4 m floor height. The zone is assumed to be in between two other office zones of similar characteristics. All internal surfaces (walls, ceiling, and floor slabs) are set to adiabatic, whereas external walls (north and south) are exposed to outdoor conditions. Building envelope characteristics are presented in Table 1. The envelope characteristics remain identical for 15 different Mediterranean cities, for the sake of comparability between buildings in different climatic conditions (Figure 3).

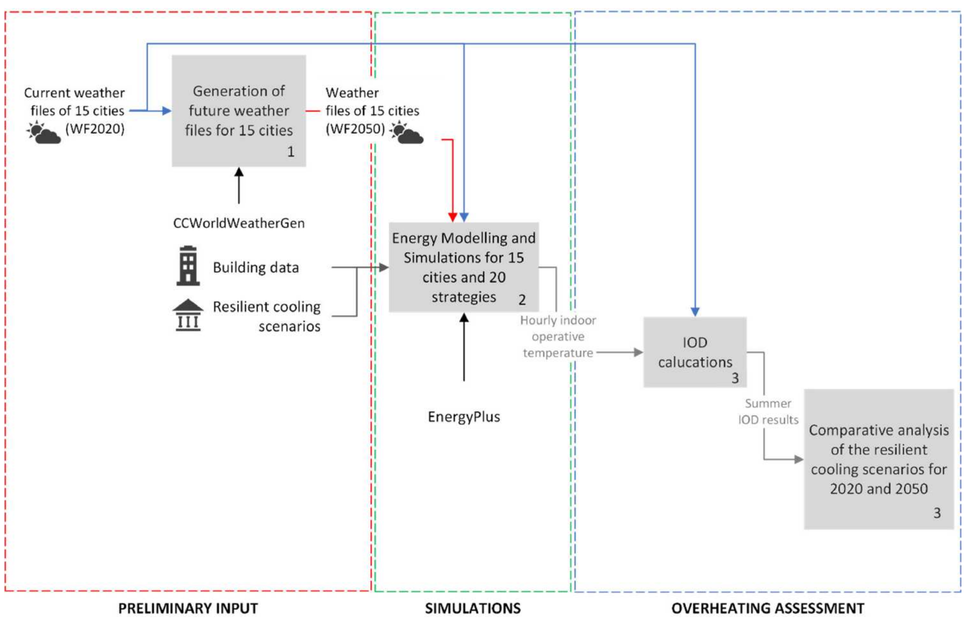

Figure 2. Simulation phases.

Table 1. Baseline construction characteristics.

Space type	Single office space
Ventilation and conditioning	No conditioning Natural ventilation
Exterior walls	Exposed to North and South U-value: 0.79 W/m^{2}K
Windows	WWR: 6.5% on the south wall Opening factor: 0.2 U-value: 2.4 W/m^{2}K SHGC: 0.85
Internal loads	Equipment: 7.64 W/m^2 Lighting: 11.84 W/m^2 People: 3.7 W/m^2 Infiltration: 0.0002 m^3/sm^2 Ventilation / person: 0.002 m^3/sm^2 Ventilation / area: 0.0003 m^3/s

Figure 3. The selected Mediterranean cities.

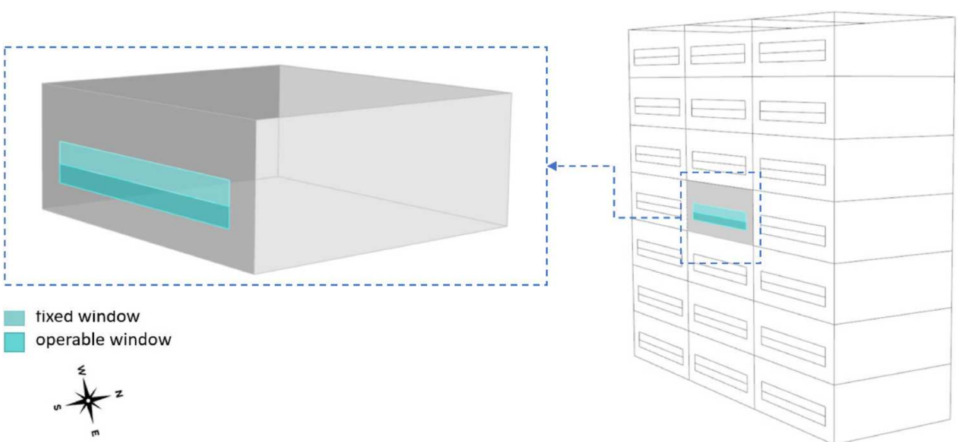

Figure 4. Building and zone geometry.

Wall U-value is set to 0.79 W/m^{2}K. For the glazing, the following parameters are used: U-value = 2.4 W/m^{2}K, and solar heat gain coefficient (SHGC) = 0.85. The simulation period is set to the summer months (June 1st to August 31st). The zone is assumed to be occupied by six people (0.05 ppl/m^2). The zone is free-running and naturally ventilated through single-sided ventilation during the simulation period. The zone loads (i.e. equipment, infiltration, lighting, and people) are set according to the U.S. Department of Energy's reference medium office building. The airflow is calculated based on the design flow rate.

Resilient cooling scenarios

After establishing a baseline building model, as described above, we modify this model for the six scenarios identified in IEA-EBC Annex 80 Category A. We then combine each scenario with one another, resulting in 15 new coupled scenarios. We eliminate two coupled scenarios as external shading and chromogenic glazing (SHDe-CHR), and internal shading and chromogenic glazing (SHDi- CHR) (Table 2). SHDe-CHR and SHDi-CHR are eliminated since chromogenic glazing is characterized by external solar control, which does not necessitate the use of external or internal shading devices. Finally, the resulting 13 combined scenarios are analyzed. The most effective strategies in controlling solar heat gain through the envelope are selected, as building envelopes have a considerable potential to control heat gain and energy demand in buildings. The construction characteristics of the selected resilient cooling strategies are listed in Table 3. The selected strategies are as follows:

a. **low SHGC glazing:** reduces solar heat transfer through glazing (Hassani, Domenighini, Belloni, Ihara, & Buratti, 2022).
b. **solar shading (internal)**, and
c. **solar shading (external):** control solar exposure and reduce heat gain (Kirimtat et al., 2016).
d. **chromogenic glazing:** an optically changeable/switchable technology such as photochromic (surface color changes with the UV exposure) or thermochromic (surface color changes with the temperature) that reduces heat gain (Lampert, 2004).
e. **ventilated double skin façades:** reduce heat gain by acting as a thermal buffer (GhaffarianHoseini et al., 2016; Zhang et al., 2021).
f. **cool envelope materials:** reflective surfaces that reduce radiative heat gain by reflecting incident solar radiation (Revel, Martarelli, Emiliani, Gozalbo et al., 2014; Zhang et al., 2021), reducing

Table 2. Scenarios.

	Acronym	Scenarios
Baseline building	B	–
Single scenarios	HP	Low SHGC glazing
	SHDe	External solar shading
	SHDi	Internal solar shading
	CHR	Chromogenic glazing
	VF	Ventilated double skin façade
	CEM	Cool envelope materials
Combined scenarios	HP-SHDe	
	HP-SHDi	
	HP-CHR	
	HP-VF	
	HP-CEM	
	SHDe-SHDi	
	SHDe-VF	
	SHDe-CEM	
	SHDi-VF	
	SHDi-CEM	
	CHR-CEM	
	CHR-VF	
	VF-CEM	

Table 3. Construction characteristics of the resilient cooling strategies.

External solar shading (SHDe)	• Type: Horizontal louver • Orientation: South, horizontal • Slat width: 30 cm • Slat span (separation): 20 cm • Slat thickness: 3 cm • Slat angle: 90°
Internal solar shading (SHDi) (Yi & Malkawi, 2009)	• Type: Fabric roller shade • Orientation: South • Solar reflectance: 0.56 • Solar transmittance: 0.11 • Thickness: 2.3 mm
Chromogenic glazing (CHR) (Sbar, Podbelski, Yang, & Pease, 2012)	• Internal pane (Clear 6 mm) and Clear state U-value: 1.6 W/m^{2}K SHGC: 0.47 • Tinted state U-value: 1.6 W/m^{2}K SHGC: 0.17 Tinted state is activated if zone air temperature is above 24°C.
Low SHGC glazing (HP)	• U-value: 3.6 W/m^{2}K • SHGC: 0.25
Cool envelope materials (CEM) (Revel, Martarelli, Emiliani, Gozalbo et al., 2014)	• Cool paint (RAL 1013, CEM with NIR-reflectance) • Solar reflectance:0.68 • Visible reflectance: 0.61 • NIR reflectance: 0.79 • Thermal emittance: 0.90
Ventilated double skin (VF)	• Type: Naturally ventilated • Orientation: South • Cavity: 60 cm • Glazing properties: U-value: 2.4 W/m^{2}K SHGC: 0.85

cooling loads, and improving indoor comfort (Boixo, Diaz-Vicente, Colmenar, & Castro, 2012; Lucero-Álvarez & Martín-Domínguez, 2019; Pisello et al., 2016; Revel, Martarelli, Emiliani, Gozalbo et al., 2014; Rosso et al., 2017; Santamouris, Synnefa, & Karlessi, 2011; Shen, Tan, & Tzempelikos, 2011; Shi & Zhang, 2011).

Generation of future weather files

Concerning the severity of future heat stress conditions, the evaluation of the effectiveness and resilience of cooling strategies for future climate conditions is particularly important. Previous studies have stressed the need for weather files indicating future climate conditions rather than using typical weather data (Herrera et al., 2017; Jentsch, Bahaj, & James, 2008; Miller et al., 2021; Rahif et al., 2021; Rey-Hernández et al., 2018). Accordingly, future weather files are generated for specific locations, climate models, and GHG emission scenarios, and used in building energy simulations in the literature (Akkose et al., 2021; Barclay, Sharples, Kang, & Watkins, 2012; Belcher, Hacker, & Powell, 2005; Chan, 2011; Farah, Whaley, Saman, & Boland, 2019; Hosseini, Bigtashi, & Lee, 2021; Nik & Arfvidsson, 2017; Wang, Liu, & Brown, 2017).

