Evaluating natural ventilation in historic buildings across US climates using CFD for future scenarios

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Abstract

As climate change continues to affect building performance, it is essential to evaluate the long-term viability of passive strategies, particularly in historic buildings. This study explores the current and future feasibility of using natural ventilation as a passive cooling strategy in historic buildings across seven US locations, each representing distinct ASHRAE climate zones. By employing a novel approach that integrates three-dimensional Computational Fluid Dynamics and energy modeling, the research investigates the impact of natural ventilation on indoor environmental conditions under present weather conditions, as well as projected climates for 2050 and 2080. A total of 42 computational models were executed for a church listed as a UNESCO World Heritage Site in San Antonio, Texas, US. The models were validated with real-world data, ensuring both their reliability and the accuracy of the simulated results. The findings indicate that coastal areas with warm climates benefit the best from natural ventilation. However, rising outdoor temperatures in future scenarios will significantly reduce the effectiveness of natural ventilation, resulting in elevated indoor temperatures in all climate zones. As climates warm, the dependency on natural ventilation for thermal comfort will become increasingly challenging, particularly during peak heat periods. While increased airflow through open windows may enhance ventilation rates, it does not always lead to improved thermal comfort, especially if not properly managed. This study highlights the limitations of relying solely on natural ventilation for passive cooling in historic buildings under future climate conditions. Additionally, it contributes to broader discussions on sustainable building practices and adaptation strategies, highlighting the pressing need to balance heritage conservation with climate adaptation. Finally, its relevance across diverse ASHRAE climate zones ensures a wide geographical applicability, making this research a vital addition to the discourse on sustainable architecture and climate resilient design.

Keywords: Historic Building; Computational Fluid Dynamics; Future Climates; Natural Ventilation; Thermal Comfort.

1. Introduction

Climate change, largely driven by human activities since the Industrial Revolution, has raised Earth's average surface temperature by approximately 1 °C (Serhan Cevik et al. 2020; Vaid 2021). A further 1 °C increase could cause irreversible damage to natural systems, emphasizing the urgent need for regulatory action (Yun and Jeong 2021; Mofolasayo 2022). Addressing this crisis requires prioritizing sustainable development and advancing both adaptation and mitigation initiatives, as the impacts of climate change extend well beyond rising temperatures.

Air conditioning now accounts for nearly 10 % of global electricity usage and is the most fast-growing energy demand in buildings (Ghaddar et al. 2024). In response, researchers are increasingly investigating passive strategies to improve thermal comfort and reduce energy consumption, especially in historic buildings that require special preservation considerations and embody cultural and architectural heritage values (Bay, Martinez-Molina, and Dupont 2022; Fiorito et al. 2022; Mellado Mascaraque et al. 2021; Nawalany, Sokolowski, and Michalik 2020). These structures were often constructed with specialized materials and techniques, feature distinctive architectural elements, envelope designs, and integrated artwork (Cho et al. 2022; Iskandar, Faubel, et al. 2024), and are protected by strict conservation guidelines (Webb 2017). Many of these buildings were originally constructed without climate control systems, and many still lack them today (Camuffo et al. 2010). While mechanical heating and cooling systems are sometimes added later to enhance occupant comfort, they can inadvertently harm the structural integrity and preservation of cultural artifacts housed within these structures (Corgnati and Perino 2013; D'Agostino 2013; Huijbregts et al. 2012). As a result, regulating indoor climate conditions presents a significant challenge, one that is further complicated by the intensifying effects of climate change. Consequently, careful planning is essential when considering energy retrofits, particularly in regions with high temperatures and humidity, such as ASHRAE climate zones 1A – Very Hot Humid (e.g., Miami, FL), 2A – Hot Humid (e.g., Houston, TX), 2B – Hot Dry (e.g., Phoenix, AZ), 3A – Warm Humid (e.g., Atlanta, GA), and 3B – Warm Dry (e.g., Las Vegas, NV) in the United States, where maintaining comfort while preserving historic integrity is especially difficult (ASHRAE Standard 169-2021, Climatic Data for Building Design Standards 2021). In these contexts, passive strategies should be prioritized before implementing active systems to mitigate climate impacts responsibly.

Natural ventilation is a promising passive cooling strategy that enhances energy efficiency and indoor thermal comfort in heritage buildings, particularly in warm climates. By regulating indoor environmental parameters such as air temperature, airflow, relative humidity, and pollutant concentrations, it reduces reliance on mechanical systems, making it ideal for historic structures without modern climate control measures (Hensley and Aguilar 2011), and modern facilities equally (Faubel, Martinez-Molina, and Suk 2024; Karaiskos, Martinez-Molina, and Alamaniotis 2023). This approach supports the preservation of these buildings and sustainability goals by minimizing energy use. It is important to acknowledge that natural ventilation also has certain limitations, particularly in the context of historic buildings. Fluctuations in outdoor conditions can disrupt indoor microclimates, harming both occupant comfort potentially damaging sensitive materials or artwork (Salehi, Torres, and Ramos 2017). Additionally, historic buildings' original layouts and spatial configurations often hinder optimal airflow patterns, leading to poor ventilation performance and increased reliance on mechanical systems (Sakiyama et al. 2021).

Advanced building simulation tools like EnergyPlus (EnergyPlus 2025), DeST (Yan et al. 2008), and IES VE (IES VE 2025) play a crucial role in evaluating natural ventilation in historic buildings, where physical testing could damage historic materials and features. These tools enable detailed analysis by incorporating specific building design features and internal conditions, including heat gain, envelope characteristics, occupancy, and ventilation patterns (Xie et al. 2023). Research has demonstrated their effectiveness in assessing natural ventilation under various climate scenarios (Ryan and Sanquist 2012; Royapoor and Roskilly 2015). Computational fluid dynamics (CFD) simulations are particularly useful for predicting airflow patterns, offering speed, accuracy, and cost advantages over experimental testing methods, such as wind tunnel or full-scale testing (Abuku, Janssen, and Roels 2009; Jiru and Bitsuamlak 2010). For instance, Rajput et al. (Singh Rajput, Padmanabhan, and Thomas 2024) assessed wall materials and airflow dynamics in low-income housing with high indoor heat using CFD simulations, showing temperature distributions across different window profiles. Similarly, Iskandar et al. (Iskandar, Bay-Sahin, et al. 2024) used CFD to compare six ventilation methods in a historic building, identifying cross-ventilation as the most effective cooling technique and highlighting the role of opening sizes in thermal comfort. These studies provide valuable insights into sustainable building practices and strategies for mitigating climate change impacts on historic structures. This body of work is critical for guiding future efforts in climate adaptation and architectural conservation, particularly in regions facing significant environmental shifts due to climate change.

