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Understanding Climate Change Impacts on Building Energy Use

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The built environment is central to an effective global strategy to both ***mitigate*** and ***adapt*** to climate change. For design practitioners, the ***mitigation*** component is clear and well established. On the other hand, ***adaptation***, which describes a building's resilience to respond to climate change related hazards, is generally not part of the design process, but is equally important.

The objectives of this article are to 1) raise awareness of the importance of climate change adaptation, particularly for the building design community, 2) increase understanding of the need for, and underlying sources and assumptions of future weather data, and 3) provide examples of climate change impacts on building energy use. This article serves as a supplement for "A Conversation on Adaptation in the Built Environment," an industry roundtable moderated by the authors of this technical feature and in this issue of the *ASHRAE Journal*.

Mitigation and Adaptation

The United States' withdrawal as a signatory of the Paris Agreement on climate change spurred many building industry groups, including the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), the American Institute of Architects (AIA), and the U.S. Green Building Council (USGBC), to reaffirm their commitment to climate change mitigation.[1–3] This comes from an industry-wide recognition that buildings emit roughly 40% of greenhouse gas (GHG) emissions.[4] Since the industrial revolution, GHG emissions have increased exponentially and the related increase in GHG concentrations in the atmosphere is very likely associated with climate-related changes.[5]

As defined by the Intergovernmental Panel on Climate Change (IPCC) Working Group III, mitigation is a "human intervention to reduce the sources or enhance the sinks of greenhouse gases."[6] For the building industry, mitigation strategies include: 1) reducing the overall energy consumption of buildings through improved component and system efficiencies, thus reducing the GHG emissions associated with source energy generation; 2) using renewable energy sources; 3) selection of lower global warming potential (GWP) refrigerants for air-conditioning systems; 4) selection of construction materials with lower embodied energy; and 5) selection of construction materials with the potential for carbon

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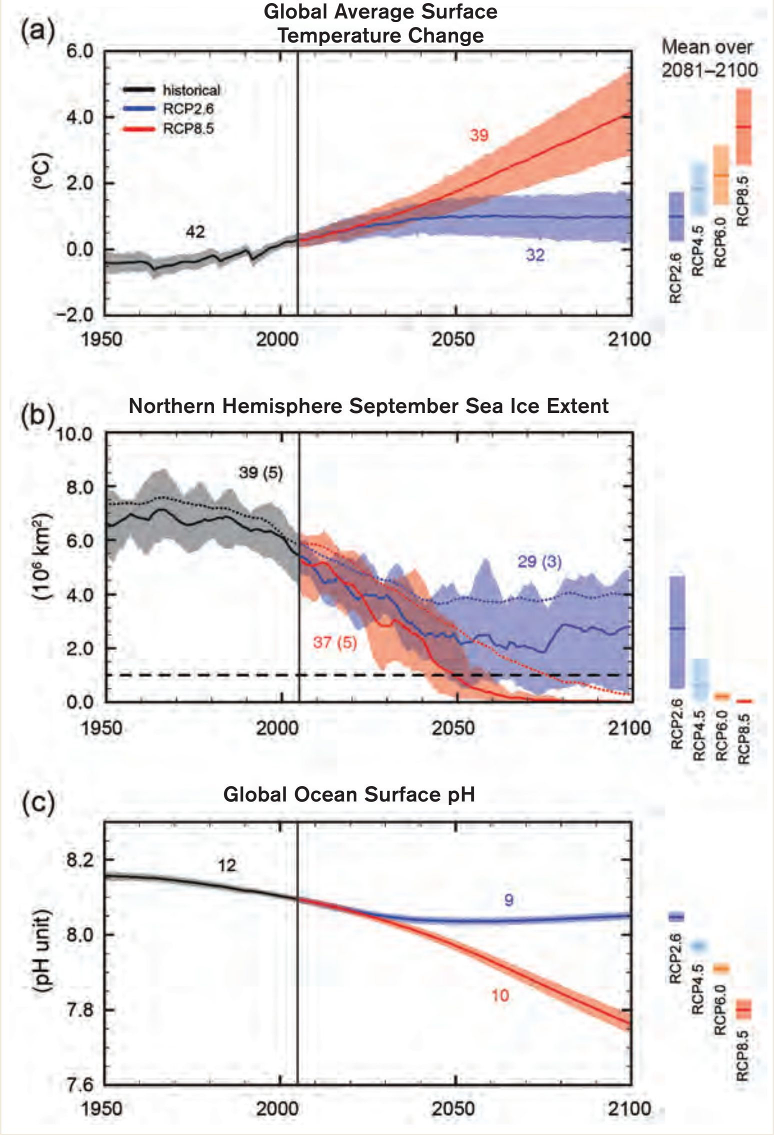
capture and sequestration.[7] This article focuses on the first item, building energy use, since in most cases this has the greatest impact on GHG emissions over the life of the building .