Two weather files are used for TMY and 2050 future climate scenarios in the study. The weather data that represents a typical weather file (TMY), (WF_{TMY}) is acquired from EnergyPlus (EPW). The future weather file (WF_{2050}) is generated by using Future Weather Generator. Future Weather Generator is the latest state-of-the-art open, and cross-platform tool that is used to predict and generate future weather files/conditions based on climate change projections (Rodrigues, Fernandes, & Carvalho, 2023). This tool utilizes various climate models and emission scenarios to generate future weather data. By incorporating factors such as temperature, humidity, solar radiation, wind speed, and precipitation, Future Weather Generator provides a comprehensive dataset that reflects potential future climatic conditions. As compared to other weather data morphing methods. Future Weather Generator is up-to-date with the latest GCM data and provides a better data interpolation method (Rodrigues et al., 2023). Future Weather Generator verifies the integrity of each variable in the original EPW file by identifying any missing values and ensuring that all variables stay within their defined limits (Rodrigues et al., 2023). It also uses EPW featuring the monthly changes for EC-Earth3 due to its high accuracy (Rodrigues et al., 2023). EC-Earth3 is based on the CMIP6 project, which constitutes a basis for the 6th Intergovernmental Panel on Climate Change (IPCC) Assessment Report (2022) (Rodrigues et al., 2023) (Figure 5).

Indoor thermal comfort evaluation

In this research, indoor overheating degree (IOD) is used to evaluate the heat stress experienced by the occupants. IOD is also an indicator of the effectiveness of the resilient cooling scenarios that are explored.

We use the adaptive thermal comfort model in IOD calculations, as is recommended in naturally ventilated buildings (Nicol & Humphreys, 2002). According to the adaptive thermal comfort model, comfort is not determined by a fixed temperature, and establishes a relationship between indoor

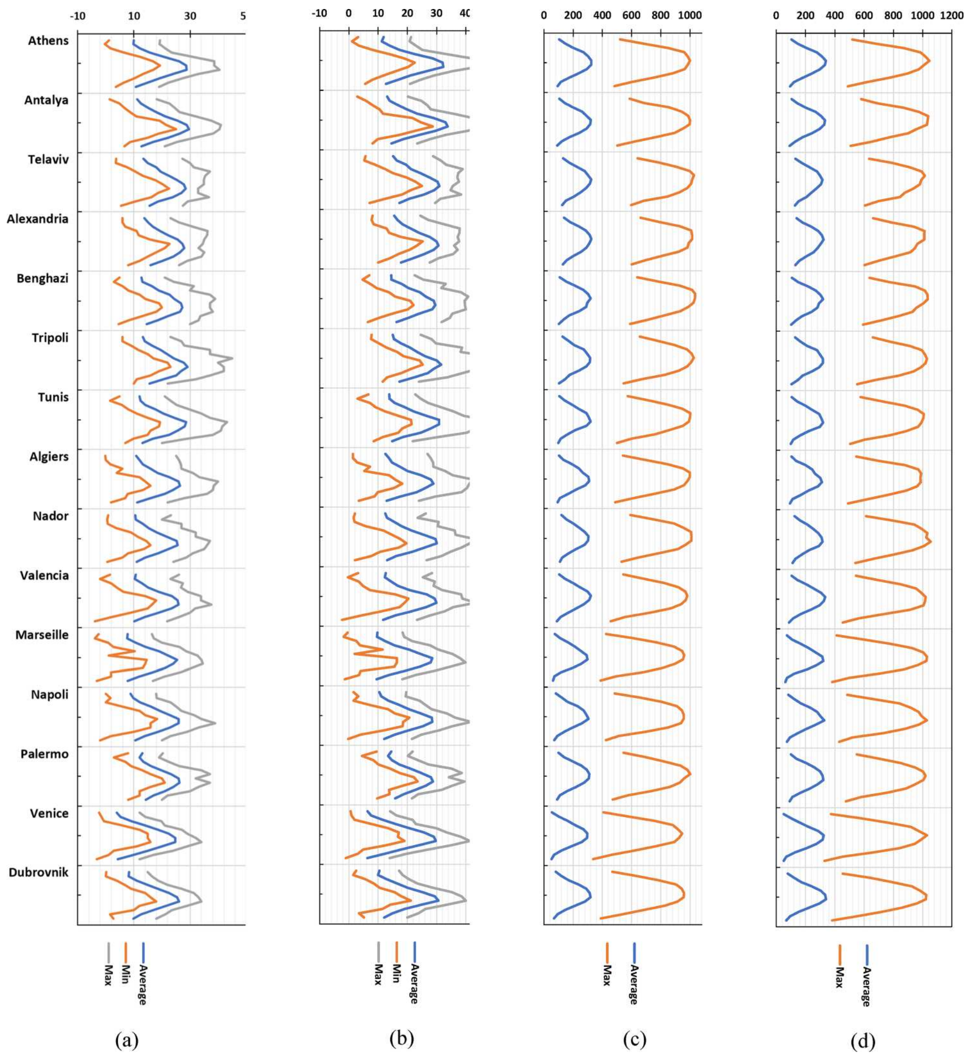

Figure 5. (a) TMY monthly outdoor temperature [°C], (b) 2050 monthly outdoor temperature [°C], (c) TMY monthly GHR [Wh/m^2-h], (d) 2050 monthly GHR [Wh/m^2-h].

neutrality temperature (T_n) that indicates the optimal comfort temperature and the outdoor air temperature (T_o) (Zhao, Lian, & Lai, 2021). There are a number of adaptive thermal comfort standards for the calculation of T_n (i.e. CIBSE, CEN and ASHRAE). In this study, the adaptive thermal comfort model of CEN (BS EN 15251) is preferred. In this respect, T_n is calculated by *1* (CEN, 2007). Acceptable comfort limits (TL_{comf}) for the comfort zone is calculated by *2*, offsetting the comfort line (T_n) ± 3 °C based on EN 15251 Adaptive Comfort Category II (80% acceptability) (CEN, 2007). To evaluate adaptive comfort, the percent time of comfort (N_{comf}) for the time of occupancy (N_{occ}) is calculated by *3*

$$T_n = 18.8 + 0.33\ T_o \tag{1}$$

$$TL_{comf} = 18.8 + 0.33\ T_o\ \pm\ 3.0 \tag{2}$$

$$N_{comf\%} = \frac{100 \sum_{i=0}^{m} N_{comf}}{\sum_{i=0}^{n} N_{occ}} \tag{3}$$

where T_n is the indoor neutrality temperature, T_o is the outdoor temperature, TL_{comf} is the acceptable comfort limits, $N_{comf\%}$ is the percent time of comfort, N_{comf} is the time of comfort, N_{occ} is the time of occupancy, i is the timestep (1H), m is the final timestep of N_{comf}, and n is the final timestep of N_{occ}.

Finally, IOD calculates overheating risks as the summation of the difference between zonal indoor operative temperature (only positive values) and the thermal comfort limit averaged over the sum of the total occupancy hours (Hamdy et al., 2017) (*Eq 4*).

$$IOD = \frac{\sum_{i=0}^{N_{occ(z)}} [(T_{op,i,z} - TL_{comf^+,i,z})^+ . t_{i,z}]}{\sum_{i=0}^{N_{occ(z)}} t_{i,z}} \tag{4}$$

where $N_{occ(z)}$ is the total occupied time for z, $T_{op,i,z}$ is the operative temperature for the zone at the timestep i, $TL_{comf,i,z}^{+}$ is the upper-temperature limit for the zone at the timestep i.

Evaluation of indoor thermal comfort

In this section, we present climatic conditions for the selected cities and then a comparative evaluation of indoor overheating. Finally, the analysis results for resilient cooling strategies are presented and discussed.

This study focuses on 15 Mediterranean cities according to their Köppen-Geiger class, outdoor temperature, and global horizontal radiation (Table 4, Figure 3).

Table 4. Regional weather characteristics.

					TMY			2050		
Cities	Country	Köp. Cli.	Lat.	Long.	CDD (○C-days)	HDD (○C-days)	GHR (Wh/m²-h)	CDD (○C-days)	HDD (○C-days)	GHR (Wh/m²-h)
Athens	Greece	BSh	37.88	23.74	544	1156	2589	907	852	2651
Antalya	Turkey	Csa	36.89	30.68	640	736	2563	1157	500	2618
Tel Aviv	Israel	Csa	32.01	34.89	617	546	2772	980	351	2725
Alexandria	Egypt	BWh	31.18	29.95	588	479	2824	974	292	2806
Benghazi	Libya	BSh	32.10	20.27	617	691	2599	912	474	2588
Tripoli	Libya	BSh	32.89	13.28	652	518	2659	984	333	2681
Tunis	Tunisia	Csa	36.85	10.21	625	762	2473	936	526	2504
Algiers	Algeria	Csa	36.69	3.22	417	1094	2421	670	804	2434
Nador	Morocco	BSh	34.98	3.02	326	1209	2507	774	804	2590
Valencia	Spain	BSk	39.49	0.47	317	1210	2488	713	908	2569
Marseille	France	Csa	43.65	7.21	250	1687	2112	537	1317	2213
Napoli	Italy	Csa	40.88	14.29	289	1276	2228	499	984	2301
Palermo	Italy	Csa	38.18	13.10	274	821	2459	512	576	2513
Venice	Italy	Cfa	45.51	12.35	173	2049	2086	536	1558	2189
Dubrovnik	Crotia	Cfa	42.56	18.27	225	1482	2331	567	1071	2424

