Title

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Sensitivity of Passive Design Strategies to Climate Change

Thermal comfort performance of natural ventilation in the future

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ABSTRACT: Observed global warming trends undermine the conventional practice of using historic weather files, such as Typical Meteorological Year (TMY), to predict building performance during the design process. In order to limit adverse impacts such as improperly sized mechanical equipment or thermal discomfort, it is important to consider how the building will perform in the future. Like all passive design strategies, natural ventilation, relies on local climate to be effective in improving building performance. This paper combines future weather files with whole building energy simulations to assess the sensitivity and feasibility of natural ventilation in providing thermal comfort in three locations, representing different climate types. The results show how building performance, as measured by thermal comfort metrics, changes over time. Natural ventilation can provide a buffer against warming climate, but only to a certain extent. Future weather files are useful for identifying where and when there is a risk that an exclusively passive design is no longer possible.

KEYWORDS: Natural Ventilation, Climate Change, Thermal Comfort, Simulation

1. INTRODUCTION

Weather is a significant predictor of building thermal performance as it relates directly to heating and cooling loads. Since weather for a given location can vary significantly from year-to-year, designers commonly use synthetic weather files, such as Typical Meteorological Year (TMY), to predict building performance. These files aggregate historic values for key weather parameters such as temperature, so that the model prediction reflects long-term performance. However, observed global warming trends undermine the validity of this practice.

The ASHRAE Handbook of Fundamentals 2013 reports increases in design day temperatures and cooling degree-days and decreases in heating degree-days over 30 years of historical weather data over all ASHRAE locations [1]. Weather files based solely on aggregating historic weather data do not capture these long-term trends, which can have significant design implications.

Future weather files can equip designers to consider the impact of climate change on building performance. These files transform existing weather files to reflect the changes predicted by global or regional climate models. Inserting the new future weather files into building performance simulations can show changes in predicted heating and cooling loads, energy consumption, thermal comfort, and other performance metrics used to quantitatively compare design options.

Passive design strategies, by definition, take advantage of the local climate to reduce or eliminate the need for auxiliary heating and/or cooling in a building. Climatic changes over the lifetime of the building can thereby influence the efficacy of passive design strategies and result in improperly sized ancillary mechanical equipment and, if unresolved, large numbers of discomfort hours.

This paper focuses on natural ventilation, which relies on pressure differences to move fresh air through openings, such as windows, through the building. Pressure differences can arise from wind or the difference between interior and exterior temperature and relative humidity. This paper uses building energy simulation to assess natural ventilation effectiveness in a specific building.

While natural ventilation offers a number of benefits, we concentrate on its potential as a passive cooling strategy in lieu of any mechanical cooling. We evaluate occupant comfort metrics with and without natural ventilation using present and future weather files. The goal is inform designers of where and when this strategy will remain effective over the lifetime of the building, even as the climate changes.

2. METHODOLOGY

We set up a parametric study to consider the impact of natural ventilation, climate change scenario, and future year on building performance for three locations in the continental United States, represented by Miami, FL, Boston, MA, and San Francisco, CA. The Köppen–Geiger system classifies these cities as tropical, continental, and temperate and the International Energy Conservation Code (IECC) classifies them as climate zones 1A, 5A, and 3C respectively [2-3].

We chose to model a residential building because passive design strategies are generally most effective for buildings with low internal heat gains. The Pacific Northwest National Laboratory's (PNNL) residential single-family EnergyPlus prototype model with a slab foundation and gas furnace heating serves as the base building for each climate [4]. Table 1 summarizes the prescriptive code requirements from Table R402.1.3 in IECC 2012 and represents physical characteristics of the PNNL model in each climate [4]. The PNNL model contains two thermal zones: 1) a living unit that spans two-stories and is 223 m^2 and 2) an unconditioned attic that is 111 m^2. The living unit contains a single window per floor and per elevation. On the north and south elevations, the window-to-wall ratio is 13% while that on the east and west elevations is 15%.

