Resilience and Future Climate Data for Modeling and Design

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ABSTRACT

Despite daily reports of record-breaking heat, rainfall, and storm events, the current environmental design process relies on weather files that can be more than thirty years old and are created to represent historic median weather conditions for a given location. In the face of a changing climate, past weather data alone are insufficient for the buildings being designed now to be standing for the next 50 to 100 years. This paper will describe a methodology for creating and using future climate weather files for architecture and engineering modeling and decision making, developed by a team of climate scientists and design and engineering professionals. These future weather files will be based on historical medians from a meteorological perspective and incorporate fine-scaled regional climate projections for use at the local level. Additionally, preliminary results from an energy and carbon modeling study of various building typologies will reveal the potential impacts of future climate on code-baseline and high-performing buildings. The process for integrating this analysis into the design process will become part of Minnesota's B3 Guidelines, a comprehensive sustainable and resilient design program required for state-funded design and construction projects. The paper will also propose considerations for rain and stormwater management modeling based on consideration of future weather files. The methodology and results described can serve as a model for similar work around the country to build capacity for future-climate informed design and increase the resilience of buildings and communities.

Background

Climate Forward?

Seeing the clear potential for architecture and engineering professionals to use future-looking climate files to inform design, a team from Minneapolis architecture firm HGA partnered with the University of Minnesota's Climate Adaptation Partnership (MCAP) to conduct a survey and produce a report on the state of future climate projection data in the architecture and engineering industry. The study (Laxo et al. 2023) consisted of a literature review to establish a baseline of knowledge, an online survey responded to by 144 professionals from the US, Canada, and United Kingdom, and four focus groups with intermediate and advanced climate projection data users. Four key points arose from the study: that sustainable design services do not generally include designing for climate change adaptation, few firms are regularly using projections to inform design decisions, there are barriers to using climate projection data which include lack of client requests, data gaps, and lack of expertise, and finally that guidance in the form of codes, standards, and training for professionals, from professionals is needed. The study also identified that a broad variety of professionals are using weather files in many different software platforms, all being driven by one dataset, as seen in Figure 1. (Laxo et al. 2023) These findings led to the current work being done by HGA, MCAP, and the Center for Sustainable Building Research (CSBR) to develop scientifically sound future climate weather files and develop a process for incorporating these files and considerations into standard practice.