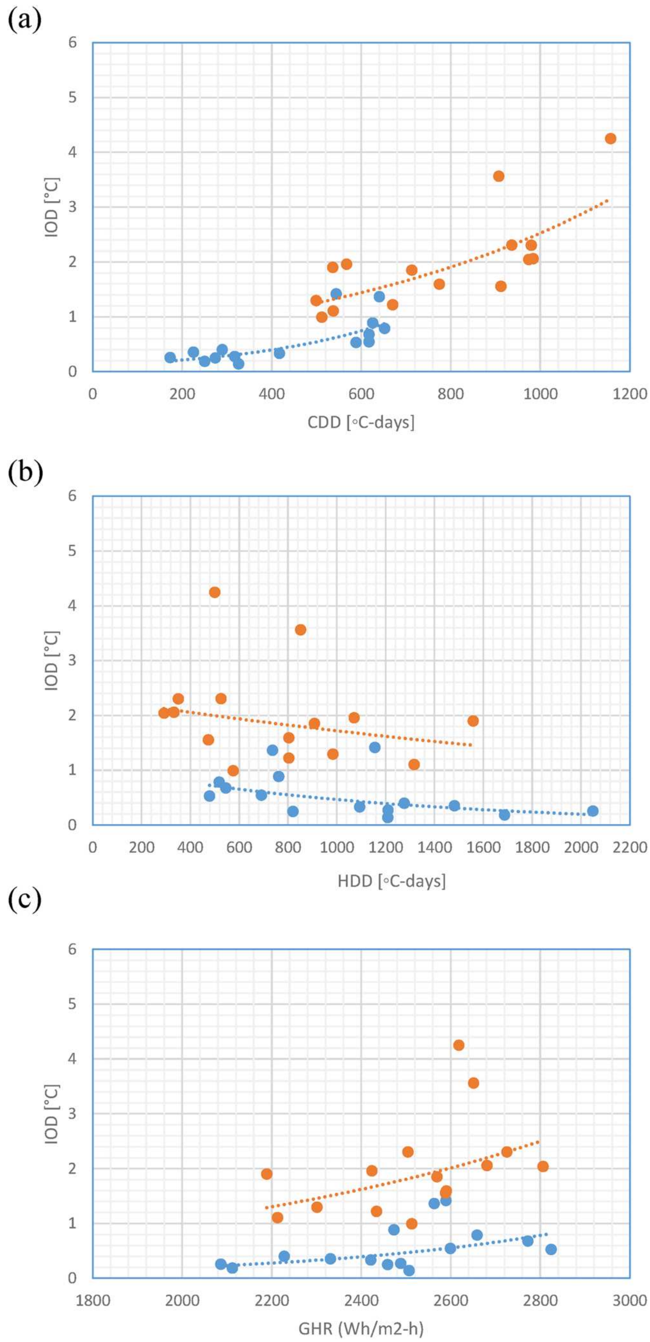

Figure 6. Correlations between (a) IOD and CDD, (b) IOD and HDD, and (c) IOD and GHR [blue indicates TMY and orange indicates 2050 scearios].

This section presents the simulation-based analysis results on the impact of resilient cooling strategies on IOD and T_{op}. The simulation data is registered hourly for the three-month summer period (June 1st to August 31st) only during occupied hours (between 8:00 and 18:00).

An initial analysis of the weather parameters suggests a strong positive correlation ($r = 0.84$) between CDD and IOD, and a medium negative correlation ($r = -0.43$) between HDD and IOD.

There is also a weak correlation ($r = 0.36$) between the GHR and IOD, which highlights the impact of the other factors that intensify IOD, (e.g. urban geometry, heat release from human activity, and heat-absorbing or retaining construction materials) (Figure 6).

Baseline building under climate change impact

The changes in indoor air temperature in all cities can be found in Figure 7. IOD values almost tripled in 2050 for all cities. Figure 8 illustrates the impact of CC by comparing TMY and 2050 scenarios for each city. When T_{op} and IOD values are averaged for all selected cities, there is an average of 3°C increase in T_{op}, leading to a 1.5°C increase in IOD when TMY and future weather scenarios are compared. In TMY scenarios, IOD values remain below 3°C, while T_{op} values range between 24.8°C and 32.9°C. In 2050, IOD values reach 6.2 °C, while T_{op} values range between 27.6°C-37.0°C. In parallel, the time in the comfort zone is significantly reduced in 2050 scenarios.

Figure 7 illustrates the adaptive comfort of the TMY and 2050 baseline scenarios for selected cities. The warming trend is observable for all cities. In the TMY baseline scenarios, the percent time of comfort ranges between 20% and 63%, whereas in 2050 baseline scenarios percent time of comfort ranges between 8% and 26%. The occupants spent 40% of their time in the comfort zone in TMY baseline conditions, whereas in 2050 time spent in the comfort zone is reduced to 16% on average. Consequently, the time spent in the comfort zone is reduced by 25% in 2050 as compared to the TMY baseline scenarios. The impact of climate change is more significant for

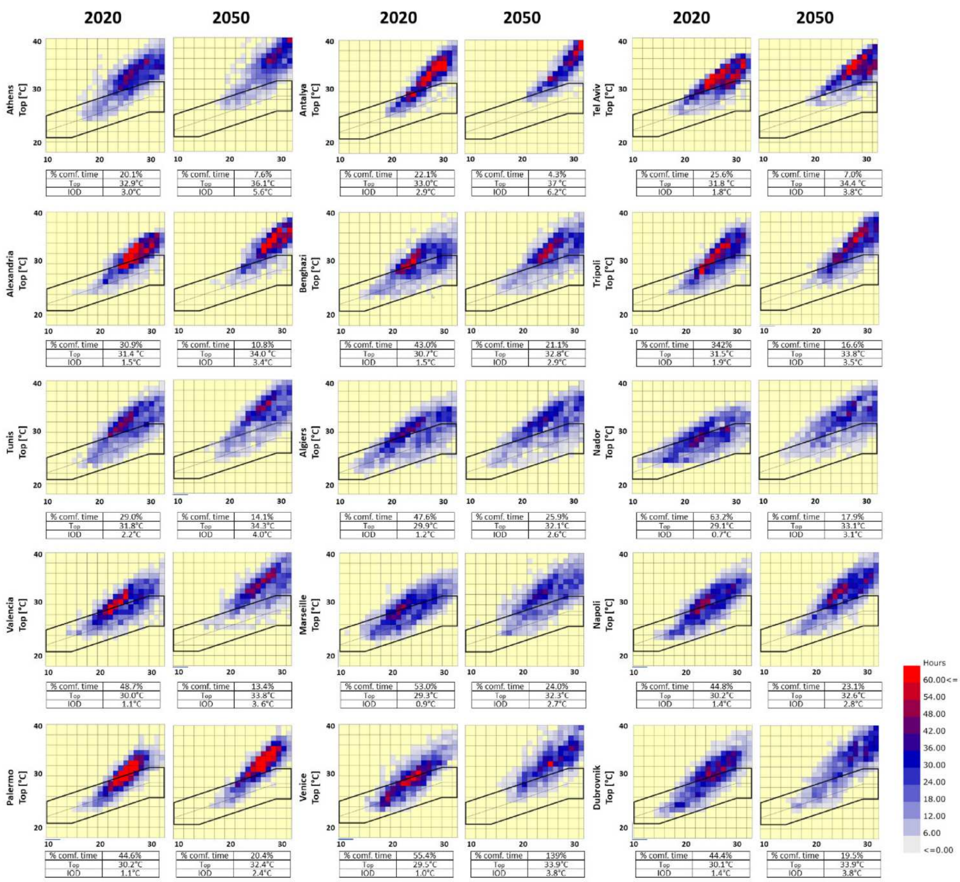

Figure 7. Adaptive comfort charts for the baseline indicating percent time of comfort (in the left-upper box) during the analysis period.