Table 1: IECC 2012 prescriptive code requirements for building envelope by location

		U-Factor (Btu/hr-sf-°F)			
Location	Fenestration SHGC	Fenestration	Ceiling	Frame Wall	Floor
Miami	0.25	NR[1]	0.035	0.082	0.064
Boston	NR[2]	0.32	0.026	0.026	0.033
San Francisco	0.25	0.35	0.030	0.057	0.047

NR: No requirement per IECC 2012 prescriptive code

[1] Miami fenestration U-Factor modelled as 0.50

[2] Boston fenestration SHGC modelled as 0.39

We modified the PNNL energy models to add natural ventilation, turn off mechanical cooling, and adjust the heating set point to 18°C in accordance with the lower limit of the adaptive thermal comfort model. For each iteration, we ran an annual simulation in EnergyPlus v. 8.9.0 to calculate the living unit's hourly mean air temperature (MAT), mean radiant temperature (MRT), and ventilation air change rate [5]. From the simulation outputs and weather file, we calculated thermal comfort performance.

The subsequent sections detail how we modelled future weather, natural ventilation, and thermal comfort for this study.

2.1 Future Weather

For a given location, we compared the results using the TMY3 weather file and a future weather file from WeatherShift^{TM} v. 2.0 [6]. We bookended our analysis with an upper and lower bound for the emission scenario and the warming percentile.

Representative Concentration Pathways (RCP) is a framework adapted by the IPCC to express four trajectories of future GHG emissions, each with different socio-economic assumptions. The RCP number refers to radiative forcing in W/m^2 in the year 2100, with lower numbers representing a smaller increase in greenhouse gas emissions. This research considers RCP 4.5 as a lower bound and RCP 8.5 as an upper bound for greenhouse gas emissions, which are the two options available from WeatherShift. Warming percentile captures uncertainty in how GHG emissions affect meteorological systems and the resulting weather parameter prediction. This study considers the 10th and 95th percentiles as a lower and upper bound respectively for the warming percentile, which are the minimum and maximum warming percentile available from WeatherShift. The combination of RCP 4.5 and 10th percentile warming forms a lower bound and RCP 8.5 and 95th percentile warming forms an upper bound for future weather due to climate change. The most recent generation of TMY weather files, TMY3, uses historical data from 1991-2005, and represents the present. We evaluate the results for three future time-periods terminating in 2045, 2075, and 2099.

2.2 Natural Ventilation

We modelled natural ventilation using simplified ventilation calculations in EnergyPlus's Wind and Stack Open Area model, in which we only considered wind-driven natural ventilation. EnergyPlus calculates the ventilation rate according to Equation (1).

$$\boldsymbol{Q_w = C_w A_{opening} F_{schedule} V} \tag{1}$$

Where Q_w is the volumetric air flow rate driven by wind (m^3/s); C_w is the opening effectiveness calculated from the window orientation and wind direction and defined as 0.3 for diagonal winds and 0.55 for perpendicular winds (EnergyPlus interpolates values for angles in between); $A_{opening}$ is the opening area (m^2); and $F_{schedule}$ is the opening area fraction, which is set by the occupancy schedule and temperature controls; V is local wind speed (m/s).

$A_{opening}$ is 50% of the total window area for the case with natural ventilation, and 0% for the case without natural ventilation. $F_{schedule}$ is set from occupancy and temperature controls, both of which must be satisfied for the window to open. The PNNL base energy model defines hourly fractional occupancy per day. We considered hours with at least one person in the thermal zone as occupied.

For temperature controls related to window opening, we set the minimum interior and exterior temperature to 18°C based on the minimum comfortable temperature in the adaptive comfort model. We set the minimum temperature difference between interior and exterior temperature as 3°C based on CIBSE AM 10 Natural Ventilation in Non-Domestic Buildings, which states that the cooling effect is very small for interior-exterior temperature differences less than 3 K (i.e. 3°C) even for high ventilation rates [7]. Since there is no mechanical cooling available, we set the maximum interior and exterior temperature to the EnergyPlus maximum for this parameter. To summarize, $F_{schedule}$ is 1 as long as the zone is occupied, the interior and exterior temperatures are both greater than 18°C, and the interior temperature is at least 3°C warmer than the exterior temperature. Otherwise $F_{schedule}$ is 0. Our assumptions for $F_{schedule}$ are appropriate for daytime comfort cooling.

2.3 Thermal Comfort

Since there is no energy use related to mechanical cooling, we evaluated building performance based on design objectives related to thermal comfort: hours with 80% acceptability and exceedance metrics.