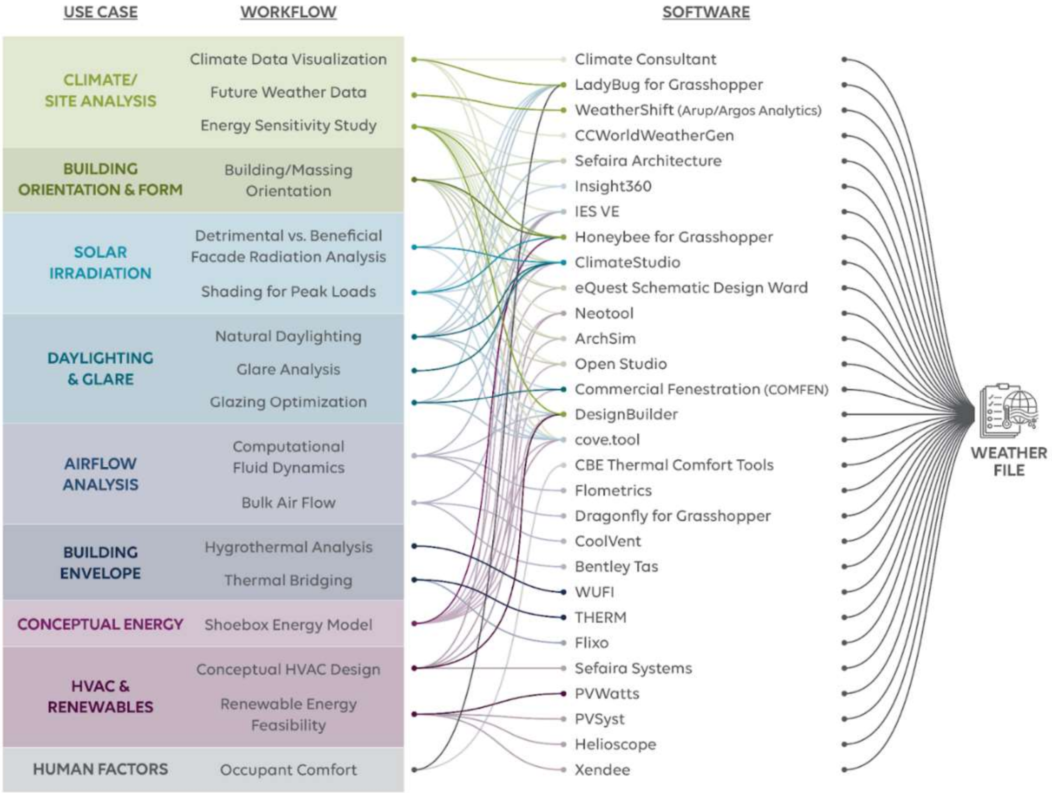


Figure 1. Diagram of Applications and Software Driven by Weather File

Previous Work

The Center for Sustainable Building Research has been actively working in resilience for years, including previous studies with future climate projection data. The partnership with MCAP and HGA has revealed gaps in previous research and methodologies which are being addressed in current work and are reflective of broad gaps in the scientific rigor of past and present use of weather and future climate data in design. The process and outcomes established by this research will be used to update previous work on resilience assessment tools and guidelines and become fully integrated into the State of Minnesota's B3 Guidelines.

Prior to the summer of 2023, the B3 Guidelines were specifically mandated to promote energy efficiency and had no legislative authority to require resilience measures. In the summer of 2023, the authorizing legislation was updated to include resilience with sustainability. Funding was provided for this effort described in this paper to integrate future climate projection data into the Guidelines. This support represents the commitment to protecting the investment of public buildings from the State of Minnesota.

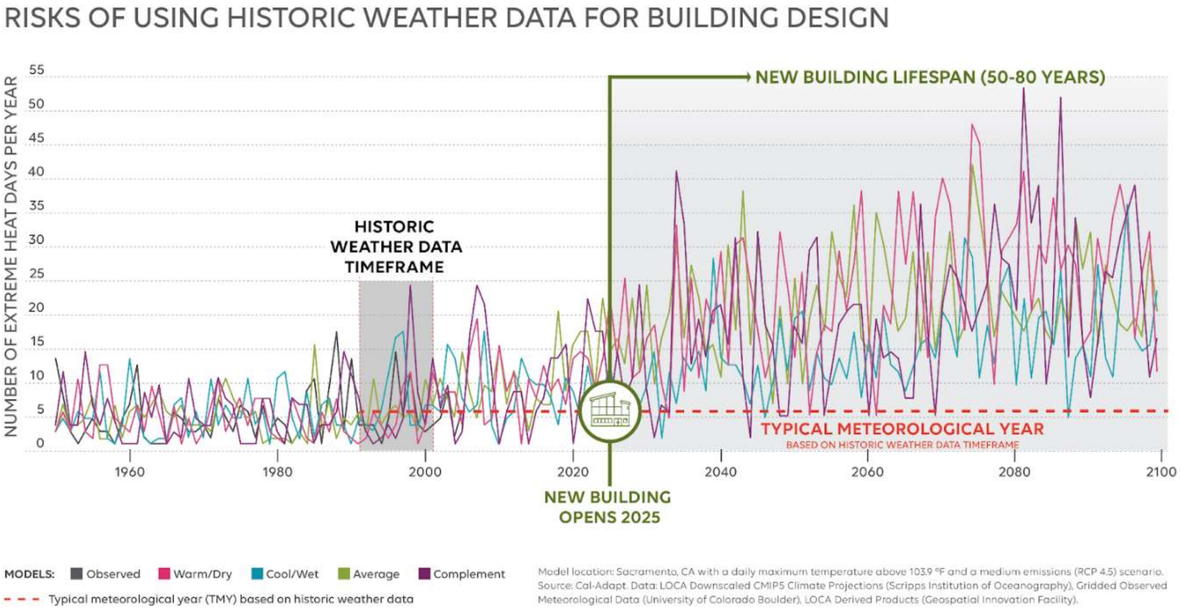
Parallel Efforts

This work builds on efforts undertaken in California, Cal-Adapt, a web-based resource for exploring climate change research. Cal-Adapt provides information for stakeholders based on global climate models which have been ’downscaled’ through a combination of underlying physics, local geographic features, and/or statistical relationships between historic larger scale and local climatic observations (Thomas, 2018). To date, Cal-Adapt has primarily been used by utilities and governments to make large scale (city, region, etc.) decisions by providing data for California, Nevada, and parts of Oregon, Arizona, and Mexico.

A similar downscaling effort was completed for Minnesota in 2022 with an online interactive tool launched in 2023, Minnesota CliMAT (Liess, 2023). The work described in this paper is the next step in operationalizing climate projection data by making it usable and relevant to designers and engineers working at the building and site scale.