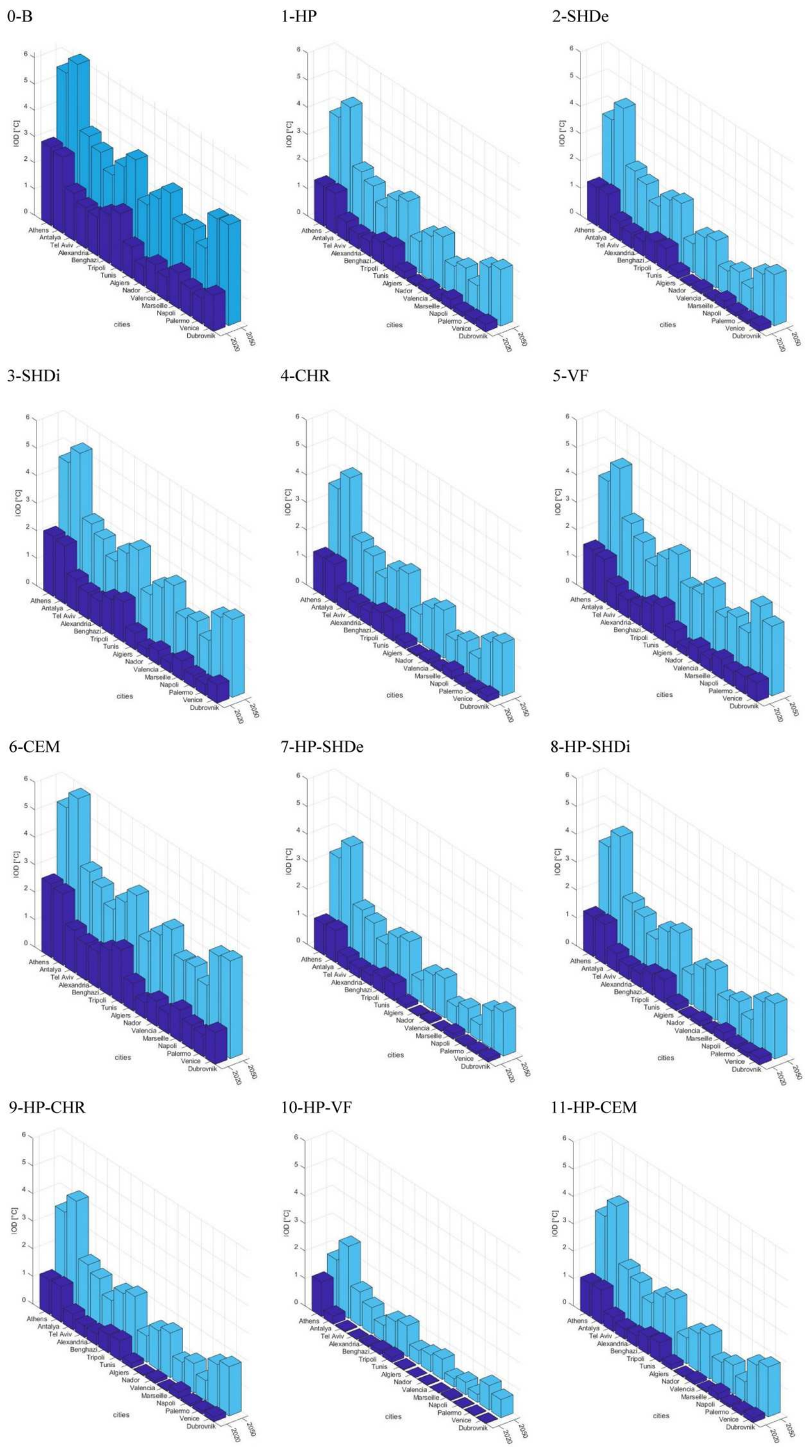

Figure 8. IOD results of the resilient cooling strategies for TMY and 2050 (cities in order on the X-axis: Athens, Antalya, Tel Aviv, Alexandria, Benghazi, Tripoli, Tunis, Algiers, Nador, Valencia, Marseille, Napoli, Palermo, Venice, and Dubrovnik).

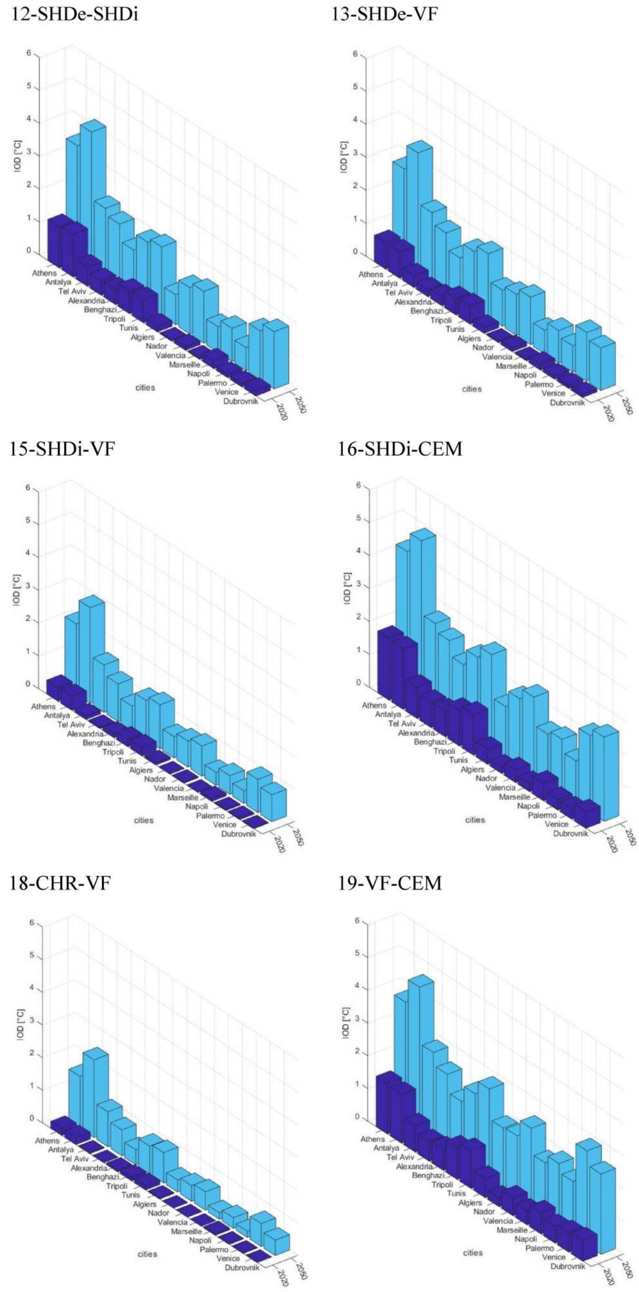

Figure 8 *Continued*

Antalya, Venice, Tel Aviv, Valencia, and Nador, where the percent time of comfort was reduced up to 80% in the 2050 baseline scenario. In Napoli and Algiers, the decrease in percent time of comfort remained below 50%.

Resilient cooling strategies

Figure 9 presents the IOD values for TMY and 2050 weather scenarios for each city and strategy. As seen in Figure 9 (a, b), IOD values for TMY scenarios are relatively more heterogeneous as

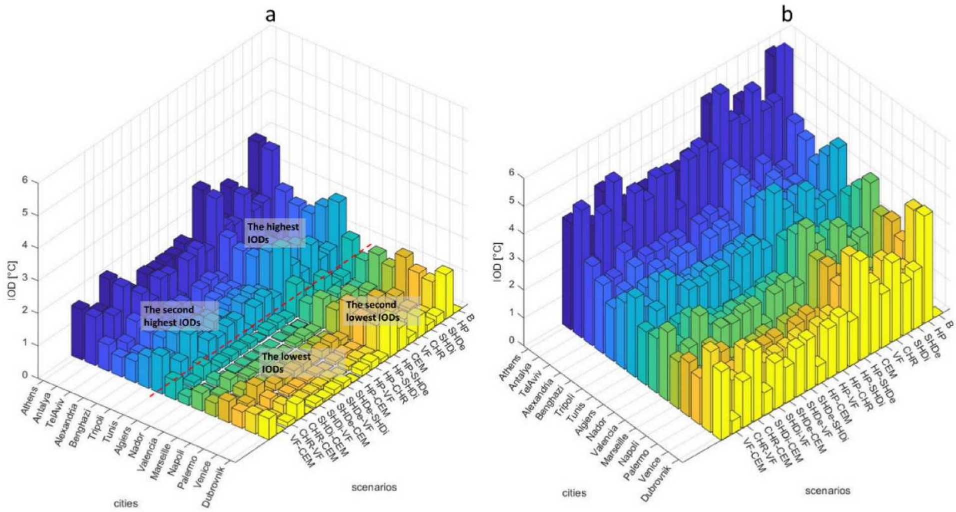

Figure 9. IODs for cities, strategies and (a) TMY and (b) 2050 weather scenarios.

compared to 2050. The results for TMY scenarios suggest that the highest IOD values are due to the single use of resilient cooling strategies in Western Asian cities such as Athens, Antalya, and Tel Aviv, and North African cities such as Alexandria, Benghazi, Tripoli, and Tunis (Figure 9(a)). On the other hand, the lowest IOD values are due to the combined use of the resilient cooling strategies in the North-Western African cities such as Algiers and Nador, and Southern European cities such as Valencia, Marseille, Napoli, Palermo, Venice, and Dubrovnik (Figure 9(b)). The single use of the strategies has a relatively lower impact on reducing the overheating risk. However, despite the significant impact of the combined strategies on IOD, the single use of the strategies in the North-Western African and Southern European cities resulted in relatively lower IOD values as compared to the combined use of the strategies in Western Asian and North African cities. Despite the relatively homogenous results of the 2050 scenarios, a similar IOD-city-strategy relationship can also be observed (Figure 9(b)).

The resilient cooling strategies, providing an effective solar exposure control, are relatively more influential on the indoor environment, which leads to lower IOD and $T_{op,}$ in both weather scenarios. Among the strategies, ventilated double skin façade combined with either low SHGC glazing, chromogenic glazing, or solar shading has the highest impact on reducing thermal discomfort. As compared to the baselines of both weather scenarios, ventilated double skin façade with either low SHGC glazing, chromogenic glazing, or solar shading resulted in an average 13% and 85% lower T_{op} and IOD, respectively. Among all strategies, using only cool envelope materials has the lowest impact on the indoor environment, which resulted in the highest T_{op} and IOD (Figures 10 and 11). For office spaces with seated light tasks, commonly 31°C is an 80% acceptable value for T_{op} (van Hoof & Hensen, 2007). Analysis results suggest that all the average T_{op} values of TMY scenarios remain below 31°C, whereas all the average T_{op} values of 2050 scenarios are slightly above 31°C. Figure 11 presents the average T_{op} for TMY and 2050 scenarios for the resilient cooling strategies. In parallel to IOD results, the combined use of resilient cooling strategies provides relatively cooler and more comfortable indoor environments (Figure 11). As compared to the single-use, the combined use of the strategies results in an average 1.3°C decrease in T_{op} for both TMY and 2050 scenarios.

