Impact assessment of climate change on naturally ventilated residential buildings in Lebanon—overheating risk under future climate scenarios

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Abstract. In light of current climate change and global warming, indoor overheating poses a significant risk. Buildings in the Mediterranean climate heavily rely on natural ventilation to maintain acceptable indoor thermal conditions. This reliance poses an increased risk to built environments in this region, particularly those occupied by low-income populations who cannot afford conditioning systems. This study assesses the thermal performance of typical residential buildings in Lebanon in response to future climate change, considering various emission scenarios and climate zones.

The study uses morphed future weather data and dynamic building simulations to assess indoor overheating and the potential for natural ventilation to establish comfortable indoor conditions. Findings indicate that indoor overheating occurrences in naturally ventilated apartments are expected to increase in both frequency and intensity in the future, across different emission scenarios, varying by climate. The risk of overheating was highest in inland region, followed by coastal then mountain regions. Regarding natural ventilation comfort hours, coastal climates saw a significant decrease (40% to 26% in the worst case), inland climates witnessed a slight reduction (27% to 23% in the worst case), and mountain climates observed a marginal increase (1% to 3%), accompanied by an increased risk of overheating during peak periods.

1 Introduction

Subjecting the human body to conditions of heat stress has been determined to negatively impact various aspects of health and well-being, with the strongest evidence for respiratory health and diabetes management [1]. This become more evident in recent studies, which consistently reveal a significant correlation between increased air temperatures and increased incidences of premature mortality and heat-related illnesses [2]. As a result, the problem of indoor overheating has become a major concern, and its severity is expected to escalate due to climate change [3].

Since global records began in 1880, the ten hottest years have all occurred post-2010, with the last nine years (2014–2022) being the warmest on record. This global temperature rise is leading to an increase in heat-related mortality, where exposure to heat either causes or significantly contributes to death. Notably, over a third of all heat-related deaths between

1991 and 2018 were directly attributed to climate change impacts [5]. Most epidemiological evidence that correlates the rise in temperature to the rise in heat-related mortality and morbidity links these complications to the rise in outdoor temperatures [6]. Evidence connecting these effects to inadequate indoor temperatures is quite limited and indirect [7], given that the indoor temperature can vary widely from dwelling to dwelling for the same outdoor conditions [8]. Nonetheless, researchers can infer that these complications are caused not only by the unusually high peak of outdoor temperature and decreases in the diurnal swing, but also by the inability of buildings to protect residents from external conditions [9].

Low-income groups stand at an increased risk from the impacts of climate change [10, 11] as they may lack access to essential heating or cooling systems in their houses, and even when available, the energy costs may be unaffordable [12, 13]. Furthermore, the availability of energy is not consistent in some nations, exacerbating the issue [14]. Additionally, a significant portion of the housing for this demographic, including newly constructed ones, are built outside official rules and regulations and marked by poorly performing building envelops [15]. In such scenarios, individuals often resort to passive alternatives to mechanical ventilation systems such as natural ventilation (NV) [16]. NV is the process of introducing outdoor air into an enclosure by natural forces, typically driven by variations in air pressure in and around the enclosure resulting from the impact of wind and temperature variations [17]. For many low-income individuals, NV is not about reducing energy or operational costs or promoting sustainability; rather, it serves as a strategy to alleviate heat stress and optimize indoor environmental conditions within the constraints of their available resources.

Countries with a Mediterranean climate are expected to suffer significant consequences from climate change, particularly increased frequency and severity of droughts and heatwaves [18]. Lebanon, a coastal country in the Mediterranean region, is not immune to these climate change implications, with its population anticipated to face heightened risks due to a variety of factors. These factors include the exceptional economic crisis faced by the country and the repeated failure of the public energy sector to provide citizens with services [19]. Lebanon has long suffered with electricity blackouts, but the issue escalated into a major crisis in 2021 when the state could not secure the foreign currency required for fuel purchases. This has resulted in the public energy sector only being able to supply electricity for 1-3 hours daily. A private market of expensive diesel generators has been supplementing the power shortage, but it is only an option for those who can afford it [20]. These circumstances heighten susceptibility to extreme weather, especially among the elderly and infants. Given the current risk state many people in Lebanon are facing, it is important to investigate whether existing typical constructions in built environments can withstand future weather conditions. Specifically, the research questions are specifically focused on the following aspects: First, what risk does future predicted weather pose to people in Lebanon who live in naturally ventilated buildings with current constructions due to indoor overheating? Second, do the typical buildings that use NV demonstrate resilience to the effects of climate change? Finally, will climate change have a significant impact on the number of comfort hours that can be maintained using NV?