Weather File Creation

Since the 1980s, designers and engineers have been using only historical weather data to inform design decisions for buildings, mechanical systems, and renewable energy potential. A common type of weather data file for computation is the Typical Meteorological Year (TMY) format. This file type includes hourly values for solar radiation and meteorological elements in a specific location for one year, which are generated from a data bank of historic measured data that includes at least 12 years ’worth of data. TMY files are designed to provide annual averages that are consistent with long-term historic averages for the specific location. The first set of TMY files use data collected between 1948 and 1980, the second edition, called TMY2, rely on data from 1961 to 1990, and the third and most recent edition, TMY3, uses data collected from 1976 to 2005 when available, and data from 1991-2005 for all other locations. (Wilcox and Marion, 2008). This type of file has been useful for environmentally responsive design in the past, but presents challenges when trying to identify the challenges of the changing climate into the future. Figure 2 illustrates an example of this challenge, showing the number of extreme heat days for a variety of future climate emissions scenarios with the darker grey box showing the timeframe data is collected for TMY files, and the lighter grey box showing the future time frame and variability possible for the lifespan of a new building (Laxo et al. 2023). Files designed to represent past averages alone are no longer appropriate for determining future climatic extremes. Additionally, the time period and data set used for TMY file creation is considered too narrow. Climate science professionals recommend testing against a full climatology (30-years or more, as defined by the National Oceanic and Atmospheric Administration) and ideally the most recent thirty years. This insight led to the development of an updated version of a TMY file, so called the Typical Historic Year.



RISKS OF USING HISTORIC WEATHER DATA FOR BUILDING DESIGN

Model location: Sacramento, CA with a daily maximum temperature above 103.9 °F and a medium emissions (RCP 4.5) scenario. Source: Cal-Adapt. Data: LOCA Downscaled CMIP5 Climate Projections (Scripps Institution of Oceanography), Gridded Observed Meteorological Data (University of Colorado Boulder), LOCA Derived Products (Geospatial Innovation Facility).

Figure 2. Timeline of Weather File Data as Related to New Building Lifespan

Typical Historic Year

A Typical Historic Year file was created first as a basis for the application of transformations derived from high-resolution (4 km) global climate projection models. This file is comprised of historic observed data from 12 months. Table 1 shows the data points included in existing TMY files, which are compiled into a spreadsheet format that is used to generate the .tmy or .epw files that are loaded into energy simulation programs. These data points were considered when identifying the historic months included in the Typical Historic Year, described below.

Table 1. Typical Historic Year File Data Points

Data Point	Unit
Dry Bulb Temperature	°C/ °F
Dew Point Temperature	°C/ °F
Relative Humidity	Percentage
Atmospheric Pressure	Pascals
Horizontal Infrared Radiation Intensity from Sky	Watt-hours / square meter
Direct Normal Radiation	Watts / square meter

Diffuse Horizontal Radiation	Watts / square meter
Wind Direction	Degrees from north
Wind Speed	Meters / second
Snow Depth	Centimeters
Liquid Precipitation Depth	Millimeters

The resulting file includes months from the years 1995 to 2014, as described in Table 2, and all data is from the Minneapolis / Saint Paul (MSP) Airport weather station (center column) and historical simulations (right column). Specific months were selected in which weather data in various categories, as shown in Table 1, show the smallest deviation from historic monthly means and multi-model means, respectively. This process is similar to the process used for the creation of the original TMY files (NREL, 2008), but with a larger and more recent data window.

Table 2. Representative Months used for MSP Typical Historic Year Files

Month	Data Year	Data Year Model
January	1996	2011 CESM2
February	2000	2003 CMCC-ESM2
March	2013	2014 IPSL-CM6A-LR
April	2003	2009 BCC-CSM2-MR
May	2004	1998 IPSL-CM6A-LR
June	2014	2005 CESM2
July	2005	2011 MIROC-ES2L
August	1997	2013 CNRM-ESM2-1
September	2006	2011 IPSL-CM6A-LR
October	1995	1996 MIROC-ES2L
November	1997	2003 CNRM-ESM2-1
December	2011	1995 BCC-CSM2-MR

After creating the Typical Historic Year files for MSP airport, both the version from observations and the version from the 120-years of the six 20-year historical model simulations are evaluated against each other and then bias correction methods are applied to the model simulations as needed. However, it is important for energy modeling that all data in the TMY files are physically consistent with one another, so a more thorough bias correction is applied to the results of the energy modeling, most likely as offsets, also called "linear scaling" (Shrestha et al., 2017; Teutschbein and Seibert, 2012) so that the difference between the results with observed weather and the results with modeled weather is added to the results with projected future weather.

Future Scenarios and File Transformation

Using regional climate projections and the Typical Historic Year file, future files representing various future time periods and possible emissions scenarios are being developed. The files include: Intermediate Emissions Scenario (SSP245[1]) for the time periods 2040-2059, 2060-2079, and 2080-2099 and Very High Emissions Scenario (SSP585) for the same time periods. The resulting six files provide a range of possibilities for the future climate that can be used in modeling programs to test how the design decisions being made now will perform under possible future conditions and allow designers to anticipate the future needs of buildings.