Accurate weather data is essential for reliable building energy simulations, particularly when assessing future energy performance and climate adaptation strategies (Hensen 1999). Some research has utilized future weather data to evaluate the efficiency of natural ventilation. For instance, Fiorito et al. (2022) examined how behavioral changes impact indoor thermal comfort in naturally ventilated buildings under future climate conditions, while Bamdad, Matour, Izadyar, and Law (2022) quantified the climatic potential of natural ventilation under present and future climate in different Australian climate zones. Other studies have examined the effectiveness of natural ventilation in historic buildings under current climate conditions only. For example, Palomo Amores et al. (2025) analyzed various natural ventilation strategies in a historic building located in a warm climate, and Shayegani et al. (2025) investigated sustainable ventilation strategies to mitigate urban overheating. Nevertheless, there remains a gap in the literature regarding the evaluation of natural ventilation efficiency in historic buildings under future climate conditions, particularly given their unique materials and preservation requirements. This study addresses that gap by investigating the viability of natural ventilation as a passive cooling solution in a historic church building, recognized as a UNESCO World Heritage Site, under a range of climatic conditions. Using current and projected weather data generated by the CCWorldWeatherGen (CCWWG) software (Jentsch et al. 2013), the analysis evaluates indoor air temperature, relative humidity, and airflow across seven ASHRAE climate zones, each with distinct temperature and humidity profiles, based on representative locations with building typologies similar to the original case study.

Environmental monitoring established baseline conditions, while energy and CFD simulations assessed both current and future scenarios. The CFD methodology aligns with emerging trends in building performance simulation, offering a nuanced visualization of airflow dynamics within the building's architectural layout and enabling a detailed examination of vertical and horizontal fluid flow patterns. By focusing on regional scales, this research contributes evidence-based insights into sustainable retrofit strategies for historic buildings, particularly in warm regions impacted by climate change. Ultimately, this study aims to guide architects, designers, and preservationists to incorporate diverse adaptation and mitigation strategies tailored to specific climate zones, as the repercussions of climate change extend beyond occupant health and comfort to encompass the sustainable conservation of heritage structures themselves.

2. Materials and Methods

The methodology employed in this investigation comprised both an experimental phase and a simulation phase, as schematically illustrated in Figure 1. The details are as follows:

- During the experimental phase, an environmental monitoring campaign was conducted in San Antonio, Texas, US, where the case study building is located. Environmental parameters, including air temperature and relative humidity, were collected using indoor and outdoor data loggers during the cooling season, specifically from May to September 2019.
- As the initial step of the simulation phase, building energy simulations were conducted using the location of the building where real field data were collected. IES VE software (IES VE 2025) was chosen for model generation, energy analysis, and CFD simulations. The accuracy of the model was evaluated by comparing the indoor air temperature and relative humidity values obtained from the energy simulations with the measured data from onsite monitoring.
- Different ventilation strategies were defined to analyze the effectiveness of natural ventilation in cooling the case study building during the cooling season: i) no ventilation, and ii) natural ventilation with openings at full capacity. Additionally, seven ASHRAE climate zones were selected, each represented by a location that also hosts a similar Spanish mission, to evaluate the effectiveness of natural ventilation as a passive cooling method across diverse climate regions. Specifically, the selected locations were: i) Phoenix, Arizona (1B, very hot-dry), ii) San Antonio, Texas (2A, hot-humid), iii) Tulsa,

Oklahoma (3A, warm-humid), iv) San Diego, California (3B, warm-dry), v) Santa Barbara, California (3C, warm-marine), vi) Baltimore, Maryland (4A, mixed-humid), and vii) Albuquerque, New Mexico (4B, mixed-dry).

- Finally, the connection between natural ventilation and indoor microclimate in present and future years was evaluated using the 2050 and 2080 future weather files generated by the CCWWG (Jentsch et al. 2013). The building energy and CFD simulations for all climate zones in the present and future years were performed using IES VE software (IES VE 2025).

2.1 Case Study Description

The selected case study is the church located at Mission Nuestra Señora de la Purísima Concepción de Acuña, 3.7 km south of Downtown San Antonio, Texas, US. Situated in a region characterized by a Cfa-Humid Subtropical Climate, San Antonio also experiences a Bsk-Semi-Arid Climate to the west, as per the Köppen classification (Kottek et al. 2006). Positioned at an elevation of 240.5 m above sea level, the city experiences temperature fluctuations from as low as 9 °C in the coldest months to highs of 32 °C in the hottest months, with an average annual temperature of 21 °C. Summer temperatures attain highs of 38 °C (US Department of Commerce 2022).

The construction of Mission Concepción Church, initiated in 1755, utilized locally sourced materials, predominantly limestone from a quarry located on the same site. Serving as the core of a self-sustaining religious compound beside the San Antonio River, its strategic placement ensured access to irrigation and security, bolstered by the nearby Presidio San Antonio de Bexar (Lydia O. Powell 1982; Leo Teran 1986; Luis Torres 1993). Designated as part of the San Antonio Missions National Historical Park in 1978 (United States Department of the Interior - National Park fire Service 1987) and later attaining UNESCO World Heritage status in 2015 (UNESCO World Heritage Convention 2015), Mission Concepción stands as a testament to historical and architectural significance. The entrance in the main facade, depicted in Figure 2, is flanked by two towering bell structures, approximately 18 m in height. The church's interior layout shown in Figure 3 comprises a central Nave, leading towards the Sanctuary. Transepts on either side precede the Sanctuary, capped by a vaulted dome ceiling as shown in the longitudinal section of the church (Figure 4). The Sacristy, accessible from the right Transept, hosts the only east-facing window and serves as an exit (Figure 3). Throughout the building, operable windows facilitate natural ventilation, while a split system heat pump aids in climate control. Operating daily from 09:00 to 17:00, the cooling system maintains a constant setpoint of 23 °C, with two weekly Mass services conducted on Sundays at 10:00 and 12:00.