The existing body of literature lacks the necessary elements for answering the questions posed. For example, Annan et al. conducted a study on the potential of NV for residential buildings in Lebanon, but only under existing weather conditions [21]. Younes et al. optimized the refurbishment of elderly dwellings that employs NV and other systems, again under current weather conditions [13]. Daaboul et al. evaluated the potential of mixed-mode ventilation considering both present and future weather conditions but for office spaces [22]. To the best of authors' knowledge, no other studies in literature have specifically assessed the risk of overheating in naturally ventilated residential apartments in the region considering future weather patterns influenced by climate change. Similarly, there is a lack of studies that

assessed the potential of natural ventilation in the region to maintain comfortable indoor conditions in residential buildings under these evolving climatic scenarios.
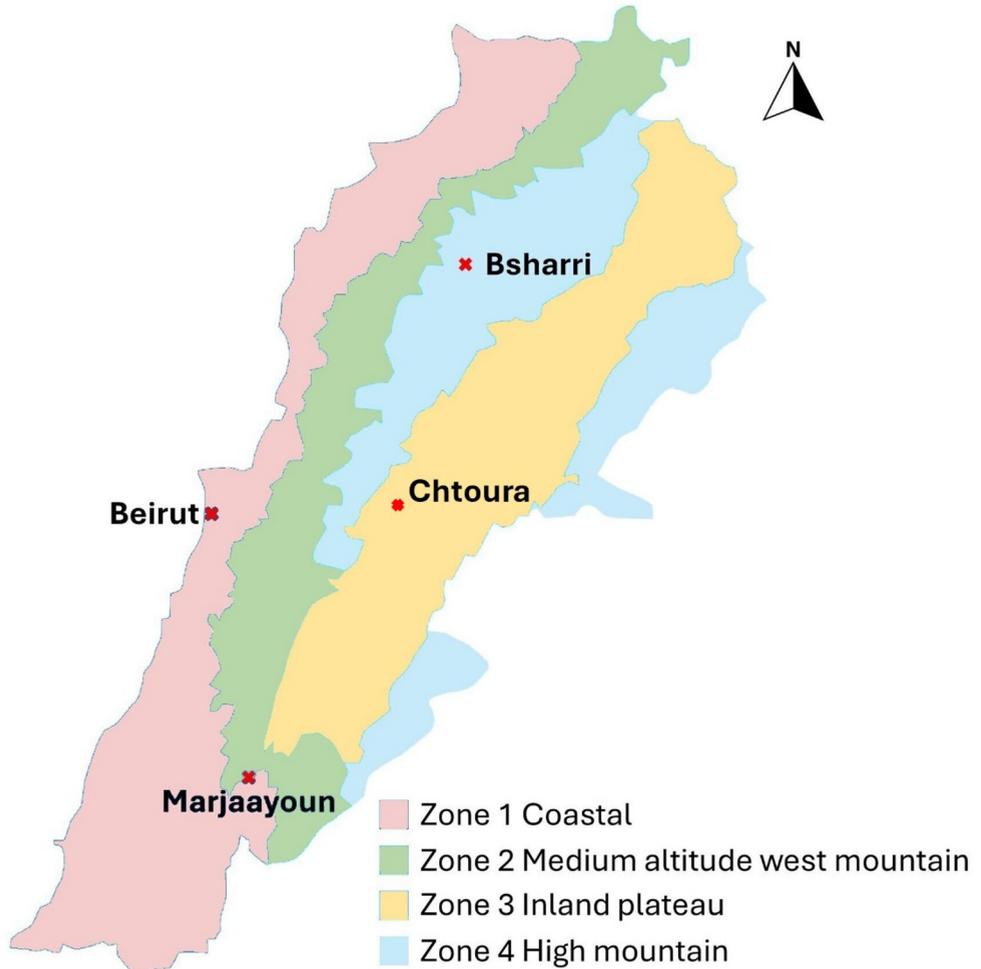
Numerical simulation methods allow for detailed examination of the impact of climate change on buildings. This involves initially predicting future weather patterns through the utilization of climate change scenarios, and then using those predictions as boundary conditions for building models to predict the corresponding indoor conditions [23]. Such techniques not only predict how buildings will respond to predicted future weather, allowing for more informed decision-making and planning, but also allow for the simulation of potential adaptations to reduce the effects of climate change on indoor conditions in buildings [24]. In these applications, stochastic methods or morphing techniques are often employed as downscaling methods to generate future weather datasets from the outputs of climate change models. Dynamic building models are then utilized for building simulations [25].

To answer the questions posed, the current study employs the widely accepted morphing technique to generate future climate data, incorporating climate change signals from global climate models and using current weather data as a baseline. Dynamic simulations of indoor conditions are performed on a representative apartment using future predicted weather under multiple climate scenarios. Indoor Overheating Degree (IOD) and Climate Change Overheating Resistivity (CCOR) are used as indicators to assess the risk of indoor overheating and the building's resistance to the effects of climate change. Furthermore, NV potential to achieve comfortable indoor conditions is assessed using the Climate Potential of Natural Ventilation (CPNV) indicator under various climate scenarios. Analyzing the impact of climate change on buildings employing NV assists in formulating recommendations for the building sector in the examined climate, thereby contributing to the mitigation of anticipated adverse effects of future climate change.
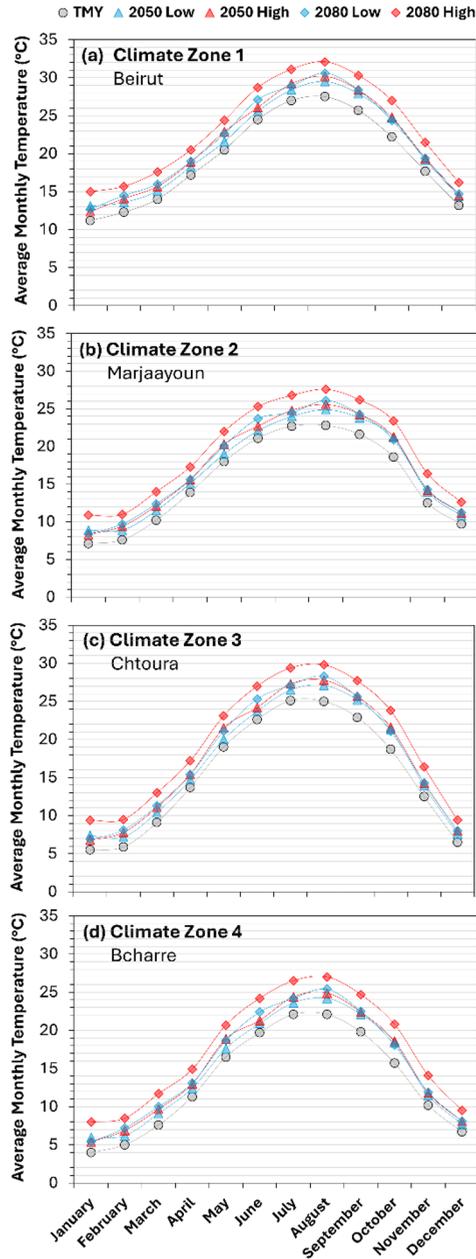
2 Methods