These future-representative weather files were created through the same process as the Typical Historic Year, but with data sets derived from projection models rather than historic data. Six models of each 20-year period in each emissions scenario are linked to create 120 years ’worth of projection data, which are then analyzed to identify the specific months that represent the mean conditions of that future period. These future months are then combined to create a single year that represents the time period and the scenario in the TMY file format.

Energy Modeling

Quality Control and Assurance

The files created via the process described above were tested in climate data visualization software including an Excel-based psychrometric calculations tool and building energy modeling software before moving into the modeling phase of the project. Climate data points evaluated include design dry bulb temperature and mean coincident wet bulb temperature from the software above, and cooling degree days and heating degree days within the energy model. Building energy simulation data points include design heating and cooling loads, unmet heating and cooling hours, the building Energy Use Intensity, design airflow, and annual utility cost. Typical Historic Year files will be created for two additional locations in Minnesota and compared against the available TMY3 data for those locations to confirm any bias corrections that were applied to the MSP file, and to inform bias corrections on the projected future weather data.

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[1] SSP: Shared Socioeconomic Pathway, an update to the previously used Representative Concentration Pathway (RCP) that provides economic and social considerations for emissions scenarios.

Sample Buildings

Project partners at Wildan utilized their cloud-based Net Energy Optimizer® tool to automate energy modeling runs, allowing the exploration of the effects of future climate on a wide variety of building types and sizes. A summary of these buildings and their basic attributes can be found in Table 3. The buildings were selected to represent a variety of load profiles ranging from internal load dominated to external load dominated. The buildings also reflect the types of projects that typically use the Minnesota B3 Guidelines, to ensure that valuable program guidance can be developed with this effort.

Table 3. Prototype Buildings for Energy Modeling

Building Type	Building Size (ft2)	Number of Floors	Aspect Ratio[2]
Small Office	10,000	1	1.5
Medium Office	150,000	3	1.5
Large Office	500,000	10	1.5
Stand-alone Retail	25,000	1	1.3
Primary School	74,000	1	E shape
Secondary School	211,000	2	E Shape
Outpatient Healthcare	41,000	1	1.4
Hospital	240,000	5	1.3
Large Hotel	122,000	6	5.1
Warehouse (non-refrigerated)	52,000	1	2.2
Low-Rise Apartment	6,000	2	2.7
Mid-Rise Apartment	33,740	4	2.7
High-Rise Apartment	100,000	12	2.7
Community Rec Center	45,000	2	1.0
Laboratory	35,000	1	1.5

2. Aspect ratio refers to the overall length in east-west direction divided by overall length in north-south direction.

Baseline

To establish performance targets for B3 buildings that exceed local requirements, the performance of a baseline was defined. An energy code-based version of each building listed above was simulated using the projected future weather files for each time period and emissions scenario. These buildings represent the least energy efficient buildings that could legally be built in Minnesota in 2024. For all buildings except the low-rise residential, the code baseline is ASHRAE 90.1-2019, with prescriptive values for ASHRAE Climate Zone 6. The low-rise residential building baseline is the 2020 Minnesota Residential Code. The performance of these buildings is summarized below, in the Modeled Results section.

High Performance

To test our current ideals of energy performance against projected future climate, several iterations of the baseline buildings were modified to test individually. First, a high-performance envelope version of each building was developed to test the performance of a more insulated envelope while maintaining code baseline HVAC performance. Envelope insulation levels were determined to match the performance that would be required for PHIUS certification. Next, multiple high performance HVAC systems were modeled with baseline envelope values to test the performance of high-efficiency mechanical systems while maintaining code baseline envelope performance. The mechanical systems assessed include air-source and ground-source heat pumps and electric resistance with VRF and heat recovery. Finally, a version of each building with combined attributes of high-performance envelope and mechanical designs was created and modeled with all the projected future climate timeframes and emissions scenarios.

Modeled Results

After creation and initial testing of the generated climate file was complete, the future-looking weather file representing the Intermediate Emissions Scenario, SSP245, for the time period 2080-2099 for the MSP airport location was used in common energy modeling programs to assess possible impacts on building performance for this climate scenario.

Changes to Weather

Initial analysis of the future weather file included comparing the temperature and precipitation data to historic weather conditions. This analysis found that in both cases, the extremes (heat/cold and dry/wet) are moving outward, while the average temperature is rising and the average moisture is falling. For the specific location and emissions scenario, the minimum temperature is 7°F lower than the minimum present in the historic weather file at -31°F and -24°F respectively. The future scenario maximum temperature is 19°F higher than the historic scenario at 118°F and 99°F respectively. These expanded extreme temperatures will have an impact on the sizing of mechanical systems and the performance of building envelopes.