We evaluate the performance change of the resilient cooling strategies due to the warming trend. The performance change of resilient cooling strategies due to CC is calculated by comparing the IOD values of TMY and 2050 weather scenarios. To investigate the impact of the resilient

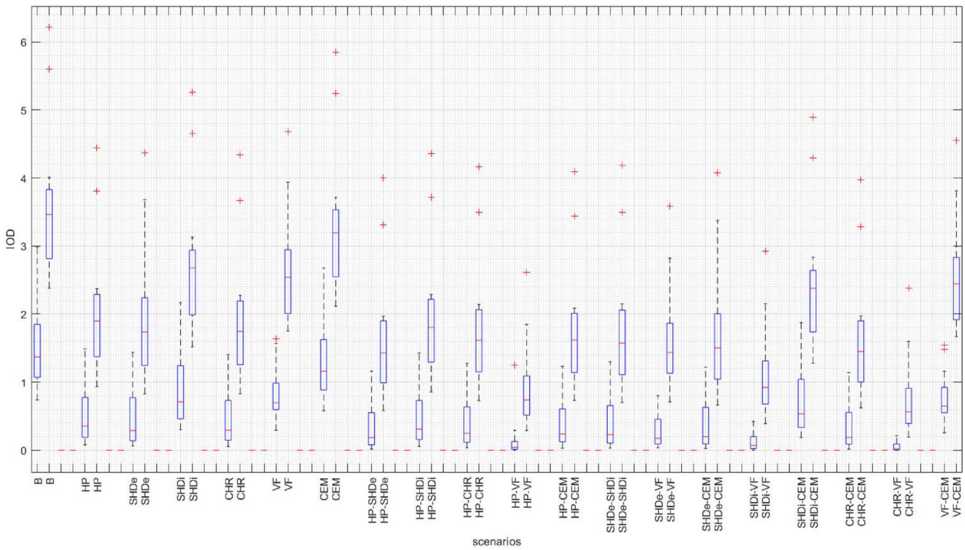

Figure 10. Overall IOD for the strategies: comparing TMY (left box) and 2050 scenarios (right box).

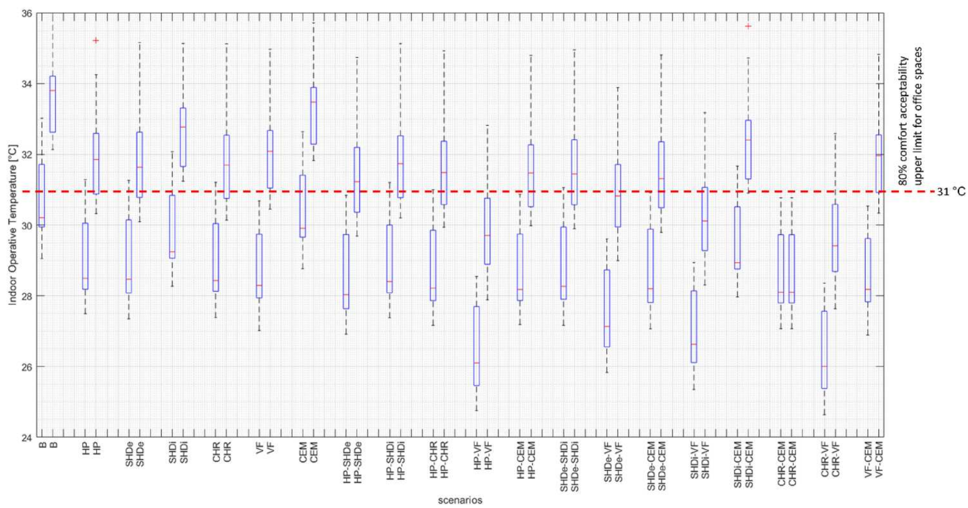

Figure 11. Indoor operative temperature and common comfort acceptability (shown in dashed line) for TMY (left box) and 2050 scenarios (right box).

cooling strategies, percent change values are also calculated by comparing the IOD values of baseline scenarios for both TMY and 2050 weather scenarios. Figure 12 illustrates (1) the change that occurred in the performance of the resilient cooling strategies, and (2) the change in IOD due to the strategies as compared to the baseline scenario of the selected weather scenario. All strategies resulted in a decrease ranging between 17% and 45%. The minimum change in performance is observed in HP-VF (17.8%) and CHR-VF (18%) remaining below 20% in 2050 as compared to TMY weather conditions. The maximum change is observed in VF (42%), CEM (41%), and VF-CEM (40.9%). The performance of CHR-CEM (30%), HP-SHDe (29.4%), and SHDi-VF (24.5%) demonstrated a decrease ranging between 20% and 30%. The rest of the strategies show a decrease ranging between 30% and 40%. In this respect, the

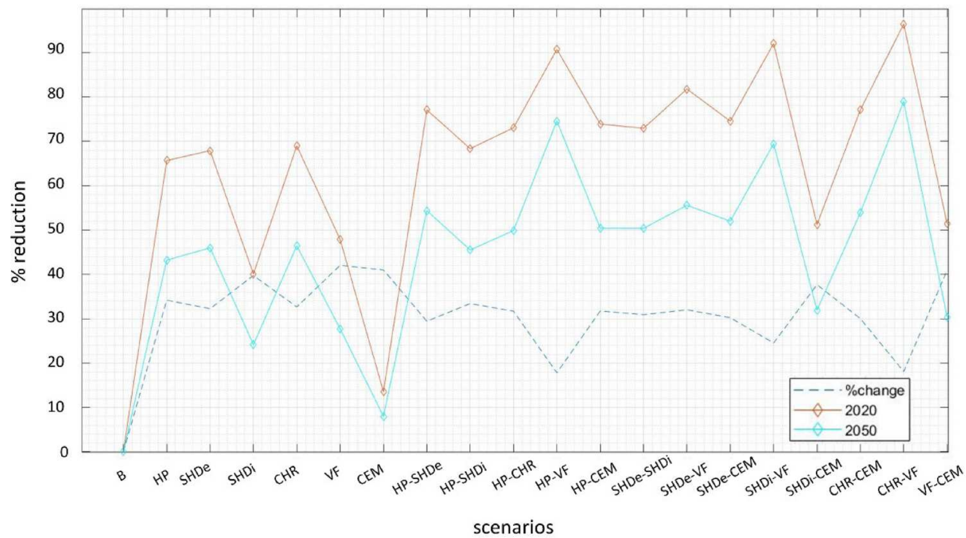

Figure 12. Percent change graph showing the % reduction of IOD by using a resilient cooling strategy and % change of the performance of resilient cooling strategies of 2050 weather scenarios as compared to TMY.

combined use of ventilated double skin façade and either low SHGC glazing or chromogenic glazing are the most resilient strategies to CC.

Depending on the climate and region, the performance of the resilient cooling strategies differs. The best and the worst-performing strategies are also investigated. Figure 13 illustrates the performance of the selected resilient cooling strategies for the selected cities. In all cities and weather conditions, all of the resilient cooling strategies contribute to reducing IOD and improving indoor thermal comfort. For the single use of the resilient cooling strategies, CHR, SHDe, and HP have the highest impact on reducing IOD for all cities for both TMY and 2050 conditions. As compared to the baseline scenarios, CHR, SHDe, and HP reduced IOD by 69% in the TMY scenario. In 2050, CHR, SHDe, and HP reduced IOD by 47%, 44%, and 42%, respectively. The performance of CHR in reducing IOD decreased by 32% in 2050 as compared to the TMY scenario, while the performances of SHDe and HP in reducing IOD decreased by 36% and 39%, respectively. Accordingly, using chromogenic glazing technologies can be regarded as a long-term benefitable design decision as compared to SHDe, and HP.

In all cities, among both single and combined use of the strategies, employing a ventilated double skin façade with chromogenic glazing (CHR-VF) has the greatest potential to minimize IOD. In TMY scenarios, CHR-VF resulted in 0.2°C IOD in Athens and Antalya, while 0.1°C IOD in Benghazi, Tripoli, and Tunis. For the rest of the cities, no indoor overheating risk is observed. In the 2050 scenarios, the positive impact of using CHR-VF on IOD has relatively declined, even though CHR-VF is still the best-performing strategy. As discussed above, among the selected cities, Southern European cities such as Napoli, Palermo, Marseille, Venice, Valencia, and Dubrovnik resulted in comparatively lower IOD. On the other hand, North African and Western Asian cities resulted in relatively higher IOD. In parallel, using CHR-VF for 2050 scenarios has led Antalya, Athens, and Tel Aviv to result in 2.4°C, 1.6°C, and 1.1°C IOD, respectively. Furthermore, Alexandria, Tripoli, and Tunis resulted in 0.8°C, 0.9°C, and 0.9°C IOD, while Algiers, Benghazi, and Nador resulted in 0.4°C, 0.5°C, and 0.5°C IOD, respectively. As expected, IOD values in Southern European countries range between 0.2°C to 0.6°C. On average, the use of CHR-VF 94% (~1.5C°) and 78% (~2.9°) reduced IOD values as compared to the average IOD of the baseline scenarios of TMY and 2050, respectively. The combined use of any other resilient cooling