2.1. Future Weather Generation

Hourly future weather data is generated using the morphing technique [26] for Lebanon using Typical Meteorological Year (TMY) weather data [27]. The recent tool 'Future Weather Generator' [28] is used for morphing. This tool was chosen for its state-of-the-art capabilities, including the use of up-to-date climate models with higher accuracy and finer spatial resolution, as well as its open-source nature that allows for continuous development and improvement. The application utilizes information derived from multiple climate change models, the predictions of which have contributed to the 6th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Morphing was applied to 4 different locations each belonging to one of Lebanon's 4 climates as shown in *Figure 1* below.

Figure 1 Climatic zones in Lebanon [29]

Two Shared Socioeconomic Pathways (SSPs) were used to generate weather projections, each based on different CO_2 emission level. SSP1-2.6 (**Low**) corresponds to a net-zero emissions post-2050, while SSP5-8.5 (**High**) corresponds to doubling of emissions by 2050. Future weather projections span two climate periods with reference years: **2050** (2036-2065) and **2080** (2066-2095). *Figure 2* depicts TMY and future predicted monthly average dry bulb temperatures for the 4 zones.

Figure 2 *TMY and future predicted dry bulb average monthly temperatures under 2 SSP scenarios for 2 periods across Climate Zones (a)1, (b)2, (c)3, and (d)4*
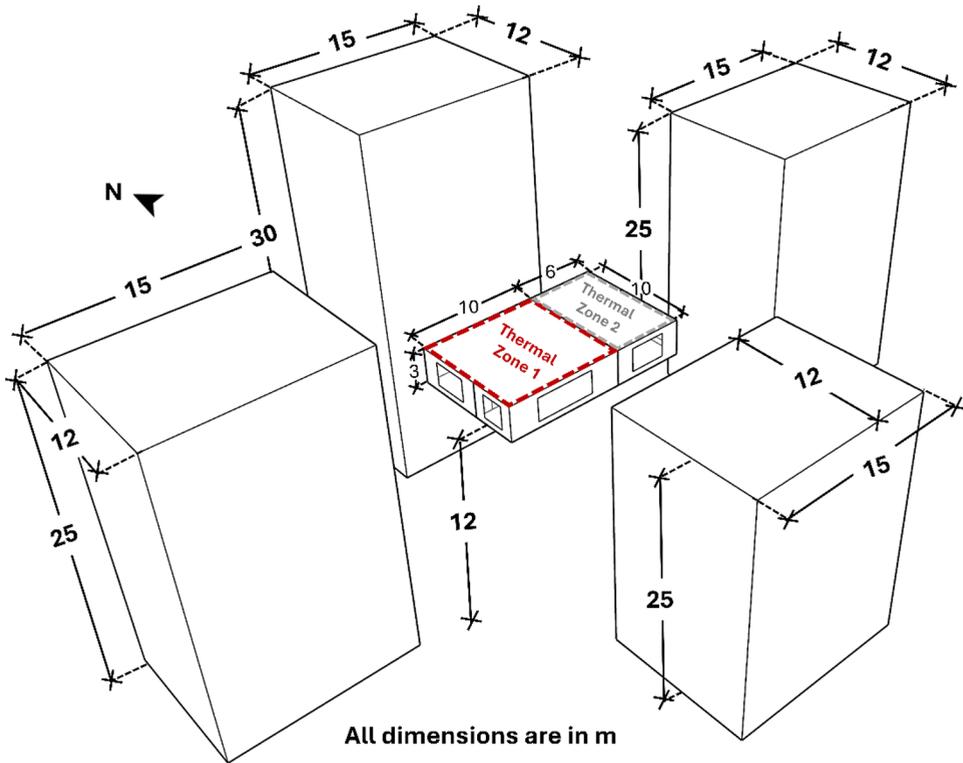
Analysing the data for the coastal climate (**(a) Zone 1**), it is evident that both 2050 scenarios (**Low** and **High** emissions) exhibit higher average monthly temperatures than the TMY values for all months. Moving to the 2080 scenarios, temperatures consistently exceed 2050 levels, with the High emissions scenario showing a more pronounced increase compared to the Low emissions scenario in both years. This trend is consistent across other climate zones (**Zone 2**, **Zone 3**, and **Zone 4**), with the key distinction being their generally cooler temperatures. The high mountain climate (**Zone 4**) registered the lowest temperatures

across all scenarios. The predicted rise in temperature due to climate change was relatively consistent in all zones. In addition to the dry bulb temperature, other parameters are modified by morphing including: the dew point, humidity, atmospheric pressure, solar radiation, wind speed, sky cover, snow depth, precipitation, and ground temperature, while assuming constant wind direction [28]**.**