Mechanical Performance

In addition to the bulk-modeling of prototype buildings described above, the team saw an opportunity to evaluate the impacts of a future-looking climate file on a recently completed project that had undergone energy modeling in the design process. The existing historic weather file in the energy model was replaced with the SSP245 2080-2099 file, with no other modifications to the building or energy model made. Table 4 shows the design heating and cooling loads and the unmet heating and cooling hours for the test building when simulated under the currently available historic weather file and the future climate file. While changes to the heating load and unmet hours are relatively small, the increase in cooling load and unmet hours is significant. This confirms the sizing implications of future weather, and is a clear example of the impact of design decisions made now have on the performance of the building in the future.

Table 4. Changes to Design Heating and Cooling Loads, Unmet Hours

Model Outputs	Design Heating Load (kBtu)	Design Cooling Load (tons)	Unmet Heating Hours	Unmet Cooling Hours
Current Historical TMY3, MSP Airport	2917	125	777	752
Projected TMY3 SSP245 2080-2099, MSP Airport	3072	145	647	2957
Percent Change	5%	16%	-17%	293%

Baseline mechanical systems were identified for each prototype building, and performance of each was modeled with the SSP245 2080-2099 file to assess changes in sizing and ventilation rates required. Envelope efficiency was not changed for these models. Figure 3 shows the design heating load change for each building type, Figure 4 shows the design cooling load change, and Figure 5 shows the design airflow volume in CFM (cubic feet/minute). For nearly all building types, design heating loads are increased in the future climate scenario, and while a few building types show an decrease in cooling loads, the majority show an increase. All building types require an increase in air volume to meet the loads in a future climate. The increased ventilation requirements are particularly notable because increasing airflow without increasing duct capacity can create friction and noise with detrimental effects on efficiency. Ducts have a lifespan of around 30 years, but generally cannot be replaced with larger ductwork due to the space constraints of an existing building.