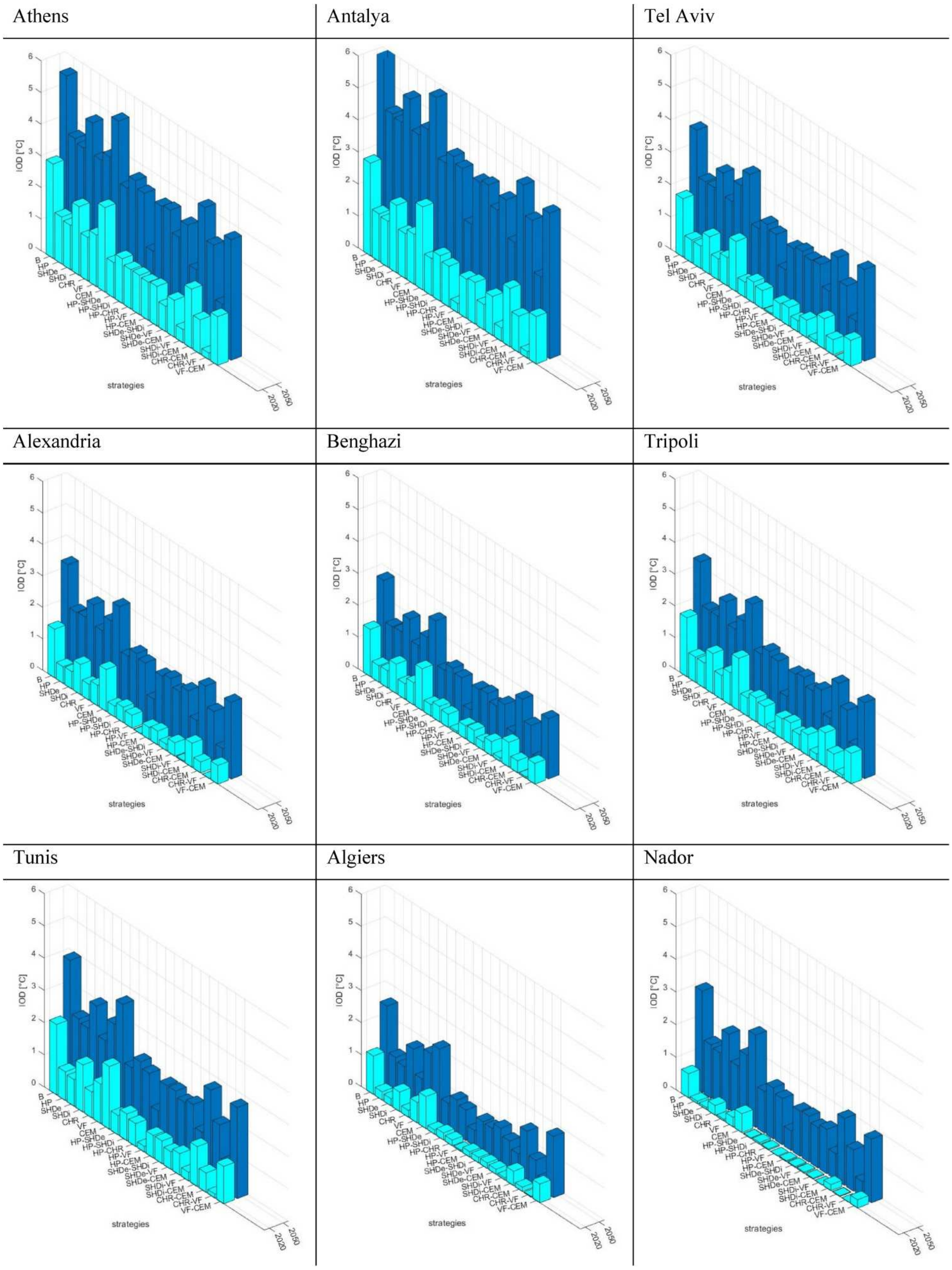

Figure 13. The performance of the resilient cooling strategies for the selected cities (strategies in order on the X axis: B, HP, SHDe, SHDi, CHR, VF, CEM, HP-SHDe, HP-SHDi, HP-CHR, HP-VF, HP-CEM, SHDe-SHDi, SHDe-VF, SHDe-CEM, SHDi-VF, SHDi-CEM, CHR-CEM, CHR-VF, and VF-CEM).

strategy that effectively controls solar exposure such as SHDi-VF, HP-VF, SHDe-VF, a HP-SHDe is also a beneficial alternative to CHR-VF. Using CEM as a resilient cooling strategy has the lowest impact on reducing IOD for all selected cities. CEM reduced IOD by 12.5% and 8.5% on average as compared to the baseline scenarios for TMY and 2050, respectively. Following CEM, the use of SHDi, VF, VF-CEM, or SHDi-CEM also has a lower impact in improving thermal comfort as compared to the other strategies.

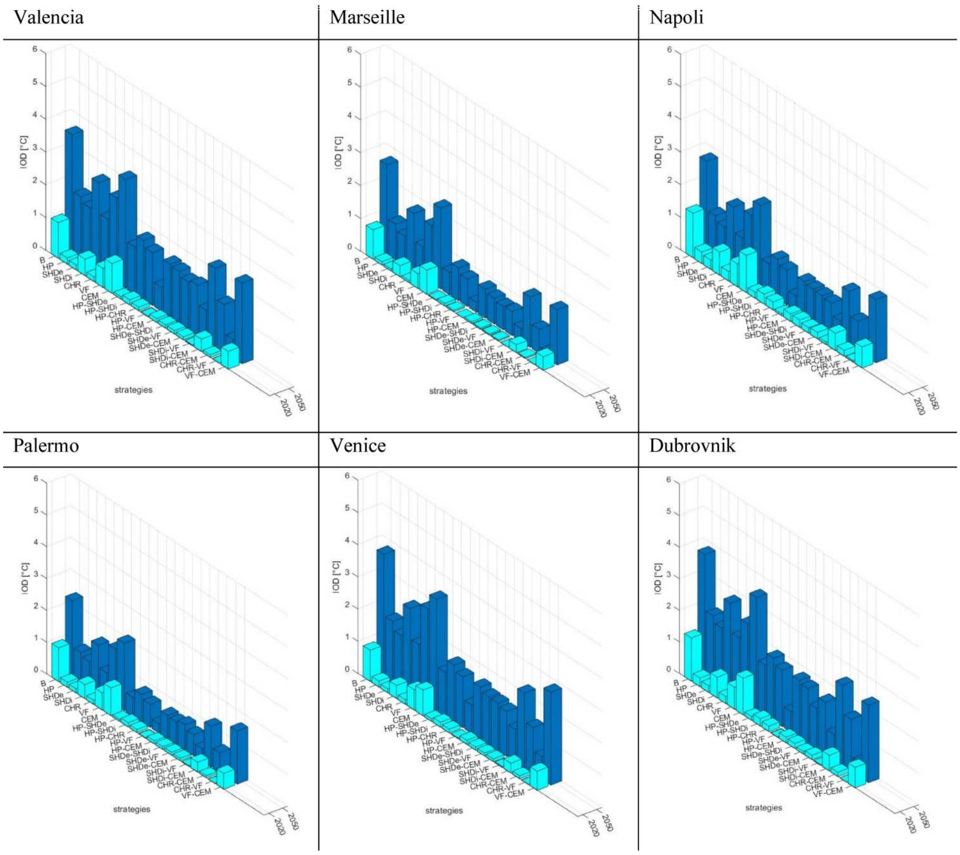

Figure 13 *Continued*

Findings

The simulation results have shown that with CC, the comfortable hours are expected to decrease by 25% on average for all Mediterranean cities. In 2050, IOD values tripled across all cities. Average T_{op} and IOD values showed a 3°C and a 1.5°C increase respectively compared to TMY and future scenarios. The time spent in the comfort zone decreased significantly: for the TMY baseline 20% to 63%, and for the 2050 baseline: 8% to 26%. On average the occupants spent 40% of their time in comfort in TMY conditions, reduced to 16% in 2050. Particularly, in Antalya, Tel Aviv, Valencia, and Nador, the impact of CC will be more severe, where the comfort time decreased to 80% by 2050. In this respect, the use of resilient cooling strategies can have a significant contribution to providing healthy and comfortable indoor thermal conditions, which comply with the existing literature. Our analysis results point that,

- the highest IOD values are due to the single use of the resilient cooling strategies, particularly their single-use leads to more drastic indoor overheating in Western Asia and North African cities,
- the lowest IOD values are due to the combined use of resilient cooling strategies, which led to a 1.3°C average T_{op} decrease in both TMY and 2050 scenarios. Their impact on reducing IOD is more significant in Southern European and North Western African cities,
- resilient cooling strategies providing effective solar exposure control are relatively more effective in reducing overheating risk, which is regarded as the fundamental strategy for reducing overheating as addressed in recent studies,

- among all strategies, using a ventilated façade with either low SHGC glazing, chromogenic glazing, or solar shading has the highest impact on reducing IOD and thermal discomfort. Ventilated double skin façade with low SHGC, chromogenic glazing, or solar shading reduced T_{op} and IOD by 13% and 85%, respectively, compared to baseline scenarios,
- using cool envelope materials has the lowest impact on indoor overheating risk, where IOD is only reduced by 12.5% and 8.5% on average compared to TMY and 2050 baselines, respectively,
- the minimum change of cooling performance of the strategies occurs in the ventilated double skin with either low SHGC glazing or chromogenic glazing, which can be regarded as the most CC-resilient strategies among the others. HP-VF and CHR-VF had the smallest decreases in their performance (17.8% and 18%) in 2050 versus TMY, while others were 30% to 40%,
- using ventilated façade, cool envelope materials, or both are the least CC-resilient strategies.

The analysis results suggest that, for TMY climate conditions, the combined use of resilient cooling strategies can provide comfortable indoor environments with a certain acceptability level. However, for future climate scenarios under CC or extreme conditions/weather events, coupling building envelope-related resilient cooling strategies may not ensure acceptable indoor comfort levels. In this respect, this study recommends coupling strategies from different resilient cooling strategy categories of IEA-EBC Annex 80.

Conclusion

In the future, local and global temperatures are expected to keep rising, which poses serious indoor overheating risks. Indoor overheating can lead to health problems for building occupants and operational risks for the built environments. Reducing indoor overheating by mechanical cooling and ventilation must be minimized to reduce GHG emissions and decelerate global warming. In this respect, resilient cooling strategies have the potential to provide healthy and sustainable solutions. In terms of resilient cooling strategies, affordable and clean energy, and carbon neutrality are two critical parameters. Depending on the climate, coupling resilient cooling strategies with NV can be an effective ventilation-cooling approach that can minimize GHG emissions while providing healthy indoor environments. Also, several resilient cooling strategies can be part of the design strategy of building envelopes since these have a considerable impact on controlling solar exposure, heat gain, and energy demand of a building. In this respect, we addressed a number of resilient cooling strategies related to the building façade coupled with NV and aimed at calculating their impact on the indoor environment.

We performed several simulations for single and combined use of solar shading, chromogenic glazing, cool envelope materials, and ventilated double skin, with NV for a hypothetical office building. The simulations are performed for TMY and 2050 weather scenarios. We implemented a simulation pipeline to calculate the micro-climatic conditions of the related scenarios. Based on the analysis results, indoor thermal comfort is evaluated via T_{op}, and IOD.