2.2. *Dynamic Building Simulations*

When simulating the thermal conditions of buildings using NV, modelling options include computational fluid dynamics (CFD), multi-zone approach, and simplified equations for ventilation based on wind speed, thermal stack effect, and opening area. CFD is used to simulate non-uniform thermal environments, whereas the multi-zone approach is used to model multiple connected spaces with uniform thermal conditions in each using a fluid network model similar to that of electrical circuits, which is especially useful for simulating cross-ventilation scenarios between rooms. Meanwhile, simplified equations are employed for single room with well-mixed indoor air conditions. In the current study EnergyPlus 22.2.0 is used for dynamic building simulations with ASHRAE simplified wind and stack open area equations for ventilation [30]. The inputs to this model include the building geometry, surrounding buildings, outdoor weather data, internal heat gains, and building construction; the main output in the studied case is the thermal conditions of the studied zone.

The studied apartment, illustrated in ***Figure 3***, serves as a representative Lebanese residential unit. It has been employed for multiple case studies on naturally ventilated buildings within the region [13, 21]. The apartment is located on the fifth floor of a 10-story building and has a 24° counterclockwise orientation from the north. For simplicity, heat transfer with upper and lower floors is disregarded, assuming that these apartments and the studied have similar thermal responses. Surrounding structures are treated as shading elements. The apartment comprises two distinct thermal zones. The study focuses on Thermal Zone 1, and it is considered to accommodate two sedentary occupants with occupancy schedule defined as per ***Table 1***; additionally, when the zone is occupied, a 100W light and 200W of electrical equipment are considered as internal loads.

Figure 3 *Studied apartment with urban surroundings*

Construction materials and window-to-wall ratio align with Lebanese standards [31]. Wall construction in EnergyPlus are considered to be composed of 25 cm of concrete sandwiched between lightweight 5 cm plaster layers, featuring a U-value of 1.8 W/m².K [31, 32]. Windows are single-glazed, using 6 mm clear glass with a solar heat gain coefficient (SHGC) of 0.81 and a U-value of 5.8 W/m².C [31-33]. Windows have only two states: completely shut or entirely open; the fully open state corresponds to a half-opened glazing area because the window in question is sliding.

Table 1 Occupancy Schedule for the studied apartment

Day	Time	Number of Occupants
Weekday	00:00-08:00	2
	08:00-15:00	0
	15:00-24:00	2
Weekend	00:00-16:00	2
	16:00-21:00	0
	21:00-24:00	2

The accuracy of the EnergyPlus model, along with input parameters and settings in the baseline building model that matches Lebanese typical parameters, has been validated by the authors in a previous study [13]. This validation involved comparing predicted mean indoor temperatures for a 24-hour period on July 26, 2013, with measured indoor temperatures

reported in literature. Throughout the validation simulations, the windows were considered to be always opened in accordance with the real building conditions.

A total of 40 simulations, all based on the same building model and spanning one year, were executed across diverse climate zones and weather scenarios. **Table 2** provides a summary of these simulations.

Table 2 Overview of analysed scenarios

Scenario	Climate Zone	Socioeconomic Pathway (SSP)
TMY	1,2,3,4	-
2050 High	1,2,3,4	SSP5-8.5
2050 Low	1,2,3,4	SSP1-2.6
2080 High	1,2,3,4	SSP5-8.5
2080 Low	1,2,3,4	SSP1-2.6

2.3. Indicators for Assessing Performance

Thermal comfort in the studied apartment is evaluated using the adaptive comfort model suitable for NV operation of buildings [30]. Adaptive models do not predict comfort responses; rather, they identify circumstances in which individuals are likely to feel comfortable. The term "adaptive" refers to the observation that people typically acclimate to their thermal surroundings by making conscious adjustments such as changing their clothing insulation, posture, and activity level, as well as unconscious physiological changes such as variations in skin blood perfusion and adaptations to bodily fluid loss. This adaptability allows for an acceptable level of comfort across a range of thermal conditions. The model of de Dear and Brager [30] compiled from extensive field studies has been used to determine the operative comfort temperature (T_{oc}) based on the monthly average outdoor temperature (T_{out}):

$$T_{oc} = 17.8 + 0.31 T_{out} \qquad (1)$$

The upper and lower operative boundary temperatures for achieving 90% acceptability are: $T_{oc}+2.5℃$ and $T_{oc}-2.2℃$, respectively [30].