On the other hand, adaptation is “the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities.”[6] Some examples of relevant climate-related changes include: 1) increased average and extreme summer temperatures; 2) sea-level rise; 3) changes in seasonal precipitation; 4) extreme storms; and 5) increased sunshine hours.[7] For buildings, adaptation strategies reduce vulnerability to climate-related changes, such as flooding, wind damage, and overheating that adversely affect building performance. Adaptation to rising temperatures may require increased energy use for air-conditioning, which is counterproductive to climate change mitigation.

Figure 1 shows historical values and climate model predictions through 2100 for global average surface temperature changes, Northern Hemisphere sea ice extent, and global ocean surface pH for multiple GHG emissions scenarios (RCP 2.6, 4.5, 6.0, and 8.5 represent increasing predicted levels of GHG emissions, which we explain in greater detail in the next section on Modeling Climate Change).

FIGURE 1 Historical values and climate model predictions through 2100 for global average surface temperature changes, Northern Hemisphere sea ice extent, and global ocean surface pH for multiple GHG emissions scenarios.[5] ©IPCC 2014: WG I-AR5



The graphs demonstrate considerable overlap between the lower and upper bound emissions scenarios through 2050. Additionally, even under the lower bound emissions scenario, all three parameters change relative to the present through 2050.[5] This means mitigation and adaptation are complementary because 1) mitigation strategies implemented today will not have an observable change for at least 30 years and 2) even if the most aggressive policies to mitigate GHG are successful, there will still be climate-related changes over the next 30 years.

The service life of a typical building is approximately 30 to 50 years before major capital renewals, adaptations, and upgrades.[8] Therefore, the buildings we design and construct today will experience climate-related changes over the course of their service life, which will expose new vulnerabilities and alter predicted performance.

When used as a predictive tool, building performance simulations can quantitatively compare multiple design options in order to select energy-efficient strategies. Weather is an important simulation model input, but the current practice of averaging historical weather records does not take into account anticipated climate-related changes. Our ability to more accurately predict the long-term performance of a building depends on a better approximation for local weather conditions during its lifespan.

Modeling Climate Change

This section describes methods climate scientists use to model climate change and predict future weather parameters (such as those shown in *Figure 1*). Models of climate change must account for two layers of uncertainty concerning climate change: 1) future GHG emissions and 2) the atmospheric response to changes in GHG concentrations.

Our approach to modeling climate change comes from the Intergovernmental Panel on Climate Change (IPCC), the world's leading authority on climate change. With the support of United Nations organizations and the endorsement of United Nations General Assembly member nations, the IPCC does not conduct original research, but synthesizes the most recent climate science findings into an assessment report to policymakers every five to seven years. The most recent IPCC report is the Fifth Assessment Report (AR5) released in 2014. However, tools based on the previous report, the Fourth Assessment Report (AR4) released in 2007, are still prevalent.