2.2 Environmental Monitoring

A network comprising 10 indoor data loggers and 2 outdoor data loggers was strategically deployed within the building to assess the prevailing environmental conditions. Figure 3 illustrates the position of the monitoring sensors, which were located following the guidelines outlined in ASHRAE 55 (ANSI/ASHRAE Standard 55 2017), specifically at a standard height of 1.10 m to maintain consistency between seated and standing occupants. Additionally, Table 1 summarizes the specifications of the data loggers. Given the public accessibility of the building, additional measures were taken to safeguard the data loggers against tampering or theft. They were discreetly positioned in concealed areas, out of reach, while ensuring the preservation of the church's architectural integrity.

The loggers tracked indoor and outdoor temperature and relative humidity at 15-minute intervals from May to September 2019 (cooling season), capturing a comprehensive range of environmental conditions within the building. This frequency not only facilitated the collection of extensive data but also enabled the identification of any recurring patterns or significant deviations throughout the monitored period. Table 2 presents the recorded monthly average indoor and outdoor air temperature and relative humidity, as well as monthly average outdoor solar radiation.

The collected data reveals that average monthly indoor air temperatures are consistently lower than outdoor values, with differences reaching 11 °C, primarily due to the high thermal mass envelope as well as the use of mechanical cooling at certain times. Relative humidity, on the contrary, was steadily higher indoors than outdoors due to moisture buffering achieved by the envelope, as well as limited ventilation and the presence of occupants. Outdoor solar radiation in the studied location varied between 420 W/m^2 in May and 580 W/m^2 in August. Wind data, a critical factor impacting natural ventilation and passive cooling, was retrieved from the San Antonio Airport weather station (Table 2 and Figure 5). The data reveals a dominant south-east wind direction, with a varying speed of 3.9 m/s in August to 5.0 m/s in May.

2.3 Climate Zone Selections

As previously mentioned, to comprehensively evaluate the effectiveness of natural ventilation in historic buildings across diverse climatic conditions, seven cities within the US have been selected, each representing distinct ASHRAE climate zones (ASHRAE Standard 169-2021, Climatic Data for Building Design Standards 2021). The locations are summarized in Table 3 and depicted in Figure 6. The chosen cities also correspond to regions where Spanish Missions or similar historic structures are present, ensuring relevance to the architectural typology under study while preserving historical and cultural significance (David J. Weber 1994). These structures often share common architectural features such as thick masonry walls, limited fenestration, and passive cooling strategies originally adapted to their local climates. By focusing on these historically significant regions, this study ensures that the findings are applicable to buildings with similar architectural and cultural contexts.

For comparative analysis, the case study orientation has been kept consistent across all locations and climates to prevent the confounding effect of other variables such as solar radiation. This approach minimizes orientation-induced variability while ensuring that the analysis reflects realistic adaptations to local climatic conditions. Such uniformity, combined with these minor adjustments, is critical to isolating the effects of climate and ventilation strategies on thermal comfort and indoor environmental quality enhancing the reliability of the analysis, providing actionable insights into the feasibility of natural ventilation as a passive cooling strategy under current and future climate scenarios.

2.4 Future Weather Data Generation

The indoor environmental conditions in the historic building were simulated using the IES VE software (IES VE 2025), which utilizes EnergyPlus Weather (EPW) format files as input parameters. These files contain information associated with weather variables such as dry and wet bulb temperatures, relative humidity, solar radiation, and wind speed and direction, which heavily impact the building energy performance and the outcomes of the simulations. Specifically, the climatic conditions of a location are described by the Typical Meteorological Year (TMY) file, representing a typical year based on historical observations summarizing recent weather patterns (Fiocchi, Weil, and Hoque 2014). For the different locations analyzed in this study, the TMY3 (historical data from 1991 to 2005) and TMYx (2007-2021) weather files required in the IES VE software were obtained from the Climate.OneBuilding repository for EPW files (Climate.Onebuilding.org 2025).

On the other hand, the future weather data were derived from the TMY3 and TMYx files using the CCWWG (Jentsch et al. 2013), a widely adopted future weather generator for creating input weather datasets in building energy performance analysis (H. Yassaghi, Mostafavi, and Hoque 2019; Hamed Yassaghi, Gurian, and Hoque 2020; Plaga and Bertsch 2023). The CCWWG utilizes the Hadley Center Coupled Model Version 3 (HadCM3) of the Atmospheric-Ocean General Circulation Models (GCMs) datasets, combined with a specific emission scenario, to generate future weather data while maintaining realistic weather patterns for any location. Specifically, the SRES A2 scenario introduced by the IPCC in the Fourth Assessment Report (4AR) was selected in this investigation (AR5 Synthesis Report: Climate Change 2014 — IPCC, 2014). This emission scenario represents the worst-case greenhouse gas (GHG) trajectory, assuming no additional measures will be implemented to mitigate emissions. While newer future weather simulation tools like the Future Weather Generator (FWG) (Rodrigues, Fernandes, and Carvalho 2023) have been developed, the authors validated the use of CCWWG by comparing the projected environmental conditions for the case study building in the different locations with those generated by the FWG, finding similar results. Finally, the nomenclature used in Section 3 is as follows: the term *Present* refers to outcomes based on the TMY3 and TMYx files, while the term *Future* corresponds to results derived from CCWWG. It is important to note that the future years 2050 and 2080 do not represent specific dates but instead reflect monthly average values for the periods 2040-2069 (for 2050) and 2070-2099 (for 2080) (HadCM3 Climate Scenario Data, 2025).