For assessing the obtained indoor thermal environmental conditions, the following 3 metrics are used:

1. **IOD** defined as the sum of positive values of the difference between the zonal indoor operative temperature and the zonal thermal comfort limit over the total number of occupied hours [34]:

$$IOD \equiv \frac{\sum_{k=1}^{N_{occ}} \left[\left(T_{op,k} - T_{oc,high} \right)^+ t_k \right]}{\sum_{k=1}^{N_{occ}} t_k} \qquad (2)$$

   where k is the simulation time counter (-), N is the simulation time (hrs.), *t* is the simulation timestep (hrs.) and $T_{op,k}$ is the indoor operative temperature at time k (℃). The IOD reflects the intensity and frequency of overheating in buildings when comfort criteria are considered.

2. **CCOR** defined as the rate of change of IOD with increase in outdoor air temperature due to climate change [35], and is used to assess the reaction of the building to the outdoor climate change. The latter is assessed by the Ambient Warmness Degree (AWD)

indicator which quantifies the severity of outdoor thermal conditions and is defined as the sum of positive values of the difference between outdoor temperature and a base temperature (suggested 18℃ for temperate climates [34]) over the total number of building occupied hours:

$$\text{AWD} \equiv \frac{\sum_{k=1}^{N_{occ}} \left[\left(T_{out,k} - T_b \right)^+ t_k \right]}{\sum_{k=1}^{N_{occ}} t_k} \qquad (3)$$

CCOR is calculated using linear regression methods assuming linearity between the IOD and AWD as follows:

$$\frac{1}{\text{CCOR}} = \frac{\sum_{Sc=1}^{M} (\text{IOD}_{sc} - \overline{\text{IOD}}) \times (\text{AWD}_{sc} - \overline{\text{AWD}})}{\sum_{Sc=1}^{M} (\text{AWD}_{sc} - \overline{\text{AWD}})^2} \qquad (4)$$
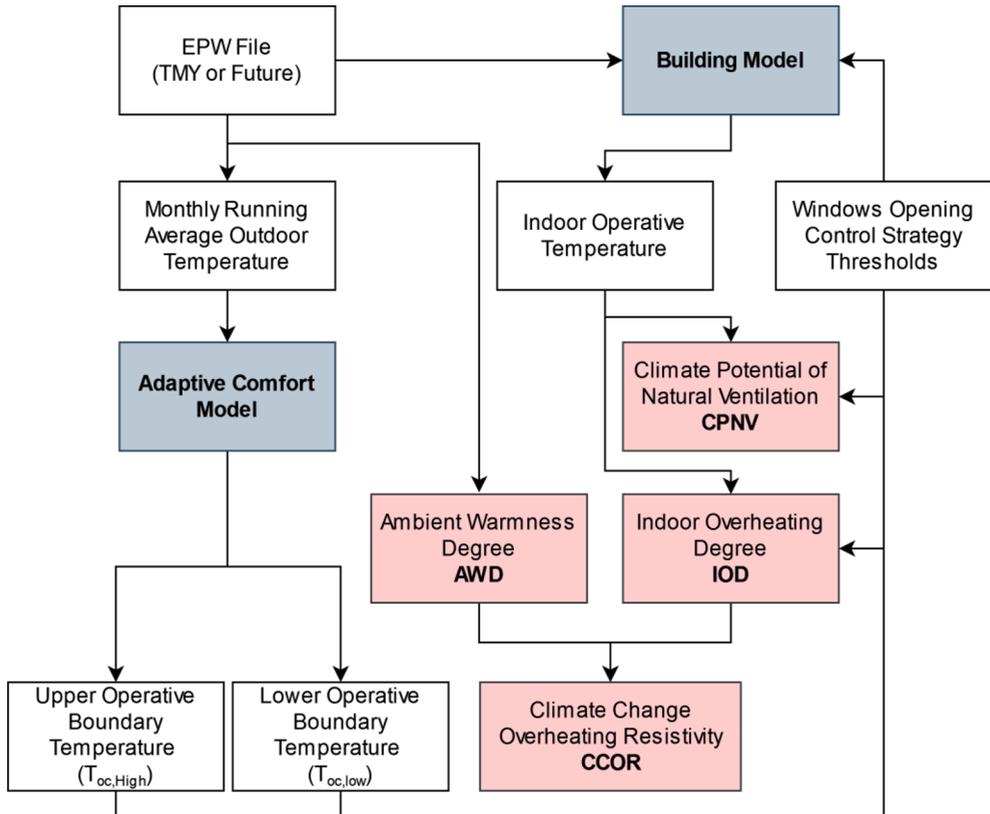
where Sc is the weather scenario counter and M is their total number. $\overline{\text{IOD}}$ and $\overline{\text{AWD}}$ are the mean of all IODs and AWDs respectively. CCOR is commonly employed to assess how different cooling strategies affect a building's resistance to climate change, a topic intended for future exploration. Here, the index is computed to evaluate how buildings utilizing NV correspond to increased outdoor warmth due to climate change across diverse scenarios and climates.