Our study contributes to the literature as it assesses the performance of single and combined use of several envelope-based resilient cooling strategies for Mediterranean cities while evaluating the change that can potentially occur in the performance of the resilient cooling strategies due to CC. Based on this, our paper presents a number of recommendations that could inform the future applications of resilient cooling strategies for design and policymaking processes under CC. Also, due to the increasing risk of overheating sourced by CC, simulation-based approaches that assess indoor overheating risks and evaluate resilient cooling strategies are necessary.

For future climate scenarios, our study addresses the potential of coupling more than two resilient cooling strategies for more comfortable indoors. There is a need for an in-depth investigation of coupling other groups of resilient cooling strategies and their impact on IEQ. Moreover, the evaluation of resilient cooling strategies under CC for future scenarios is particularly crucial to ensure the building performance of both the existing building stock and new buildings. We leave this issue as future work.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Günsu Merin Abbas http://orcid.org/0000-0002-4845-6854
Çağla Meral Akgül http://orcid.org/0000-0001-8720-1216
Ipek Gursel Dino http://orcid.org/0000-0003-2216-9192

References

Abbas, G. M., Gursel Dino, I., & Percin, M. (2023). An integrated pipeline for building performance analysis: Daylighting, energy, natural ventilation, and airborne contaminant dispersion. *Journal of Building Engineering*, *75*, 106991. doi:10.1016/j.jobe.2023.106991

Akkose, G., Meral Akgul, C., & Dino, I. G. (2021). Educational building retrofit under climate change and urban heat island effect. *Journal of Building Engineering*, *40*, 102294. doi:10.1016/j.jobe.2021.102294

Ascione, F., Bianco, N., de Masi, R. F., de Rossi, F., & Vanoli, G. P. (2015). Mitigating the cooling need and improvement of indoor conditions in Mediterranean educational buildings, by means of green roofs. Results of a case study. *Journal of Physics: Conference Series*, *655*, 012027. doi:10.1088/1742-6596/655/1/012027

Attia, S., & Gobin, C. (2020). Climate change effects on Belgian households: A case study of a nearly zero energy building. *Energies (Basel)*, *13*(20), 5357. doi:10.3390/en13205357

Attia, S., Levinson, R., Ndongo, E., Holzer, P., Berk Kazanci, O., Homaei, S., … Heiselberg, P. (2021). Resilient cooling of buildings to protect against heat waves and power outages: Key concepts and definition. *Energy and Buildings*, *239*, 110869. doi:10.1016/j.enbuild.2021.110869

Barbosa, R., Barták, M., Hensen, J. L. M., & Loomans, M. G. L. C. (n.d.). Ventilative cooling control strategies applied to passive house in order to avoid indoor overheating. www.tue.nl/taverne.

Barclay, M., Sharples, S., Kang, J., & Watkins, R. (2012). The natural ventilation performance of buildings under alternative future weather projections. *Building Services Engineering Research and Technology*, *33*(1), 35–50. doi:10.1177/0143624411427460

Belcher, S. E., Hacker, J. N., & Powell, D. S. (2005). Constructing design weather data for future climates. *Building Services Engineering Research and Technology*, *26*(1), 49–61. doi:10.1191/0143624405bt112oa

Boixo, S., Diaz-Vicente, M., Colmenar, A., & Castro, M. A. (2012). Potential energy savings from cool roofs in Spain and Andalusia. *Energy*, *38*(1), 425–438. doi:10.1016/j.energy.2011.11.009

Brambilla, A., Bonvin, J., Flourentzou, F., & Jusselme, T. (2018). On the influence of thermal mass and natural ventilation on overheating risk in offices. *Buildings*, *8*(4), 47. doi:10.3390/buildings8040047

C.E. de N. (CEN). (2007). Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics, EN 15251. Retrieved April 1, 2022, from http://ci.nii.ac.jp/naid/20001266485/en/.

Chan, A. L. S. (2011). Developing future hourly weather files for studying the impact of climate change on building energy performance in Hong Kong. *Energy and Buildings*, *43*(10), 2860–2868. doi:10.1016/j.enbuild.2011.07.003

Ciancio, V., Salata, F., Falasca, S., Curci, G., Golasi, I., & de Wilde, P. (2020). Energy demands of buildings in the framework of climate change : An investigation across Europe. *Sustainable Cities and Society*, *60*, 102213. doi:10.1016/j.scs.2020.102213

Dino, I. G., & Meral Akgül, C. (2019). Impact of climate change on the existing residential building stock in Turkey: An analysis on energy use, greenhouse gas emissions and occupant comfort. *Renewable Energy*, *141*, 828–846. doi:10.1016/j.renene.2019.03.150

Engelmann, P., Kalz, D., & Salvalai, G. (2014). Cooling concepts for non-residential buildings: A comparison of cooling concepts in different climate zones. *Energy and Buildings*, *82*, 447–456. doi:10.1016/j.enbuild.2014.07.011

European Comission. (2022). European Comission. Climate change consequences. https://ec.europa.eu/clima/climate-change/climate-change-consequences_en.

Farah, S., Whaley, D., Saman, W., & Boland, J. (2019). Integrating climate change into meteorological weather data for building energy simulation. *Energy and Buildings*, *183*, 749–760. doi:10.1016/j.enbuild.2018.11.045

Figueiredo, A., Kämpf, J., & Vicente, R. (2016). Passive house optimization for Portugal: Overheating evaluation and energy performance. *Energy and Buildings*, *118*, 181–196. doi:10.1016/j.enbuild.2016.02.034

Figueroa-Lopez, A., Arias, A., Oregi, X., & Rodríguez, I. (2021). Evaluation of passive strategies, natural ventilation and shading systems, to reduce overheating risk in a passive house tower in the north of Spain during the warm season. *Journal of Building Engineering*, *43*, 102607. doi:10.1016/j.jobe.2021.102607

Gamero-Salinas, J., Monge-Barrio, A., Kishnani, N., López-Fidalgo, J., & Sánchez-Ostiz, A. (2021). Passive cooling design strategies as adaptation measures for lowering the indoor overheating risk in tropical climates. *Energy and Buildings*, *252*, 111417. doi:10.1016/j.enbuild.2021.111417

GhaffarianHoseini, A., GhaffarianHoseini, A., Berardi, U., Tookey, J., Li, D. H. W., & Kariminia, S. (2016). Exploring the advantages and challenges of double-skin facądes (DSFs). *Renewable and Sustainable Energy Reviews*, *60*, 1052–1065. doi:10.1016/j.rser.2016.01.130

Giorgi, F., & Lionello, P. (2008). Climate change projections for the Mediterranean region. *Global and Planetary Change*, *63*(2-3), 90–104. doi:10.1016/j.gloplacha.2007.09.005

Gupta, R., Howard, A., Davies, M., Mavrogianni, A., Tsoulou, I., Jain, N., … Wilkinson, P. (2021). Monitoring and modelling the risk of summertime overheating and passive solutions to avoid active cooling in London care homes. *Energy and Buildings*, *252*, 111418. doi:10.1016/j.enbuild.2021.111418

Hamdy, M., Carlucci, S., Hoes, P. J., & Hensen, J. L. M. (2017). The impact of climate change on the overheating risk in dwellings—A Dutch case study. *Building and Environment*, *122*, 307–323. doi:10.1016/j.buildenv.2017.06.031

Hassani, A. R., Domenighini, P., Belloni, E., Ihara, T., & Buratti, C. (2022). Evaluation of the solar heat gain coefficient of innovative aerogel glazing systems: Experimental campaigns and numerical results. *Journal of Building Engineering*, *62*, 105354. doi:10.1016/j.jobe.2022.105354

Hay, R., & Ostertag, C. P. (2015). Innovative double skin facąde (DSF) with high performance green hybrid fiber-reinforced concrete (HP-G-HyFRC) for resilient and sustainable buildings. In *AEI 2015: Birth and Life of the Integrated Building - Proceedings of the AEI Conference 2015* (pp. 120–133). March 24–27, 2015. Milwaukee, WI: American Society of Civil Engineers (ASCE). doi:10.1061/9780784479070.011.

Heracleous, C., & Michael, A. (2018). Assessment of overheating risk and the impact of natural ventilation in educational buildings of Southern Europe under current and future climatic conditions. *Energy*, *165*, 1228–1239. doi:10.1016/j.energy.2018.10.051

Herrera, M., Natarajan, S., Coley, D. A., Kershaw, T., Ramallo-González, A. P., Eames, M., … Wood, M. (2017). A review of current and future weather data for building simulation. *Building Services Engineering Research and Technology*, *38*(5), 602–627. doi:10.1177/0143624417705937

Hosseini, M., Bigtashi, A., & Lee, B. (2021). Generating future weather files under climate change scenarios to support building energy simulation – A machine learning approach. *Energy and Buildings*, *230*, 110543. doi:10.1016/j.enbuild.2020.110543

IPCC. (2021). Summary for Policy Makers. doi:10.3724/sp.j.7103161536

Jentsch, M. F., Bahaj, A. B. S., & James, P. A. B. (2008). Climate change future proofing of buildings—generation and assessment of building simulation weather files. *Energy and Buildings*, *40*(12), 2148–2168. doi:10.1016/j.enbuild.2008.06.005

Kirimtat, A., Koyunbaba, B. K., Chatzikonstantinou, I., & Sariyildiz, S. (2016). Review of simulation modeling for shading devices in buildings. *Renewable and Sustainable Energy Reviews*, *53*, 23–49. doi:10.1016/j.rser.2015.08.020

Kuczyński, T., & Staszczuk, A. (2020). Experimental study of the influence of thermal mass on thermal comfort and cooling energy demand in residential buildings. *Energy*, *195*, 116984. doi:10.1016/j.energy.2020.116984

Kuglitsch, F. G., Toreti, A., Xoplaki, E., della Marta, P. M., Zerefos, C. S., Türke, M., & Luterbacher, J. (2010). Heat wave changes in the eastern Mediterranean since 1960. *Geophysical Research Letters*, *37*(4), 1–5. doi:10.1029/2009GL041841

Lampert, C. M. (2004). Chromogenic smart materials. *Materials Today*, *7*, 28–35.