Section 5.4 of ASHRAE Standard 55-2017 Thermal Environmental Conditions for Human Occupancy defines criteria for 80% acceptability [8]. We calculated the prevailing mean outdoor air temperature, T_{pmo}, as the 30-day running average of the exterior dry bulb temperature (DBT) from the weather file. We calculated operative temperature, T_o, as the mean of the MAT and MRT, which is valid for air velocities less than 0.2 m/s [8]. We used Equation (2) to define temperature thresholds for 80% acceptability [9].

$$T_{comfort} = 18.9 + 0.255 \times T_{pmo} \qquad (2)$$

Where $T_{comfort}$ is the optimum comfort temperature (°C) and T_{pmo} is the prevailing mean outdoor temperature (°C). The design criteria for 80% acceptability is T_o within $\pm$ 3.5°C of $T_{comfort}$.

We also calculated exceedance, but considered only warm discomfort since we are assessing the effects of natural ventilation as a cooling strategy. In this regard, exceedance represents the percent of occupied hours when the operative temperature is warmer than the 80% acceptability threshold (i.e. 20% discomfort). Equation (3) describes exceedance, E, mathematically [10].

$$E = \sum_{i=0}^{\text{all hours}} \begin{array}{l} n_i \text{ if discomfort } > 20\% \\ 0, \text{ if discomfort } \leq 20\% \end{array} \Bigg/ \sum_{i=0}^{\text{all hours}} n_i \qquad (3)$$

Where n_i is the number of occupants in hour i, and discomfort is the percent of people who are dissatisfied and is set to 20%, which complements the definition of 80% acceptability. European standard EN15251 recommends that no more than 5% of occupied hours fall outside of acceptable values for indoor environmental conditions, which serves as a rule of thumb for assessing exceedance [11].

3. RESULTS AND DISCUSSION

The following subsections describe results from the parametric study.

3.1 Future Weather

Before analysing changes in building performance, we compared weather parameters pertinent to natural ventilation in the present for each location, as well as how those weather parameters changed in the future based on WeatherShift's morphing methodology. The climatic variables most relevant to natural ventilation performance are the exterior dry bulb temperature (DBT), relative humidity (RH), wind speed, and wind direction.

Figure 1 shows the daily average exterior DBT in the present and the monthly change in exterior DBT relative to the present in 2099 for each study location. Looking first at present conditions, unsurprisingly from the Köppen–Geiger system classification, Miami is overall the warmest, Boston has extremely cold winters and hot summers, and San Francisco has mild temperatures year round.

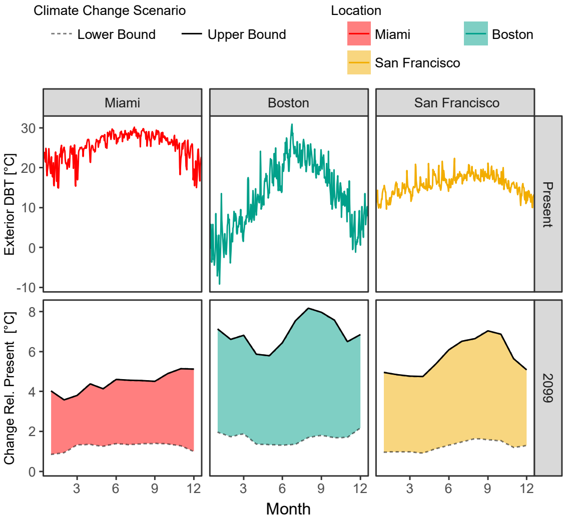

Figure 1: present day exterior drybulb temperature (DBT) and change in exterior DBT relative to the present in 2099 for each location.

Predictions for the future suggest that all study locations experience a net warming, even for the lower bound climate change scenario. In Miami, the temperature increase is relatively constant throughout the year. In Boston and San Francisco, the temperature increase in the upper bound climate change scenario varies seasonally, with the largest increases occurring in the late summer and early fall. It is interesting to note that even though San Francisco is a relatively mild climate in comparison to Boston, the ΔDBT increases predicted for the future are somewhat comparable for the summer, while Boston will experience more warming in the winter. We found that monthly average RH and wind speed did not change significantly and wind direction did not change under WeatherShift's morphing methodology. Therefore, changes in exterior DBT drive the changes in building performance observed in subsequent sections.

3.2 Natural Ventilation

With regard to window opening, temperatures acts as both a driving force and a response variable. Changes in exterior temperature affect when windows can open, but the act of opening a window also changes the interior temperature, which in turn affects the interior-exterior temperature difference, and may eventually lead to windows closing.