3. **CPNV** defined as the number of hours in a year when natural ventilation allows for indoor conditions that meets a certain criterion over the whole number of hours in a year [36]. Considering the criterion to be the 90% satisfaction as per the introduced adaptive model, CPNV becomes:

$$\text{CPNV} = \frac{\sum_{k=1}^{N} (a_k t_k)}{N};\qquad (5)$$

$$a = \{1 \; if \; T_{oc,low} \leq T_{op,k} \leq T_{oc,high}, 0 \; otherwise\}$$

The flow chart in ***Figure 4*** outlines the simulation process and methodology for computing key indices and indicators. Initiated by the EPW file, which may be historical (TMY) or future-predicted under the SSP scenarios, the flow involves determining monthly running average outdoor temperatures to establish adaptive upper and lower boundaries for that specific month within the specified SSP scenario and climate zone. Additionally, the EPW file is utilized to compute AWD and simulate the building model. A simple control strategy is applied on windows. This entails establishing a schedule dictating the minimum indoor temperature for triggering window closure, aligning with the lower temperature boundary of the adaptive model. Since the studied apartment is considered to employ only NV for cooling, there exists no imposed maximum indoor temperature that triggers window closure. Upon simulating the building model and predicting indoor conditions, indices such as IOD and CPNV are computed based on the predicted operative indoor temperature. Finally, CCOR is derived from AWD and IOD in the last step of the process.
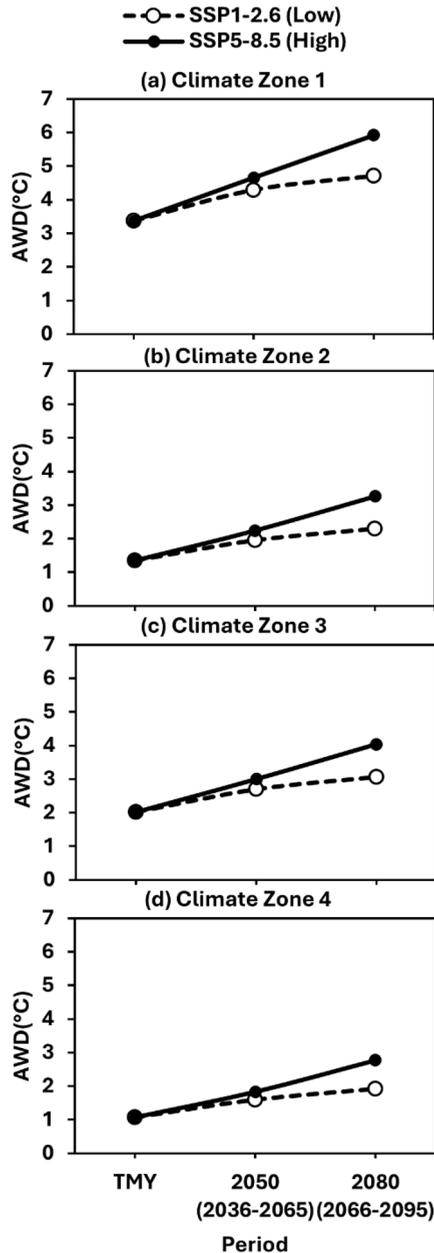
Figure 4 Simulation flow chart and method for computing utilized indices and indicators

Results and Discussion

Twenty simulations were conducted over three time periods (TMY, 2050, 2080) encompassing two SSP scenarios, namely SSP1-2.6 (low) and SSP5-8.5 (high), and four climate zones (Climate Zones 1, 2, 3, 4). Across all cases, the metrics of AWD, IOD, CPNV, and CCOPR were computed.

Figure 5 illustrates the AWD for different scenarios. Generally, AWD exhibits an increasing trend with time with a consistent slope for the high SSP and a decreasing slope for the low SSP. Different climate zones have similar AWD slopes, but different AWD magnitude. Notably, in the low-emission SSP1 scenario, AWD is lower, and its slope decreases from 2050 to 2080, contrasting with the constant slope observed in SSP5. For SSP1 in Climate 1, AWD increased by 0.93°C from TMY to 2050 but only by 0.42°C from 2050 to 2080. Conversely, in SSP5, AWD in Climate 1 rose by 1.29°C from 2050 to 2080 and a similar 1.27°C from 2050 to 2080. This trend was consistent across other climates.

The continual rise of the AWD is linked to global warming, where future climates are projected to be warmer even in the most optimistic scenario, SSP1. The reduced slope observed between 2050 and 2080, compared to the slope between the TMY and 2050 in SSP1, is explained by the fact that the SSP1-2.6 scenario aligns with net-zero emissions post-2050, leading to a significant slowdown in global warming.
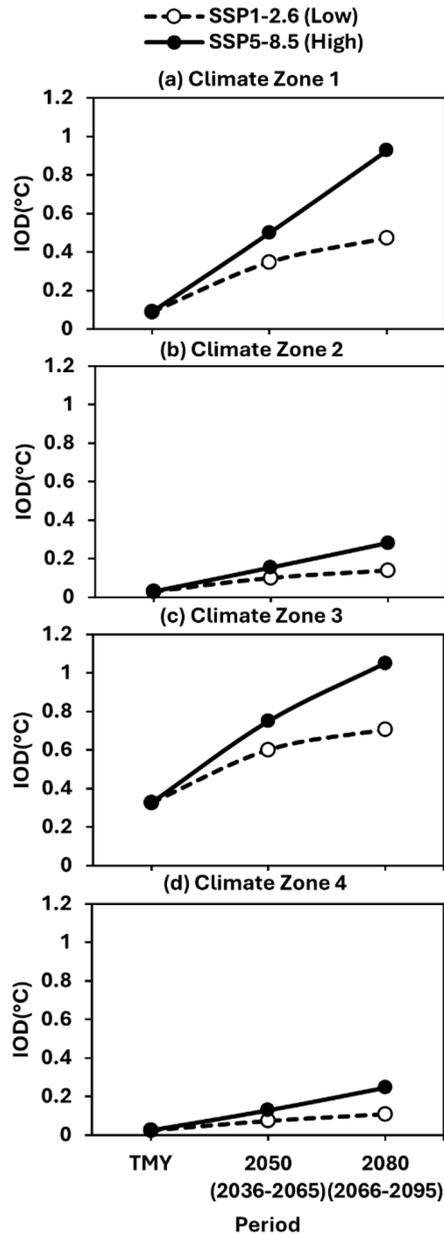
Figure 5 *Ambient Warmness Degree (AWD) in the examined scenarios and climates*