2.5 Energy and CFD Simulations and Validation

IES VE software (IES VE 2025) is an advanced energy and CFD simulation tool widely used for building energy performance analysis (Corcoran et al. 2025; Freewan 2022; Alyami et al. 2022; Catto Lucchino et al. 2021), carbon assessment and life cycle analysis (Xinyu Zhang, Ge, and Patel 2025; Newberry, Harper, and Norman 2023). Additionally, IES VE complies with industry standards like ASHRAE 140 and CIBSE TM33 (Software Validation and Approval IES VE 2025), which support the potential for reliable and accurate simulation results when the software is applied correctly by knowledgeable users. In this study, the software is utilized to perform numerical simulations using the finite volume method, investigate heat transfer processes and airflow trends indoors and outdoors, and to test wind-driven ventilation for the different locations of the case study building. The main steps of internal CFD simulations are diagrammatically shown in Figure 7. Overall various modules, namely ModelIt, MacroFlo, MicroFlo, and VistaPro, were utilized. Specifically, the entire building was modeled using ModelIt, with the parameters of the structure, carefully collected to ensure realistic outcomes reflecting real-world conditions, summarized in Table 4. Moreover, to analyse infiltration and natural ventilation realistically, the church's three types of openings (side hung window, bottom hung window, and fixed window) were assigned. To define the opening characteristics, all relevant input data concerning building apertures, such as exposure types, aerodynamic (or equivalent) free area percentages as the openable area, degrees of opening, and modulation profiles over daily, weekly, or yearly periods, were specified within the MacroFlo module and listed in Table 5. This IES VE component employs a zonal airflow model to evaluate the overall air movement within and across the building, considering infiltration and natural ventilation.

Finally, different modulating profiles were then generated in this module corresponding to the ventilation strategies analyzed in this investigation:

- Scenario 1 (S1): All windows and doors remain fully closed to analyze the structure without any ventilation, only accounting for infiltration. The air infiltration rate of the structure was set to 2.032 l/(s·m^2) in the simulations, considering the case study building as a leaky construction due to its current condition. This value was based on both proposed rates for historic buildings and the experience of past investigations (Hanam, Finch, and Hepting 2011). This scenario served as a reference point to evaluate the effect of natural ventilation.
- Scenario 2 (S2): This scenario, which aims to assess the effectiveness of passive cooling in the case study building, focuses on natural ventilation with varying window types and sizes. Specifically, all windows and doors are opened 24 hours per day during the cooling period. Infiltration is also considered.

At Mission Conception, a stone structure, thermal sinks and sources are primarily associated with the high thermal mass of the stone masonry. The stone walls and floors act as thermal sinks by absorbing heat during warmer periods and gradually releasing it when ambient temperatures drop. This helps to moderate indoor temperature fluctuations. Internal heat gains from occupants would typically serve as thermal sources; however, these were excluded from the analysis, as the building was tested in its free-floating state without occupants and mechanical systems. After assigning all construction materials and thermal zones, detailed energy simulations were performed using IES VE. To ensure the reliability of the simulations, the building model was validated using indoor air temperature and relative humidity measurements collected during the monitoring campaign. Representative days, namely July 14, 15, and 16, were chosen for validation. This period, during the peak of the cooling season, experienced the highest temperatures and was selected based on the study's objectives. The validation parameters, specifically indoor air temperature and relative humidity, are critical for evaluating thermal comfort and indoor air quality, and the accuracy of measurements is essential to ensure robust validation. Furthermore, these parameters have been widely used as CFD validation metrics in similar investigations (Yohana et al. 2017; Lerma et al. 2021; Bay, Martinez-Molina, and Dupont 2022; Iskandar, Bay-Sahin, et al. 2024). Both the monitored data and simulated values from the VistaPro module in IES VE were obtained at a standard height of 1.10 m, following ASHRAE 55 guidelines to maintain consistency between seated and standing occupants (ANSI/ASHRAE Standard 55 2017). These results are illustrated in Figure 8 for the representative days.

Uncertainty indices, such as normalized mean biased error (NMBE) and coefficient of variation of the root mean square error (CV(RMSE)), were computed according to ASHRAE Guideline 14 (ASHRAE Guideline 14 2014) using equations (1) and (2). In these equations, Y_i represents the measured value for the indoor air temperature and relative humidity, $\widehat{Y_i}$ stands for the simulated value for the same variables given by IES VE software, and $\overline{Y}$ corresponds to the average of measured values Y_i. Moreover, N is the total number of data points used in the analysis, and p denotes the modifiable model parameter. ASHRAE guidelines recommend that for hourly validation, the NMBE should not exceed ±10 % and the CV(RMSE) should not exceed 30 %. The obtained NMBE and CV(RMSE) values were: i) -2.5 % and 5.4 % for temperature, and -9.6 % and 15.2 % for relative humidity on July 14, ii) -3.3 % and 5.1 % for temperature, and -8.1 % and 16.8 % for relative humidity on July 15, and iii) -3.7 % and 8.9 % for temperature, and -3.2 % and 13.9 % for relative humidity on July 16, respectively. These results confirm the accuracy and reliability of the model predictions, demonstrating its validity. It is important to note that the model was also validated for the entire cooling season, not just these representative days, with the NMBE and CV(RMSE) failing within the accepted ASHRAE recommendations. As previously mentioned, the representative days shown in Figure 8 were selected based on the study's objectives, as this period, during the peak of the cooling season, experienced the highest temperatures.

$$\mathrm{NMBE}\ (\%) = \frac{1}{\bar{\bar{Y}}} \frac{\sum_{i=1}^{N} \left(Y_i - \hat{Y}_i\right)}{N - p} \times 100\,, \quad (1)$$

$$\mathrm{CV(RMSE)}\ (\%) = \frac{1}{\bar{\bar{Y}}} \sqrt{\frac{\sum_{i=1}^{N} \left(Y_i - \hat{Y}_i\right)^2}{N - p}} \times 100\,. \quad (2)$$

Finally, to test airflow characteristics in both present and future years (2050 and 2080), 2 different scenarios (S1 and S2) and 7 climate files were set in IES VE CFD module to create 42 CFD models. The simulations were run for a typical cooling day, July 15. This representative date was chosen after the analysis of the current environmental data from San Antonio to obtain indoor air temperature and air velocity values considering that July is the common cooling month for all selected locations. Noon (12:00) was chosen for the CFD simulations due to its alignment with high outdoor temperatures and solar radiation intensity which together contribute significantly to the building's thermal load. This time is ideal for analyzing the building's response to such conditions, providing critical insights into its behavior during periods of maximum heat stress (Fatnassi et al. 2023). Moreover, noon serves as a consistent reference point for comparing the different ventilation strategies, enabling clear evaluations of temperature and airflow patterns. To ensure a focused assessment of natural ventilation for passive cooling, the simulations were conducted with the building in its free-floating state, i.e. without mechanical cooling systems and with occupancy set to zero, thereby eliminating external influences.