In Figure 2, the upper graphs show the total number of hours windows were open per month in the present, and the lower graphs show the change in the number of "open" hours relative to the present in 2099 for each study location. The ventilation air change rate serves as a proxy simulation output to measure the window controls described in Section 2.2. We considered windows open when the living unit ventilation air change rate was greater than 0.25 air changes per hour, which is the baseline infiltration rate.

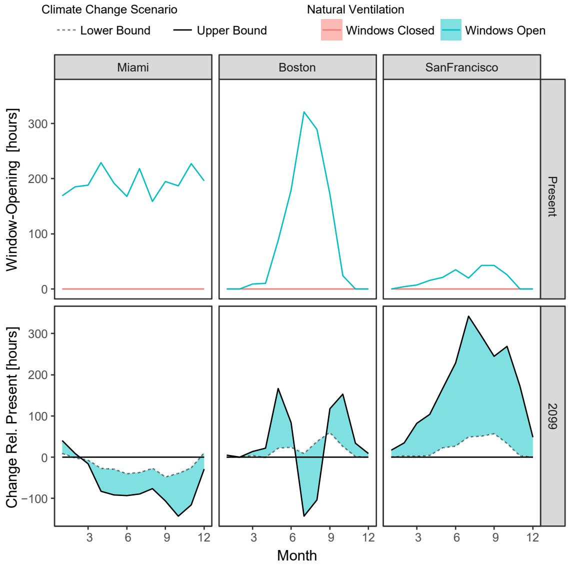

Figure 2: Monthly present day window-opening hours and change in window-opening hours relative to the present in 2099 for each location.

In the present, windows open for about 200 hours per month year-round in Miami. In Boston, windows open for as much as 300 hours in the summer months, but substantially less at other times in the year. In San Francisco, windows open less than that in the other two locations, only a maximum of 50 hours per month, due to this location's limited need for cooling.

In the future, in Miami, windows open for less time throughout the year than in the present under both climate scenarios. A notable exception is January, where window-opening hours increase. In Boston, in the spring and fall, window-opening hours increase relative to the present under both climate change scenarios. The increase in exterior DBT in the spring and fall results in more hours where the exterior DBT is greater 18°C, the minimum exterior temperature for windows to open in our controls. In the summer, window-opening hours increase in the lower bound climate change scenario, but decrease under the upper bound climate change scenario. Large increases in exterior DBT as predicted by the upper bound climate change scenario for the summer, make it harder to satisfy the condition of a minimum interior-exterior temperature difference of 3°C. In San Francisco, window-opening hours increase relative to the present throughout the year under both climate change scenarios. In terms of magnitude, the largest change in window-opening hours occurs in San Francisco and the least in Miami.

3.3 Thermal Comfort

Figure 3 shows the number of hours per year within 80% acceptability in all three locations with and without natural ventilation, with the x-axis representing time between the present and 2099.

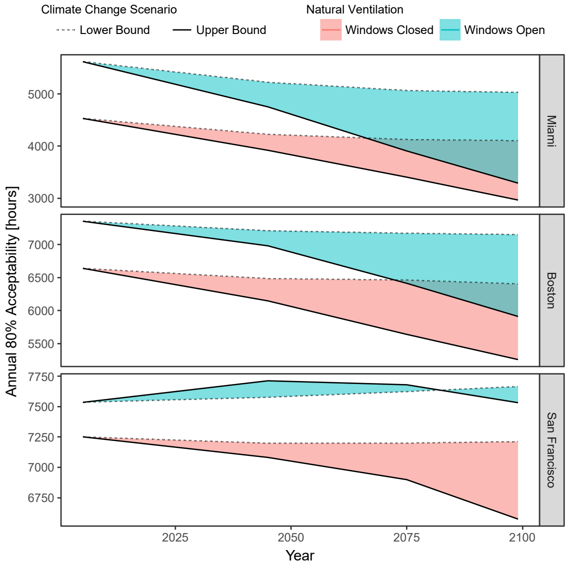

Figure 3: Annual 80% acceptability hours over time for the case with and without natural ventilation in each location.

In all three locations, natural ventilation increases the number of hours within 80% acceptability relative to the case without natural ventilation (and no mechanical cooling), regardless of year. In the future, without natural ventilation, the number of thermally comfortable hours decreases over time in all three locations. With natural ventilation, the number of thermally comfortable hours decreases over time in Miami and Boston, where the outdoor climate is getting much warmer than the upper limit of the adaptive comfort zone, but stays relatively constant in temperate San Francisco.