Figure 6 illustrates the IOD across diverse climatic zones and under various SSP scenarios. Notably, the IOD exhibited a positive slope across all climatic zones and SSP scenarios. However, distinct trends were observed when comparing the period between TMY and 2050, and that between 2050 and 2080. Among the examined climates, Climate 3 (Inland Plateau) demonstrated the highest IOD, followed by Climate 1 (Coast), and the two mountain climates, 2 and 4. Focusing on Climate 3 and the low SSP scenario, the IOD increased by 0.27°C between TMY and 2050 and by 0.11°C from 2050 to 2080. In contrast, under the high SSP scenario for the same climate, IOD increased by 0.42°C between TMY and 2050 and by 0.3°C from 2050 to 2080. Noteworthy variations were observed in IOD values at
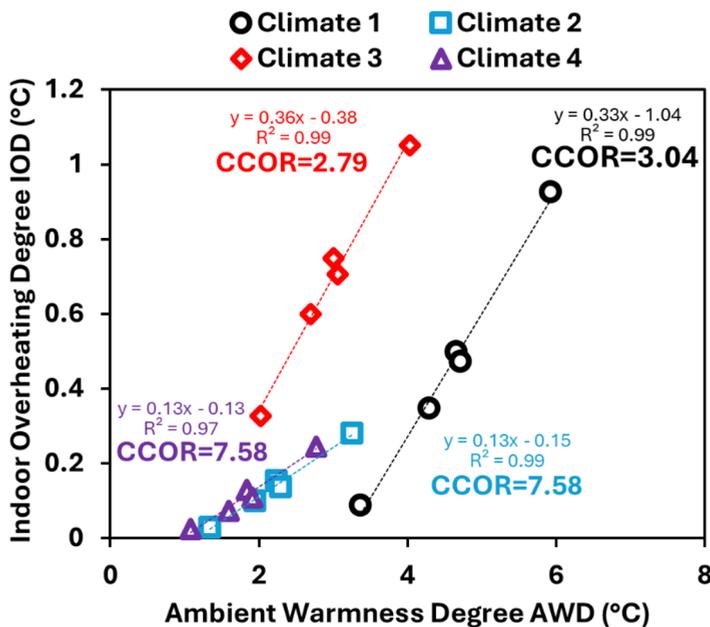
TMY, with Climate 1 registering 0.09 and Climate 3 recording 0.33; by 2080 SSP5, these values escalated to 0.93 and 1.05, respectively. Conversely, the remaining two climates exhibited low IOD values near 0 at TMY, gradually increasing over time and peaking at 0.28.

The presented increase in the IOD signifies an increased frequency and/or intensity of indoor overheating occurrences. IOD and AWD exhibit similar trends, with a reduced slope between 2050 and 2080 in SSP1 and a consistent steep positive slope in high-emission scenario-SSP5. This is due to the strong impact of outdoor conditions, especially during NV operation, on indoor conditions.

Figure 6 *Indoor Overheating Degree (IOD) in the examined scenarios and climates*
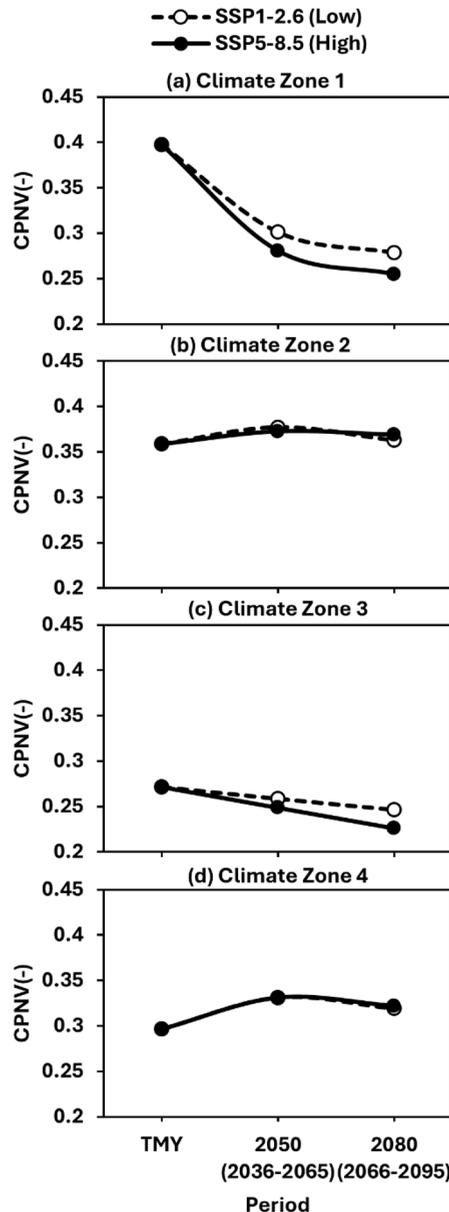
Figure 7 presents the CCOR in different scenarios and climates. The slopes of the lines denote the relationship between indoor overheating and outdoor climatic changes, with CCOR representing the inverse of this slope. Lower CCOR indicate lower building resistance to climate change effects. Notably, Climate 3 had the lowest CCOR at 2.79, indicating that buildings in that region are least resistant to the climate there. Following this, Climate 1 displayed a CCOR of 3.04, and the mountain climates exhibited a CCOR of 7.58. These findings indicate that naturally ventilated buildings in different climate zones within Lebanon have significantly different levels of resilience to the effects of climate change. Buildings situated in colder mountain regions displayed only marginal susceptibility through small increase in IOD indicator, even under the most severe scenario (2080 SSP5). Conversely, buildings in the warmer coastal and inland plateau areas demonstrate lower resistance to the impacts of climate change.