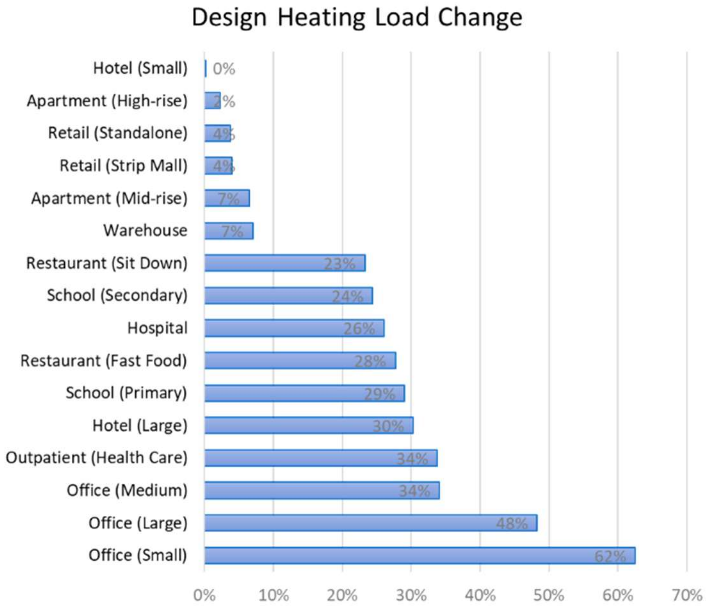

Figure 3. Percent change in heating load in future climate

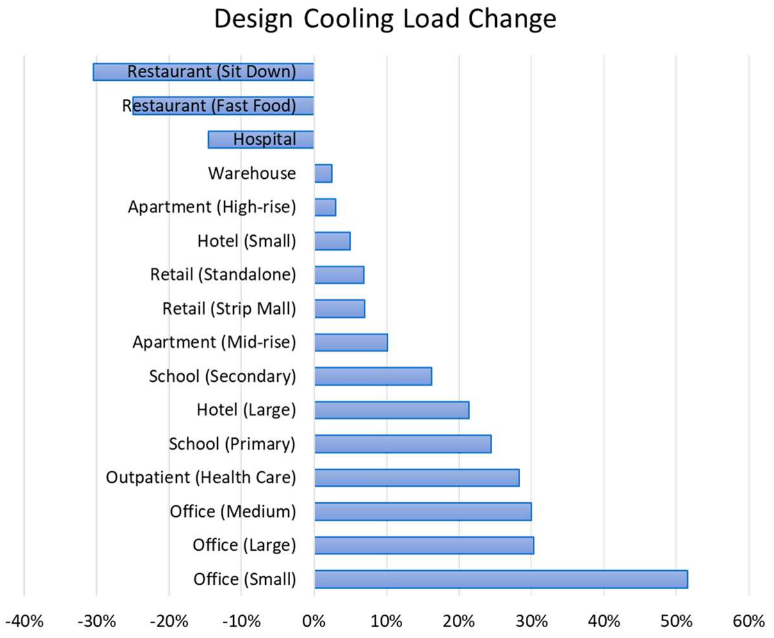

Figure 4. Percent change in cooling load in future climate

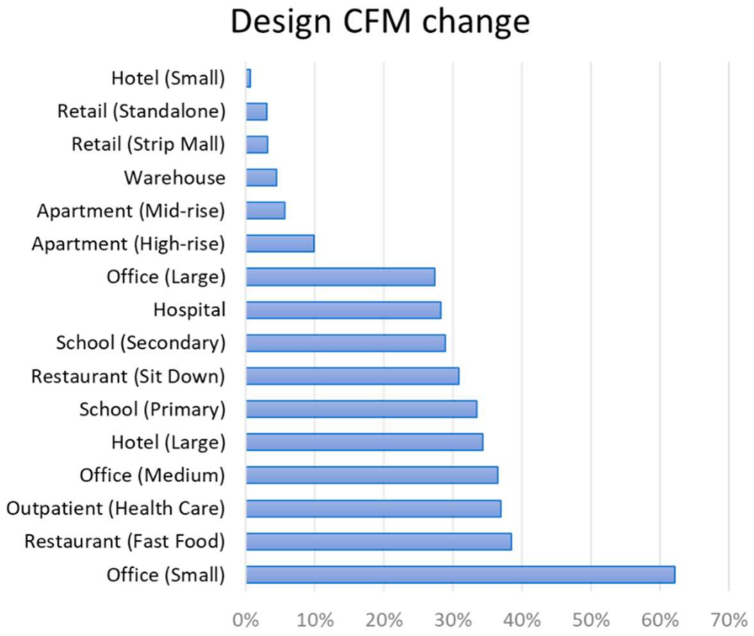

Figure 5. Percent change in ventilation rate in future climate

Envelope Improvements

The previously discussed prototype buildings were modeled and assessed with a baseline and an improved envelope performance with the SSP245 2080-2099 file. The envelope upgrade was run in isolation from any mechanical changes. The prototypes of the buildings were not modified with any conventional passive strategies such as orientation optimization or solar shading. Key performance levels of the envelope include: R-32 wall assembly, R-36 roof assembly, and glazing with a U-Value of 0.16 and SHGC[2] of 0.32. Baseline values match those of the prescriptive requirements for ASHRAE Climate Zone 6 in ASHRAE 90.1-2019. Figure 6 shows the cooling load change for all prototype buildings, Figure 7 shows the heating load change, and Figure 8 shows the required airflow supply reduction which contributes to the efficiency of both heating and cooling systems. For all buildings, a high performance envelope reduces both heating and cooling loads in this future weather scenario. The reduction percentage varies based on the typical window-to-wall area ratio of the buildings, wall-to-floor area ratio, and the internal loads of each building type.

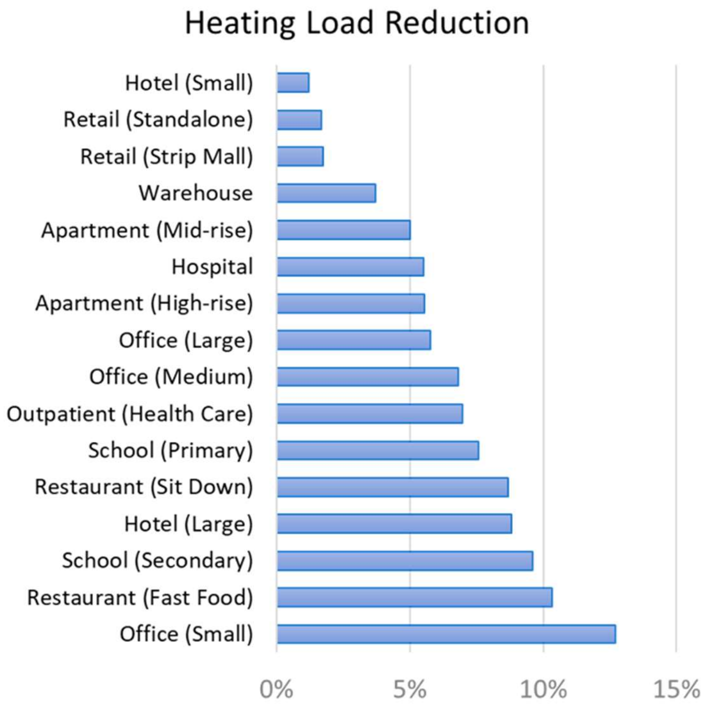

Figure 6. Percent change in heating load with a high performance envelope in future climate

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[2] SHGC: Solar Heat Gain Coefficient, the fraction of solar radiation admitted through a window, door, or skylight and subsequently released as heat inside a home. Lower values correspond to less radiation and heat.