While Figure 3 shows the total number of thermally acceptable hours, it does not tell us anything about the magnitude of the deviations from comfort. Figure 4 uses a density plot to show the distribution of the difference between T_o and $T_{comfort}$ for the present and 2099 under the lower and upper bound climate change scenario. A temperature difference of 0 on the x-axis means that T_o is the ideal comfort temperature from Equation (2). The design criteria for 80% acceptability allows T_o to be $\pm$ 3.5°C of $T_{comfort}$, marked as dashed lines in Figure 4. Therefore, the part of the curve falling within the dashed lines represents conditions of 80% acceptability.

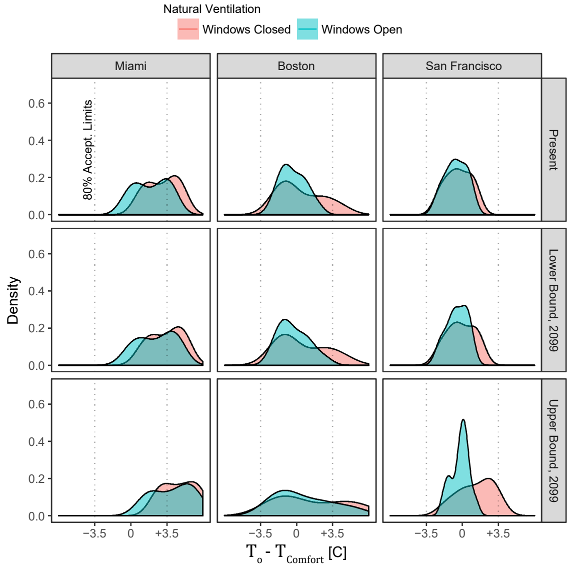

Figure 4: Distribution of $T_o - T_{comfort}$, in each location for present and lower and upper bound climate chance scenarios in 2099. Limits for 80% acceptability included for reference.

Looking first at the upper graphs for the present, in Miami, the distribution's median is greater than 0 for both the case with and without natural ventilation, meaning that T_o tends to be warmer than $T_{comfort}$ most of the time, but in Boston and San Francisco, the distribution is centred closer to 0. In the present in San Francisco the case with and without natural ventilation is nearly identical because as we saw in Figure 2, windows are open for relatively few hours in comparison to Miami and Boston. For all locations, in the case without natural ventilation T_o is warmer, i.e. higher values for $T_o - T_{comfort}$.

In all three locations, the distribution in 2099 under the lower bound climate change scenario is similar to that of the present. From Figure 1, in the lower bound climate change scenario, the monthly average temperature increase is 1-2°C. The adaptive comfort model, $T_{comfort}$ is a function of the prevailing outdoor mean temperature to account for behaviour adjustments by occupants, such as changing expectation. The distribution being similar in the present and in 2099 under the lower bound climate change scenario suggests that occupants can adjust to this level of warming, allowing the building to maintain a similar level of thermal comfort in the future. The ability to apply an adaptive comfort model can therefore contribute to the design's overall resiliency.

In 2099 at the upper bound climate change scenario, the distribution's median for Miami increases relative to the present, i.e. the peaks shift to the right. In addition, there is less of a distinction between the case with and without natural ventilation. From Figure 2, we see that in Miami windows are open for fewer hours in the upper bound climate change scenario, so it follows that the two cases will have similar operative temperatures.

In 2099 in Boston, the median of the distribution is similar to that in the present, but the variance increases, i.e. the peaks flatten. This is likely because, from Figure 2, in Boston windows are open more in the spring and fall, but less in the summer. Additionally from Figure 1, we see that in the upper bound climate change scenario, the temperature increase is greatest in the summer, which results in a large increase in the number of overheated hours, or when $T_o - T_{comfort}$ is greater than +3.5°C.

In San Francisco in the future, the case with natural ventilation has a lower variance than that of the present, i.e. the peak is taller and the spread is narrower. In the case without natural ventilation, the distribution biases towards higher temperature differences, but is still mostly within 80% acceptability.

We can quantify the percentage of time that temperatures fall on the warm side of the 80% acceptability zone shown in Figure 4 by using the exceedance metric. Figure 5 shows the exceedance per year over time in all three locations with and without natural ventilation. We include the 5% threshold from EN15251 as a dashed line for reference.