Figure 7 Climate Change Overheating Resistivity (CCOR) in the examined scenarios and climates

Figure 8 illustrates the CPNV across various scenarios and climates, representing the percentage of hours in a year when natural ventilation achieves comfortable indoor conditions. The CPNV trend exhibits variability under different SSPs and climate zones. In coastal (climate 1) and inland plateau (climate 3) zones, the transition from TMY to future predicted weather reveals a noteworthy disparity between lower SSP (SSP1) and higher SSP (SSP5). Specifically, SSP1 demonstrates significantly less reduction in NV comfortable hours. Conversely, mountain climates (2 and 4) exhibit no significant difference between the two SSPs. Notably, the coastal climate is most adversely impacted by climate change, experiencing a decline in comfortable NV hours from 40% (TMY) to 30%, 28%, 28%, and 26% for the respective 2050 SSP1, 2080 SSP1, 2050 SSP5, and 2080 SSP5 scenarios. In the inland plateau climate, NV comfortable hours decrease from 27% to 26%, 25%, 25%, and 23% for the same scenarios. Surprisingly, the low mountain climate (C2) demonstrates an increase in NV comfortable hours from 36% to 38%, 36%, 37%, and 37% for the corresponding scenarios. Additionally, the high mountain climate exhibits an increase from 30% to 33%, 32%, 33%, and 32% for the same scenarios.

Climate 1 experienced the greatest impact, being a mild climate with significant potential for NV. In contrast, Climate 3 was less affected, given its lower NV potential. This is due to the substantial temperature fluctuations in this climate, with extremely cold nights and very warm days, resulting in a limited window of suitable hours for NV use. Climate zones 2 and 4, characterized by cold mountain climates, face constraints in utilizing NV. This limitation is attributed not only to ambient warmth but also to ambient coolness. The hours unsuitable for NV use due to cool outdoor temperatures exceed those unsuitable due to high temperatures. Climate change, however, transforms a portion of these cool hours into a comfortable range for NV use, surpassing the hours rendered uncomfortable by excessive heat.

Figure 8 *Climate Potential of Natural Ventilation (CPNV) in the examined scenarios and climates*

Conclusion

In summary, this study examined the thermal behaviour of typical residential buildings in Lebanon in response to projected climate change impacts across diverse emission scenarios and climate zones. Key parameters evaluated include indoor overheating and the feasibility of utilizing NV to establish comfortable indoor conditions. Main findings of study include:

Indoor overheating is expected to rise in naturally ventilated apartments in Lebanon under all emission scenarios.

Among naturally ventilated units, apartments on the inland plateau (climate 2) have the highest risk of indoor overheating.

NV potential decreased significantly in coastal climates, which initially had a high potential for NV during TMY conditions (40% to 26% in the worst case). Because of their lower initial potential, inland climates saw a marginal decrease in NV comfort hours (27% to 23% in the worst case).

Mountain climates exhibited an increased potential for natural ventilation due to climate warming, enhancing NV potential. However, despite having increased NV potential on colder days pre-climate change, these buildings face elevated overheating during peak temperature days.

It is important to note that the current study has limitations, such as the exclusion of the urban heat island effect, as the data were not sourced from central city locations, potentially leading to an underestimation of risks in urban settings. Additionally, the study assumes that building and construction practices did not change during the investigated period, and that buildings lifespan extend to cover future scenarios under study.

Planned future research will utilize the same employed frameworks and assessment tools to explore the feasibility of cost-effective adaptation strategies, targeting the reduction of climate change impacts on low-income populations inhabiting naturally ventilated spaces.

Acknowledgement

Nomenclature

AWD	Ambient Warmness Degree (℃)
CCOR	Climate Change Overheating Resistivity (-)
CPNV	Climate Potential of Natural Ventilation (-)
IOD	Indoor Overheating Degree (℃)
SSP	Shared Socioeconomic Pathways
TMY	Typical Meteorological Year

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