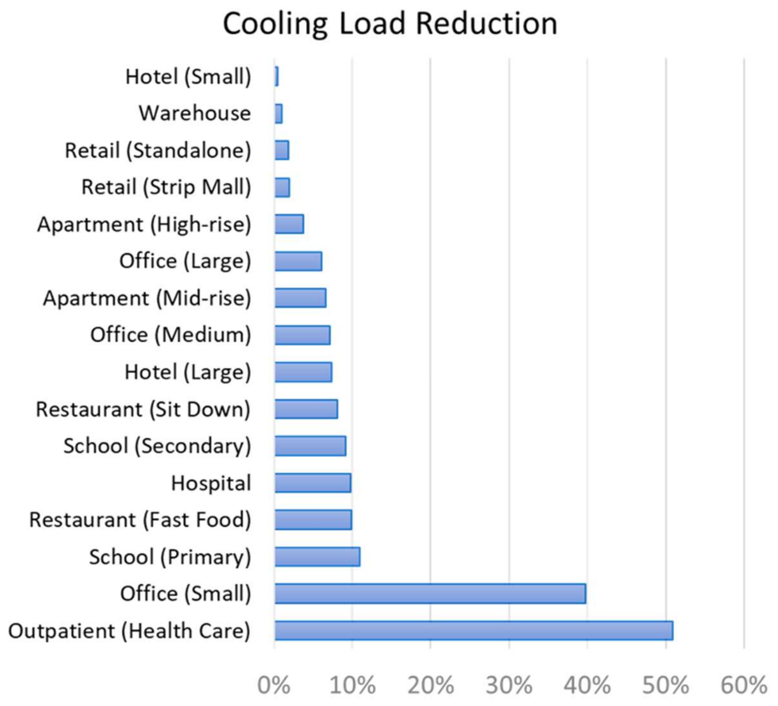

Figure 7. Percent change in cooling load with a high performance envelope in future climate

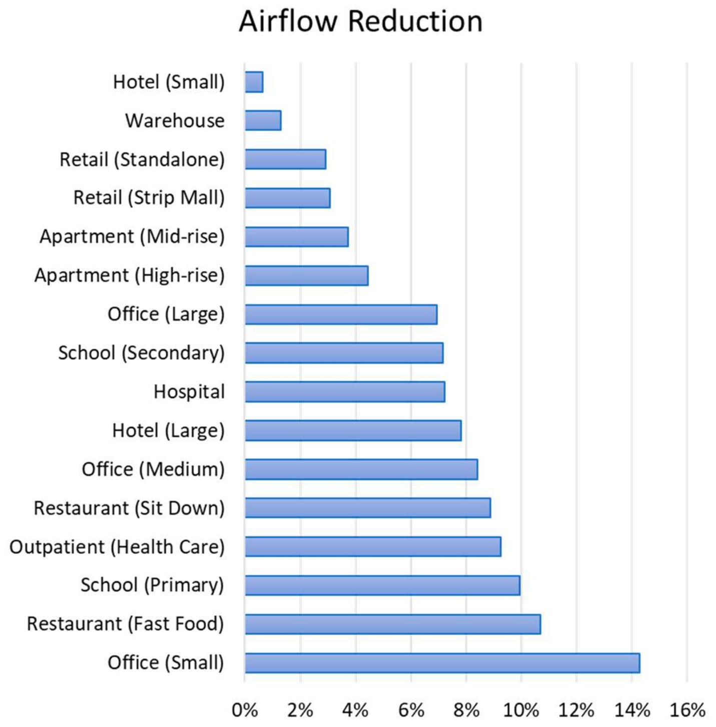

Figure 8. Percent change in ventilation air required with a high performance envelope in future climate

An initial test of the concept of thermal passive survivability, the building's ability to maintain a thermally-safe interior temperature in the event of a power failure, was completed for the mid-rise apartment building. In the case of a power outage in the hottest summer days, the high-performance envelope building maintained a temperature below 86°F for 30 hours, while the baseline building maintained the same temperature for 21.5 hours. While the envelope improvements extend the safely-habitable time, the basic improvement does not do enough to meet expected performance targets. Modeling indicates that in the case of the apartment building, the largest heat gains are solar heat, so site and building-specific design elements such as solar shading, foliage, and building orientation will have a significant impact on this performance and were not considered in the early phase modeling. Other building types may show internal loads as the dominant heat gain, in which case passive ventilation strategies will have an impact.

Next Steps

Work on this project will continue for the next year and includes assessment of high performing HVAC systems in future climate, which was not complete at publication time for this paper, and the creation of future-looking climate files for other emissions scenarios and time frames, as mentioned previously. A similar study of building prototype modeling will be conducted with the various climate files, to provide an understanding of the range of possibilities for the future weather and climate, and to understand the implications of the full range on the buildings being designed and constructed now.