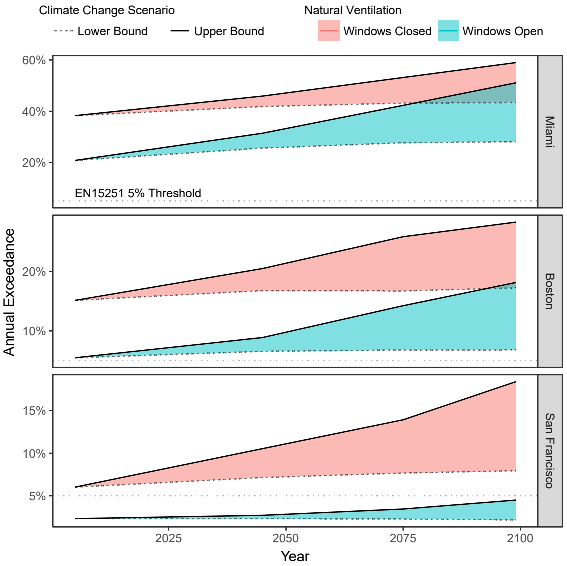

Figure 5: Annual exceedance over time for the case with and without natural ventilation in each location. Exceedance threshold of 5% from EN15251 included for reference.

In all three locations, exceedance increases over time, and is lower for the case with natural ventilation. As observed with 80% acceptability in Miami and Boston, the difference between the case with and without natural ventilation shrinks over time. Larger increases in exterior DBT, particularly in the summer, result in fewer hours that windows can open, and so the case with and without natural ventilation approach each other. In San Francisco, natural ventilation can keep exceedance below the 5%

threshold through 2099, even for the upper bound climate chance scenario. In Boston, the lower bound climate change scenario has an annual exceedance of 5-7%, which is close to but does not satisfy EN15251.

4. CONCLUSIONS

In this paper, we used future weather files to compare thermal comfort performance over time with and without natural ventilation in three locations representing different climates. The results inform where and when natural ventilation will continue to be a viable strategy for passive cooling as the climate warms.

For a tropical climate, like Miami, for the simplified building used in these simulations, natural ventilation cannot exclusively provide thermal comfort either in the present or in the future. While performance does improve with natural ventilation, this benefit shrinks as the climate warms and there are fewer hours when opening windows provides a cooling advantage. Even with a more climatic responsive building than the PNNL model, this future trend is likely to still be relevant.

In a continental climate, like Boston, using natural ventilation exclusively for cooling is nearly possible in the lower bound climate change scenario, and maybe entirely possible in combination with other passive design strategies. However, in the upper bound climate change scenario, natural ventilation alone cannot achieve thermal comfort due to summertime overheating. In this scenario, while windows can open more frequently in the spring and fall, reduced opening hours in the summer offsets the overall passive cooling benefit.

In a temperate climate, like San Francisco, it is possible to cool exclusively with natural ventilation. As the climate warms in the future, increased window-opening hours provides sufficient cooling to maintain and even improve thermal comfort relative to the present.

From this analysis, we find that using future rather than historical weather files may be less informative for natural ventilation design in a tropical climate like Miami, where it’s already a challenge to rely entirely on this passive strategy (again noting that this simulation was based on a fairly generic model and these results might change when simulating a more sophisticated design) present. However, future weather files are still important to ensure adequately sized mechanical cooling systems, given that the thermal comfort metrics clearly changed moving forward.

In a continental climate like Boston, natural ventilation design is very effective both in the present and in the lower bound climate change scenario. However, in the upper bound climate change scenario, entirely natural ventilation design is no longer sufficient for maintaining comfort. Further refinement of boundary conditions for future weather scenarios can help manage risk in terms of thermal comfort performance.

In a temperate climate like San Francisco, future weather files are informative in showing that natural ventilation can still achieve thermal comfort through 2099 even under the upper bound climate change scenario.

Finally, even if natural ventilation is not exclusively sufficient now or in the future for a particular climate, it still contributes towards improving thermal comfort, and thereby offsets the mechanical cooling load needed for acceptable building performance. Another interesting takeaway from this work is that due to adaptive comfort, occupants can adjust to limited temperature increases, such as those predicted by the lower bound climate change scenario, which contributes towards the building’s overall resiliency.

Further work will expand to more climates, building types, and passive strategies and evaluate the sensitivity of these results to different window opening controls algorithms. In addition, we will consider weighting exceedance not only by occupancy, but also by the magnitude of overheating.

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