In this study, only internal CFD simulations were conducted. The computational domain was confined to the interior of the building, rather than embedding the structure within a larger external domain. Figure 9 depicts the internal CFD computational domain used in the simulations. Boundary conditions were derived from Apache simulation results using the VistaPro module and exported to MicroFlo for analysis of airflow during the cooling season, focusing on natural ventilation and passive cooling. As a first step in the CFD simulations, boundary conditions related to radiation were automatically established using energy simulation results since MicroFlo does not have a built-in radiation model. It configures internal boundary conditions based on the selected day and time using data exported from VistaPro. These included prevailing wind direction, wind speed, and both indoor and outdoor air temperatures. The boundary condition file also incorporated detailed parameters such as atmospheric pressure, external moisture content, room air and radiant temperatures, and surface temperatures of walls and windows. This data is significant for this module which employs a steady-state three-dimensional convection-conduction heat transfer and flow model based on the finite volume method formulation for equations.

The predominant airflow direction was aligned with the grid axes in the model. Before initiating the CFD simulations, inlet and outlet functionality was verified through MacroFlo to ensure accurate representation of natural ventilation behavior. This system allows flexibility in cell size across the space to better capture important variations in airflow and temperature. Moreover, the CFD grid was designed to maintain a maximum cell aspect ratio of 12:1 to ensure a high level of resolution. As seen in Figure 9, MicroFlo features a structured non-uniform Cartesian grid to balance accuracy and computational efficiency. The Standard k-e turbulence model was available in IES VE as a default one and was utilized to evaluate turbulent viscosity within the grid cells. This model's proven reliability and computational efficiency in modeling indoor airflow, especially for naturally ventilated spaces (Chen 1995; Nielsen 2004). Authors acknowledge that a significant portion of the simulation setup was handled by the IES VE software, which indeed limits the degree of customization and control over certain parameters. This is a limitation of the IES VE CFD module, which is designed primarily for ease of use and integration within a building performance simulation workflow, rather than for detailed CFD studies.

A grid-independence study was conducted to ensure the reliability and robustness of our CFD simulation results. Specifications of the CFD model utilized in the MicroFlo module are outlined in Table 6. The computational mesh (total number of cells) is set as $7\text{-}8.7\times10^6$ to capture the fine details of the flow with accurate predictions. The authors did not increase the number of cells to not unnecessarily increasing computational time. For this, we followed the IES VE grid setting statistics, such as optimum grid spacing, cell aspect ratio, grid line merge tolerance, which should be less than or equal to 0.1 m, and number of X, Y, and Z cells. These numbers also affect the maximum cell aspect ratio, which should be less than 12:1 (IES VE 2025) to ensure a high level of resolution. This provides a validation of the grid independence in IES VE before running the simulation. Based on this, the mesh density range of $7\text{-}8.7\times10^6$ cells was selected as an optimal balance between computational efficiency and result accuracy.

To offer a deeper understanding, CFD plots were produced as graphical outputs complementing the tabular results in Section 3.3. The northwest-southeast orientation, corresponding to the real-life case study building in San Antonio, was selected as the reference orientation for all the climate locations under consideration. This decision was made to ensure consistency and to eliminate the influence of building orientation on the simulation results, including the confounding effects of solar path variations. However, the climate file of each studied location reflects its unique climatic characteristics for the purposes of this study.

Internal heat gains from occupants, lighting, and equipment were intentionally excluded from the simulations in order to isolate and analyze the specific impact of natural ventilation on indoor thermal conditions under a controlled baseline scenario. The primary goal was to assess the passive performance of natural ventilation across diverse climate zones without the confounding influence of occupancy-related variables. By omitting internal loads, the study ensures that any observed changes in indoor temperature or humidity are attributable solely to the effects of natural ventilation and outdoor climatic conditions. Future work aims to incorporate internal loads and occupancy schedules to evaluate dynamic conditions more representative of real-world use.

3. Results and Discussion

3.1 Climate Zones Environmental Data

The nomenclature used in this section is described as follows: the term *Present* refers to outcomes based on the TMY3 and TMYx files, while the term *Future* corresponds to results obtained using weather data files derived from CCWWG for 2050 and 2080. It is important to note that the future years 2050 and 2080 do not represent specific dates but instead reflect monthly average values for a typical year for the periods 2040-2069 (for 2050) and 2070-2099 (for 2080) (HadCM3 Climate Scenario Data, 2025).

The trends for outdoor environmental variables at the studied locations, resulting from the energy simulations, are shown in Figure 10. In the present weather data (TMY3 files), the lowest outdoor temperatures were recorded in Santa Barbara (3C, warm-marine), with May being the coldest month (average of 14 °C) and September the hottest month (average of 18 °C). Outdoor temperatures in San Diego (3B, warm-dry) followed a similar trend with slightly higher average monthly values (16 °C in May and 21°C in September). This pattern deviates from the other five studied locations that followed the typical cooling patterns observed in most US cities, where temperatures begin to drop after July. This can be attributed to the fact that the Pacific Sea Surface Temperatures peak during the fall period and subtropical Pacific high-pressure systems linger over the western states (Tamrazian et al. 2008). These factors amplify late-season warming, creating a unique thermal profile for these coastal areas. In Albuquerque (4B, mixed-dry) and Baltimore (4A, mixed-humid), the lowest temperatures were recorded in May (average of 18 °C) and the highest in July (average of 25 °C). In San Antonio (2A, hot-humid) and Tulsa (3A, warm-humid), July temperatures reached a high of 30 °C, with lows of 21 °C in Tulsa in May and September and 24 °C in San Antonio in September. The warmest location was Phoenix (1B, very hot-dry), with highs of 35 °C recorded in July and lows of 27 °C in May, a trend consistent with its arid climate and susceptibility to heat extremes (Fan et al. 2024). The patterns for simulated outdoor temperatures were consistent under the generated future weather data for all locations with an average increase of 3 °C in 2050 and 5 °C in 2080.