Implications for B3

As noted above, the Minnesota B3 Guidelines now include a requirement for resilience along with sustainable design (energy, water, site materials, indoor environmental quality, etc.). This study of future projection data and the implications on future building operations will inform some of the resilience strategies that will be incorporated into the Guidelines.

Workflow Integration

The current workflow of a project following B3 guidelines includes the use of a simple energy modeling platform, the SB 2030 Standards tool built on the previously referenced Net Energy Optimizer tool. This tool enables design teams to set their energy efficiency target and identify strategies to meet the target. The tool also shows estimated energy usage data by end-use category, energy costs, peak demand, and carbon emissions. The energy modeling tool selects the weather file for simulation from the existing TMY3 database based on proximity to the project address. This functionality will be used to allow design teams to run their building models in projected future climate scenarios. The project team is developing projection files for all areas of the state, and the SB 2030 tool will select the appropriate geographic location and provide time frame and emissions scenario options to the design team. Similar outputs of energy use will be shown and compared to current conditions. The full potential of the integration into the energy modeling tool will be revealed through the modeling study, which will be run on the same platform.

Guideline Development

The results and takeaways from the modeling study will inform the detailed development of guidelines for resilience as related to energy. These guidelines may include things like battery storage for backup power, circuits wired specifically for a low-power mode, or allowance for larger mechanical equipment installed in the future. These measures will likely be specific to building use types and the expected functionality of those buildings in a scenario which affects the power supply.

It is likely that some aspects of the building that have typically been analyzed for sustainability and energy efficiency, such as the cost effectiveness or return on investment of building envelope upgrades, will require higher-than-typical performance to support resilience goals. For example, while energy efficiency may show that additional insulation value upgrades to the wall systems are not "cost effective" because the value of energy efficiency has been exhausted, a resilience review could show that the wall system upgrades enhance the ability to resist climate changes for the building's interior and to allow the building to be able to use the interior of the building for thermal storage, creating a resilience benefit in the case of lost heating capacity. Future guideline development will need to reconcile the two perspectives and reconsider the standard evaluation of simple payback or return on investment.

Other guidelines relating the durability of envelope, the thermal performance of envelope over time, and landscape considerations will also be developed and required as appropriate. These guideline areas have been explored in past work and will now become part of the program.

Future Work

Site and Water

Parallel to the study of TMY files and energy modeling, the project team has begun developing a plan for a similar study for site and water considerations. The project team has considerable experience in energy modeling but lacks expertise in the site and water topic area. To this end, the project team has engaged landscape architects, civil engineers, and watershed management organizations to seek guidance. The team has begun to identify a similar workflow that allows the existing data used by site and water professionals to be the basis for future projection weather data that can be used in existing workflows. Current practice for stormwater infrastructure design involves referencing the National Oceanic and Atmospheric Administration's Atlas 14 document which provides precipitation frequency estimates for Midwestern states. The data used to inform the estimates are historic precipitation records and statistical extrapolation of extremes (Perica, 2013) and while the considered data set is larger than that used for TMY files, the concern of using past data to inform future design is similar. Researchers at the University of Minnesota's Water Resources Center have developed a process using a previous version of dynamically downscaled global climate projection models (Liess et al., 2022) to calculate the percent difference between historic and projected future rainfall data (Noe, 2022), and this process can be applied to the updated climate data used in this study.

There is also a need for a Soil-Water-Balance (SWB) model. This model, provided by the United States Geological Survey, calculates the spatial and temporal variations in groundwater recharge and provide information useful in water quality protection, ecosystem management, and groundwater flow modeling (Westenbroek, 2010). The project team is working to develop a modeling protocol for considerations at the building and immediate site scale using prototypes similar to the various building typologies previously described. Site prototypes will range in size, building area to site area ratio, pre-construction condition, and location in the state. This developing study will likely impact the advancement of site and water guidelines in the B3 program.

Initial discussions with watershed districts show that localized flooding will be difficult to manage with existing stormwater infrastructure and that significant upgrades to the systems will take time. Therefore, building guidelines will need to consider the role of the building and building site to hold intense rainfall that will overwhelm the stormwater infrastructure systems and provide capabilities to minimize the risk from the stormwater, water and waste water systems during flood events. (Provide a localized flooding map from Met Council?)

Wall systems and other research

Future research is also underway to use the future climate files in the modeling of dew points to resists condensation in wall systems. Initial work points to the need to develop wall system designs capable of resisting a wide range of temperature and humidity variations in the selection of insulation, water and vapor barrier components to resist condensation and mold growth in walls.

As future climate files are developed, the design and research communities will need to review the wide range of applications in the design process to develop new data and workflows to integrate resilience to future climate impacts.

Acknowledgements

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