Li, X., Taylor, J., & Symonds, P. (2019). Indoor overheating and mitigation of converted lofts in London, UK. *Building Services Engineering Research and Technology*, *40*(4), 409–425. doi:10.1177/0143624419842044

Lucero-Álvarez, J., & Martín-Domínguez, I. R. (2019). The effect of solar reflectance, infrared emissivity, and thermal insulation of roofs on the annual energy consumption of single-family households in México. *Indoor and Built Environment*, *28*(1), 17–33. doi:10.1177/1420326X17729194

Miller, W., Machard, A., Bozonnet, E., Yoon, N., Qi, D., Zhang, C., … Levinson, R. (2021). Conceptualising a resilient cooling system: A socio-technical approach. *City and Environment Interactions*, *11*, 100065. doi:10.1016/j.cacint.2021.100065

Mohamed, S., Al-Khatri, H., Calautit, J., Omer, S., & Riffat, S. (2021). The impact of a passive wall combining natural ventilation and evaporative cooling on schools' thermal conditions in a hot climate. *Journal of Building Engineering*, *44*, 102624. doi:10.1016/j.jobe.2021.102624

Mulville, M., Jones, K., & Huebner, G. (2014). The potential for energy reduction in UK commercial offices through effective management and behaviour change. *Architectural Engineering and Design Management*, *10*(1-2), 79–90. doi:10.1080/17452007.2013.837250

NASA. (2022). NASA. Global, climate change: vital signs of the planet. https://climate.nasa.gov/evidence/.

Nicol, J. F., & Humphreys, M. A. (2002). Adaptive thermal comfort and sustainable thermal standards for buildings. *Energy and Buildings*, *34*(6), 563–572. doi:10.1016/S0378-7788(02)00006-3

Nik, V. M., & Arfvidsson, J. (2017). Using typical and extreme weather files for impact assessment of climate change on buildings. *Energy Procedia*, *132*, 616–621. doi:10.1016/j.egypro.2017.09.686

Ozarisoy, B. (2022). Energy effectiveness of passive cooling design strategies to reduce the impact of long-term heatwaves on occupants' thermal comfort in Europe: Climate change and mitigation. *Journal of Cleaner Production*, *330*, 129675. doi:10.1016/j.jclepro.2021.129675

Pisello, A. L., Paolini, R., Diamanti, M. V., Fortunati, E., Castaldo, V. L., & Torre, L. (2016). Nanotech-based cool materials for building energy efficiency. In F. P. Torgal, C. Buratti, S. Kalaiselvam, C.-G. Granqvist, & V. Ivanov (Eds.), *Nano and biotech based materials for energy building efficiency* (pp. 245–278). Cham: Springer.

Psomas, T., Heiselberg, P., Duer, K., & Bjørn, E. (2016). Overheating risk barriers to energy renovations of single family houses: Multicriteria analysis and assessment. *Energy and Buildings*, *117*, 138–148. doi:10.1016/j.enbuild.2016.02.031

Qadourah, J. A. (2023). Evaluating solar-active shading solutions: A study of energy performance in Mediterranean residential architecture. *Architectural Engineering and Design Management*, 1–16. doi:10.1080/17452007.2023.2267570
Rahif, R., Amaripadath, D., & Attia, S. (2021). Review on time-integrated overheating evaluation methods for residential buildings in temperate climates of Europe. *Energy and Buildings*, *252*, 111463. doi:10.1016/j.enbuild.2021.111463
Rahif, R., Hamdy, M., Homaei, S., Zhang, C., Holzer, P., & Attia, S. (2022). Simulation-based framework to evaluate resistivity of cooling strategies in buildings against overheating impact of climate change. *Building and Environment*, *208*, 108599. doi:10.1016/j.buildenv.2021.108599
Rahif, R., Norouziasas, A., Elnagar, E., Doutreloup, S., Pourkiaei, S. M., Amaripadath, D., … Attia, S. (2022). Impact of climate change on nearly zero-energy dwelling in temperate climate: Time-integrated discomfort, HVAC energy performance, and GHG emissions. *Building and Environment*, *223*, 109397. doi:10.1016/j.buildenv.2022.109397
Revel, G. M., Martarelli, M., Emiliani, M., Celotti, L., Nadalini, R., de Ferrari, A., … Beckers, E. (2014). Cool products for building envelope - part II: Experimental and numerical evaluation of thermal performances. *Solar Energy*, *105*, 780–791. doi:10.1016/j.solener.2014.02.035
Revel, G. M., Martarelli, M., Emiliani, M., Gozalbo, A., Orts, M. J., Bengochea, M. Á., … Hermanns, S. (2014). Cool products for building envelope - part I: Development and lab scale testing. *Solar Energy*, *105*, 770–779. doi:10.1016/j.solener.2014.03.029
Rey-Hernández, J. M., Yousif, C., Gatt, D., Velasco-Gómez, E., San José-Alonso, J., & Rey-Martínez, F. J. (2018). Modelling the long-term effect of climate change on a zero energy and carbon dioxide building through energy efficiency and renewables. *Energy and Buildings*, *174*, 85–96. doi:10.1016/j.enbuild.2018.06.006
Robert McNeel & Associates. (2020). Rhinoceros. https://www.rhino3d.com/6/features#beyond.
Rodrigues, E., Fernandes, M. S., & Carvalho, D. (2023). Future weather generator for building performance research: An open-source morphing tool and an application. *Building and Environment*, *233*, 110104. doi:10.1016/j.buildenv.2023.110104
Rosso, F., Pisello, A. L., Castaldo, V. L., Cotana, F., & Ferrero, M. (2017). Smart cool mortar for passive cooling of historical and existing buildings: Experimental analysis and dynamic simulation. *Energy Procedia*, *134*, 536–544. doi:10.1016/j.egypro.2017.09.560
Rosso, F., Pisello, A. L., Castaldo, V. L., Ferrero, M., & Cotana, F. (2017). On innovative cool-colored materials for building envelopes: Balancing the architectural appearance and the thermal-energy performance in historical districts. *Sustainability (Switzerland*, *9*(12), 2319. doi:10.3390/su9122319
Rutten, D. (2007). Grasshopper 3D.
Sabunas, A., & Kanapickas, A. (2017). Estimation of climate change impact on energy consumption in a residential building in Kaunas, Lithuania, using HEED software. *Energy Procedia*, *128*, 92–99. doi:10.1016/j.egypro.2017.09.020
Santamouris, M., Synnefa, A., & Karlessi, T. (2011). Using advanced cool materials in the urban built environment to mitigate heat islands and improve thermal comfort conditions. *Solar Energy*, *85*(12), 3085–3102. doi:10.1016/j.solener.2010.12.023
Sbar, N. L., Podbelski, L., Yang, H. M., & Pease, B. (2012). Electrochromic dynamic windows for office buildings. *International Journal of Sustainable Built Environment*, *1*(1), 125–139. doi:10.1016/j.ijsbe.2012.09.001
Sengupta, A., Steeman, M., & Breesch, H. (2020). Analysis of resilience of ventilative cooling technologies in a case study building. *ICRBE Procedia*, *1*(1), 1–10. doi:10.32438/icrbe.202041
Sghiouri, H., Charai, M., Mezrhab, A., & Karkri, M. (2020). Comparison of passive cooling techniques in reducing overheating of clay-straw building in semi-arid climate. *Building Simulation*, *13*(1), 65–88. doi:10.1007/s12273-019-0562-0
Shen, H., Tan, H., & Tzempelikos, A. (2011). The effect of reflective coatings on building surface temperatures, indoor environment and energy consumption - An experimental study. *Energy and Buildings*, *43*(2-3), 573–580. doi:10.1016/j.enbuild.2010.10.024
Shi, Z., & Zhang, X. (2011). Analyzing the effect of the longwave emissivity and solar reflectance of building envelopes on energy-saving in buildings in various climates. *Solar Energy*, *85*(1), 28–37. doi:10.1016/j.solener.2010.11.009
Spentzou, E., Cook, M. J., & Emmitt, S. (2022). Low-energy cooling and ventilation refurbishments for buildings in a Mediterranean climate. *Architectural Engineering and Design Management*, *18*(4), 473–494. doi:10.1080/17452007.2021.1926898
Todaro, V., Oria, M. D., Secci, D., Zanini, A., & Tanda, M. G. (2022). Climate change over the Mediterranean region : local temperature and precipitation variations at five pilot sites. *Water*, *14*(16), 2499. doi:10.3390/w14162499. Special Issue Evolution of the Hydrological Regime in Relation to Climate Change.
UN Climate Action. (2022). Fast facts on climate and temperature rise. doi:10.1128/9781683671077.ch42.
van Hoof, J., & Hensen, J. L. M. (2007). Quantifying the relevance of adaptive thermal comfort models in moderate thermal climate zones. *Building and Environment*, *42*(1), 156–170. doi:10.1016/j.buildenv.2005.08.023
Wang, L., Liu, X., & Brown, H. (2017). Prediction of the impacts of climate change on energy consumption for a medium-size office building with two climate models. *Energy and Buildings*, *157*, 218–226. doi:10.1016/j.enbuild.2017.01.007
Yi, Y. K., & Malkawi, A. M. (2009). Thermal efficiency of the window shade. In *Build simul* (pp. 1693–1698). Glasgow Scotland: IBPSA. doi:10.26868/25222708.2009.1693-1698
Zhang, C., Kazanci, O. B., Levinson, R., Heiselberg, P., Olesen, B. W., Chiesa, G., … Zhang, G. (2021). Resilient cooling strategies – A critical review and qualitative assessment. *Energy and Buildings*, *251*, 111312. doi:10.1016/j.enbuild.2021.111312
Zhao, Q., Lian, Z., & Lai, D. (2021). Thermal comfort models and their developments: A review. *Energy and Built Environment*, *2*(1), 21–33. doi:10.1016/j.enbenv.2020.05.007