Regarding outdoor relative humidity resulting from the simulations, current weather data indicated that Phoenix was the driest location, with the lowest average monthly values recorded in June (20 %) and the highest in August (30 %). Albuquerque recorded slightly more humid conditions, with lows of 32 % in May and highs of 47 % in August. San Antonio, Baltimore, Tulsa, and San Diego exhibited consistent outdoor relative humidity levels ranging between 60 % and 70 % throughout the studied period, except in September, where values increased above this range, excluding San Diego. Santa Barbara was the most humid location, with highs of 82 % in July and lows of 77 % in May. These differences in humidity reflect regional variations in moisture availability, which are critical for designing effective cooling strategies (Hu et al. 2023). Future weather data showed no significant changes in outdoor relative humidity for Phoenix and Baltimore, apart from a slight decrease in May and June. The same applies to Santa Barbara, except for a slight decrease perceived in July (6 % in 2050 and 2 % in 2080). Albuquerque witnessed a 5 % average decrease in 2050, with no notable changes between 2050 and 2080. San Antonio followed the same pattern as present weather data (TMY3 files), with July being the driest month and September the most humid. An average decrease of 10 % was observed between the present and 2050, and 6 %

between 2050 and 2080. Tulsa experienced a 9 % decrease by 2050 and 7 % by 2080. Conversely, San Diego showed a 5 % increase in 2050, with no further changes by 2080. These findings align with Simpson et al.'s (Simpson et al. 2024) observation that atmospheric water vapor is not increasing as expected with climate change, particularly in arid and semi-arid regions, based on observations over the last four decades. This highlights significant risks to water resources, wildfire management, and ecosystem resilience in these vulnerable areas. These changes can also alter thermal comfort and perceived cooling, especially when relying on passive cooling strategies.

As for outdoor air velocity, present weather data in the simulations revealed relatively constant values throughout the studied period in Santa Barbara (average of 2.65 m/s), San Diego (3.37 m/s), and Baltimore (3.25 m/s). In Phoenix, outdoor air velocity peaked in May (3.87 m/s) and reached a low of 2.13 m/s in September. A similar pattern was observed in San Antonio with the lowest values recorded in May (2.17 m/s) and the highest in July (3.35 m/s). Tulsa recorded a high of 4.36 m/s in July and a low of 3.23 m/s in September. Albuquerque demonstrated a decreasing trend, with a high of 4.68 m/s in May and a low of 3.49 m/s in September. No significant changes in outdoor air velocity were observed between present and future data across all locations. As a result, outdoor air velocity was not treated as a varying parameter for assessing the impact of natural ventilation in this study.

3.2. Impact of Natural Ventilation on Indoor Environmental Conditions

To assess and quantify the effectiveness of natural ventilation as a passive cooling method in the case study building across the different climate zones and throughout the current century, the following quantities were defined:

$$\Delta T = T_{S1} - T_{S2}\,, \tag{3}$$

$$\Delta RH = RH_{S1} - RH_{S2}\,, \tag{4}$$

$$\Delta Q = Q_{S1} - Q_{S2} \,, \quad (5)$$

where T, RH, and Q represent the indoor air temperature, relative humidity and ventilation rates for each scenario, namely S1 (no natural ventilation), and S2 (full natural ventilation). The numerical values for the indoor air temperature, relative humidity and ventilation rate simulated using IES VE software for S1 and S2 are summarized in Table 7. Additionally, Figure 11 depicts the monthly averages of the simulated indoor environmental variables given in Eqs. (3-5) during the cooling season across the investigated climate zones using IES VE software. Results for present were derived from the corresponding TMY3 file, while projections for 2050 and 2080 were generated using CCWWG.

The impact of natural ventilation on indoor air temperature, based on the present weather data (TMY3 files), varied among different climate zones. Santa Barbara (3C, warm-marine) experienced an overall decrease of around 1 °C in S2 compared to S1 during the cooling season, demonstrating the effectiveness of natural ventilation as a passive cooling method in this location. Conversely, full natural ventilation did not contribute to cooling the building in other locations. Specifically, Alabama (4B, mixed-dry), Baltimore (4A, mixed-humid), San Antonio (2A, hot-humid), San Diego (3B, warm-dry) and Tulsa (3A, warm-humid) showed an increase of approximately 1 °C in S2, while Phoenix (1B, very hot-dry) experienced a more significant increase of around 4.5 °C. In 2050, the simulated data indicated that natural ventilation did not contribute to a decrease in indoor air temperature. While Santa Barbara recorded similar temperatures in S1 and S2 ($\Delta T \simeq 0$), the other climate zones experienced a significant increase in S2 compared to S1, reaching up to 2 °C. Interestingly, San Antonio showed an overall increase of approximately 5 °C. This trend was repeated in 2080 across the various locations, with San Antonio recording an increase of 2 °C in S2 compared to S1, similar to the other regions.

On the other hand, natural ventilation under present weather conditions increased indoor air relative humidity in almost all the locations in S2 compared to S1, with the highest increment of around 5 % recorded in Santa Barbara. Conversely, natural ventilation decreased indoor relative humidity by approximately 5 % in S2 compared to S1 in Phoenix throughout May and June, but this trend diminished toward the end of the cooling season. San Diego exhibited the opposite behavior, with a decrease of around 5 % in S2 compared to S1 at the end of the cooling season in September. In the future years analyzed, the increase in relative humidity in S2 compared to S1 ranged from 0.5 % to 5 % in the different locations, except for San Antonio in 2050 and Phoenix in 2050 and 2080. The former location experienced an overall decrease in S2 compared to S1 of 5 %, reaching a maximum of 10 % in the middle of the cooling season, while the latter location showed an overall decrease of approximately 2 % in S2 compared to S1.

It is important to note that since the simulations were conducted without accounting for internal heat gains (e.g., occupants, equipment, or lighting), the observed results are primarily due to the introduction of hot outdoor air without any compensating internal loads that could be offset by thermal mass. In occupied scenarios, the thermal mass of the building could help buffer internal gains for a limited period, depending on the magnitude of internal loads and the building's thermal inertia.

Finally, the impact of natural ventilation on the ventilation rate, based on the present weather data, was as follows. The ventilation rates in S2 ranged from 1.7 to 3.2×10^3 l/s in the different locations during the first part of the cooling season, with the maximum recorded in Tulsa in July. Towards the end of the cooling season, these rates tended to converge to more similar values across all locations, ranging from 2 to 2.5×10^3 l/s. A similar trend was observed in the future years analyzed in this study, with an overall increase of less than 0.5×10^3 l/s in 2050 compared to the present, and around 0.5×10^3 l/s in 2080 compared to the present. This slight increase in future ventilation rates may be attributed to the higher temperature differentials and potentially increased buoyancy-driven flow during warmer periods.

3.3. CFD Analysis on a Representative Day

In this section, the results of the CFD simulations conducted for a representative day during the cooling season, namely July 15 at 12:00, are discussed for the present, 2050 and 2080. Specifically, Figures 12 to 18 illustrate the air temperature and air velocity distributions for the structure across different locations and various ventilation strategies. All CFD plots for S1 include only temperature data, as the building was tested with closed windows. In contrast, S2 was analyzed using both temperature and air velocity plots. Since indoor data loggers were positioned at 1.10 m above the floor, as an average for standing and seated positions in accordance with ASHRAE Standard 55 (ANSI/ASHRAE Standard 55 2017), the CFD plots for floor plans were created accordingly. For airflow plots, the perspective view from southwest was used in all cases.

The natural ventilation strategy, implemented by fully opening windows (S2), increased the average indoor air temperature in the structure located in San Antonio (2A, hot-humid) compared with the no-natural-ventilation scenario (S1) by about 3 °C under present weather conditions, 6.7 °C in 2050, and 5 °C in 2080, respectively (Figure 12 and Table 8). These results highlight the limited effectiveness of natural ventilation in decreasing indoor temperature when the building is unoccupied because in this location, the increased airflow indoors facilitated by natural ventilation brings in hotter outdoor air, causing a rise in indoor temperature. Due to their distance from the openings, the nave and chancel consistently had lower temperatures than other zones on the same floor (Figure 3), such as infirmary, across different years. The temperature distribution was uniform throughout the different zones, with slightly higher values observed in the infirmary. It is important to note that airflow near the two openings of the infirmary on the south and east facades resulted in higher temperatures. Finally, when the windows were closed (S1), an increase in the average indoor air temperature of about 1 °C was observed from the present (27.2 °C) to 2050 (28.3 °C), with an additional 4 °C increase between 2050 and 2080 (32.3 °C). On the other hand, when the windows were open (S2), the air temperature increased by about 4.2 °C from the present (30.8 °C) to 2050 (35.0 °C), with an additional 2.4 °C increase between 2050 and 2080, when the average indoor air temperature reached 37.4 °C (Figure 12 and Table 8).

In Phoenix (1B, very hot-dry), opening windows on the representative cooling day led to a substantial temperature rise of almost 7 °C under present weather conditions, and 5 °C in 2050 and 2080 (Figure 13 and Table 8). This indicates that despite increased airflow, ventilation brought in hotter air, with Phoenix showing one of the worst impacts of opening windows, as indoor temperatures increased drastically due to hot outside air, suggesting that natural ventilation is not an effective cooling strategy in this case. In this climate zone, temperature distribution was consistent across the different zones of the church, with slightly higher values in the infirmary (Figure 3). When the windows were closed (S1), an air temperature increase of 2 °C was observed between the present (31.4 °C) and 2050 (33.4 °C), and an additional 1.5 °C increase between 2050 and 2080 (34.9 °C). On the other hand, when the windows were open (S2), air temperature remained unchanged in 2050 compared to the present scenario (38.3 °C), while an increase of 1.7 °C occured in 2080, reaching 40.0 °C (Figure 13 and Table 8). These results demonstrate that natural ventilation could have been effective in this location if outdoor temperatures were lower.

Opening the windows in Tulsa (3A, warm-humid) resulted in an average temperature increase of 3.4 °C under the current weather conditions for the studied representative day. This difference surged to 4.4 °C in 2050 and 5.1 °C in 2080 even though air velocity showed a decreasing trend, particularly in 2080 (Figure 14 and Table 8). These results highlight an exacerbating effect of natural ventilation under future weather conditions. Temperature distribution was generally constant throughout the church, except in the infirmary, similar to the case of Phoenix. When the windows were closed (S1), the average air temperature increased by 2.9 °C in 2050 (29.8 °C) compared to the present (26.9 °C), and by an additional 2.8 °C in 2080 (32.6 °C). Conversely, when the windows were opened (S2), the difference in average indoor air temperature was higher compared to S1. An increase of 4 °C was recorded between the present (30.3 °C) and 2050 (34.2 °C), and 3.5 °C between 2050 and 2080 (37.7 °C) (Figure 14 and Table 8). This indicates that, in this case, opening the windows had an adverse effect on cooling the church both in the present and in the future. With increased indoor temperatures under future weather conditions, mechanical cooling becomes necessary to ensure thermal comfort and preserve the structure.

San Diego (3B, warm-dry) and Santa Barbara (3C, warm-marine) were selected to represent climate zones 3B and 3C, respectively. For San Diego, when windows were closed (S1), the lowest indoor average temperature under current weather conditions was 19.7 °C, rising to 21.1 °C in 2050 and 22.5 °C in 2080 (Figure 15 and Table 8). In Santa Barbara, under the same conditions, the increase in indoor air temperature was higher, with almost no air movement occurring inside the structure (Figure 16). The temperature distribution remained similar across both locations and scenarios, although when airflow occurred indoors, the temperature difference between present and future scenarios was more pronounced in Santa Barbara compared to San Diego.

These findings suggest that natural ventilation is a viable cooling strategy in both locations under current weather conditions. In San Diego, even in future scenarios, opening windows (S2) resulted in only slight temperature increases, making it a sustainable option. However, in Santa Barbara, while natural ventilation remained effective in 2050, outdoor conditions in 2080 were more comfortable than indoors, indicating its diminishing effectiveness in this location. San Diego, therefore, maintains a more comfortable indoor environment with open windows, while Santa Barbara may require alternative strategies in the future.

In Baltimore (4A, mixed-humid), the average indoor air temperature under closed window conditions (S1) was 24.1 °C in the present, increasing to 26.4 °C in 2050 (Figure 17 and Table

8). By 2080, this value reached 28.3 °C, representing a consistent rise in temperature like in most other locations. With open windows (S2), the indoor temperature increased by about 1.8 °C from the present to 2050 and an additional 2.4 °C by 2080, reaching 30.7 °C. This indicates that natural ventilation led again to higher indoor temperatures rather than cooling, as airflow near the main door accumulates warmer air in localized zones. In this location's humid climate, open windows resulted in a 2.4 °C increase in indoor temperature under current weather conditions, allowing more heat and moisture to enter. The gap between S1 and S2 remained consistent in future scenarios, with natural ventilation becoming less effective as outdoor conditions worsen, leading to uncomfortable indoor environments by 2080.

In Albuquerque (4B, mixed-dry), the indoor air temperature distribution remained relatively uniform with closed windows (S1). The average indoor temperature was 24.0 °C in the present, but future scenarios saw the infirmary reach the highest temperature of 27.8 °C by 2080 (Figure 18 and Table 8). With open windows (S2), the average indoor temperature rose to 26.6 °C in the present, following a similar distribution trend. The chancel recorded the lowest temperature, while the infirmary remained the warmest zone. By 2050, increased airflow from the southeast caused indoor temperatures to rise by 2.9 °C compared to S1. The impact of natural ventilation on indoor air temperature distribution was most pronounced in the present and 2050, with higher air velocities creating more uniform temperature distribution throughout the structure. These results suggest that natural ventilation in Albuquerque, like Baltimore and some other locations, led to indoor warming due to outdoor heat entering the building. Although airflow improved uniformity in temperature, open windows resulted in consistently higher indoor temperatures in future scenarios, emphasizing the need for alternative cooling strategies in harsher climates.

4. Conclusions

This paper provides a comprehensive analysis of the impact of climate change on the indoor thermal environment of historic buildings, specifically focusing on the effectiveness of natural ventilation in high thermal mass colonial-era churches across various climates in the United States. A high thermal mass historic church in San Antonio, Texas, US, part of a Spanish colonial mission, served as the case study. Additionally, six other representative locations across the US, each belonging to different ASHRAE climate zones (1B, 2A, 3A, 3B, 3C, 4A, and 4B), and hosing similar Spanish colonial structures, were analyzed for their potential benefits from natural ventilation. The applicability of natural ventilation for cooling was evaluated across three weather scenarios: current conditions and projected conditions for 2050 and 2080, with future weather files generated using the morphing method. The analysis utilized dynamic energy simulation software for both energy and CFD analysis, focusing on the cooling period from May 1 to September 30. Internal loads were excluded to isolate the effects of natural ventilation and better understand its passive performance across climate zones.

The findings reveal significant variability in the effectiveness of natural ventilation, in high thermal mass structures similar to the case study, based on geographic location:

- Coastal regions such as San Diego (3B, warm-dry) and Santa Barbara (3C, warm-marine) demonstrate that natural ventilation is an effective strategy under present weather conditions. Cooler outdoor temperatures allow for window operation that enhances thermal comfort and supports sustainability by reducing reliance on mechanical cooling systems.
- Hotter climates like Phoenix (1B, very hot-dry) and San Antonio (2A, hot-humid) present major challenges. Rising outdoor temperatures result in increased indoor temperatures and relative humidity values when windows are opened, making natural ventilation ineffective both now and in future climate scenarios.
- Mixed climate zones such as Baltimore (4A, mixed-humid) and Albuquerque (4B, mixed-dry) also do not benefit from natural ventilation, especially as relative humidity levels increase.

- Across all locations and climate zones, future weather projections indicate an upward trend in both outdoor and indoor temperatures, raising concerns about the long-term viability of relying solely on natural ventilation.
- Since the simulations excluded internal heat gains, representing unoccupied conditions, the findings should not be interpreted as a blanket inefficacy of natural ventilation but rather as specific to the modeled conditions. In unoccupied periods, sealing the building may indeed be more effective, whereas the dynamics would shift under typical occupancy.

The findings underscore the importance of context when evaluating ventilation strategies for historic buildings. It emphasizes that a tailored approach is necessary, as the effectiveness of natural ventilation is highly dependent on local climatic conditions. Additionally, the study contributes to the broader discourse on climate change and building performance by addressing a gap in the literature regarding the impact of regional climatic variations on natural ventilation. Future projections indicate a clear upward trend in both outdoor and indoor temperatures across all climate zones and locations, raising concerns about the long-term viability of relying solely on natural ventilation as outdoor temperatures continue to rise. This highlights the need for innovative solutions that integrate modern climate-responsive design principles with traditional architectural practices.

In conclusion, this research serves as a valuable resource for understanding the interplay between climate change and historic building preservation in different climate zones. It calls for a proactive approach to climate adaptation, encouraging stakeholders to explore hybrid ventilation systems that combine natural and mechanical methods to optimize indoor comfort while minimizing energy consumption. Ongoing monitoring of indoor environmental conditions is essential to inform adaptive strategies for evolving climatic conditions. Ultimately, the study emphasizes the importance of collaboration among architects, conservationists, and researchers to develop sustainable practices that protect architectural heritage while ensuring the comfort and well-being of future generations. By embracing these challenges and opportunities, we can navigate the complexities of climate change and safeguard our historic buildings for years to come.

Data Availability Statement

All data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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Appendix A

Table 7 summarizes the simulated results for the average indoor air temperature, relative humidity and ventilation rates for the different ventilation scenarios, locations and years analyzed in this study during the entire cooling season. Additionally, Table 8 presents the numerical values for the average outdoor air temperature, and average indoor air temperature and ventilation rates for S1 and S2 on the representative day analyzed in Section 3.3 for the selected climate zones.

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