In AR5, the IPCC defines a set of four emissions scenarios, called Representative Concentration Pathways (RCP): RCP 2.5, RCP 4.5, RCP 6.0, and RCP 8.5. Emissions scenarios capture the first layer of uncertainty by exploring the range of possible human impact on future GHG emissions given factors such as population growth, economic development, technological innovation, and policy interventions. The RCP numbers refer to radiative forcing values, i.e. the difference between incoming insolation absorbed by the Earth and energy radiated back to space, in 2100 relative to pre-industrial levels, in W/m^2. Lower levels of radiative forcing correspond to lower GHG emissions and concentrations. The four RCP pathways span the range of radiative forcing levels found in the literature.[9]

FIGURE 2 Historical values and climate model predictions through 2100 for global fossil-fuel emissions in petagrams (10^{15} grams) of carbon per year. The inset graph shows historical and projected atmospheric concentrations of CO$_2$, a significant GHG.[10] ©IPCC 2014: WG I-AR5

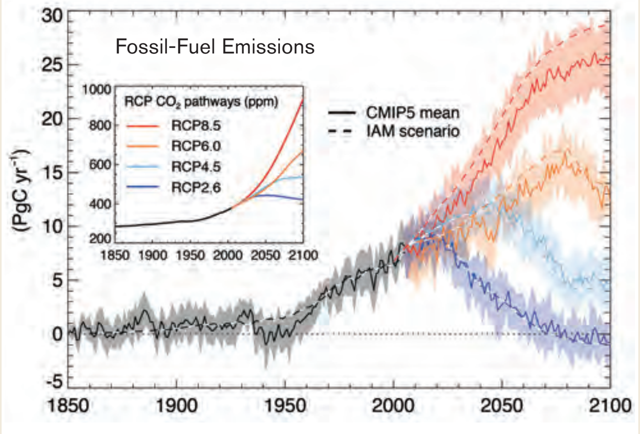


Figure 2 shows annual global fossil-fuel emissions throughout history and as projected for each emission scenario. The policy interventions modeled by the IPCC come from the United Nations Framework Convention on Climate Change (UNFCCC) Secretariat, established in 1992 when member countries signed the UNFCCC as the first nonbinding treaty to stabilize GHG concentrations. Since then, UNFCCC member countries signed the Kyoto Protocol in 1997, which required 37 industrially developed countries to monitor and reduce GHG emissions by an average of 5% relative to 1990 levels by 2012, and the Paris Agreement in 2016, which aims to limit the global average temperature increase to within 2°C (3.6°F) of pre-industrial levels.

The emissions scenarios serve as an input for the second layer of modeling uncertainty, predicting the atmospheric responses and resulting future weather. Climate scientists use numerical models to simulate interactions between atmospheric and oceanic processes at a global scale, called general circulation models (GCM). There can be lot of variation across climate models because they involve stochastic processes and are highly dependent on initial conditions. As an analogy, think about the variability in weather forecasts for the next day, week, or month from different sources. Projecting forward a decade or several decades only magnifies differences between multiple climate models.

To counter this uncertainty, the World Climate Research Programme's (WCRP) Coupled Model Intercomparison Project (CMIP) involves 20 climate-modeling groups from around the world who perform a set of coordinated climate model experiments. Using the same boundary conditions on multiple GCMs gives a better understanding of the range of climatic response. CMIP5 is the fifth set of coordinated experiments and uses the RCP emissions scenarios defined in AR5 as boundary conditions.[11] Revisiting *Figure 1*, each of the colors in the graph represents a different emissions scenario from AR5 and the shaded region represents the uncertainty across CMIP5 climate models.

Creating Future Weather Files

Of greater relevance for analyzing climate change impacts on the built environment is how to access and use the results from climate models. Designers are already accustomed to using weather-related data in the building design process, be it heating or cooling degree-days, ASHRAE design conditions for sizing equipment, or hourly weather files for energy simulation.

Linking future weather parameters reported by GCM into building performance simulations for a specific location requires an extra step because of differences in spatial and temporal scales. GCMs divide the Earth's surface into 100 to 300 km (62 to 186 mile) grid cells as part of the numerical simulation. The time step for GCM calculations may be a few hours to an entire month.[12] In comparison, weather files for building simulations expect local hourly weather data.

Downscaling is the process to take information known at a large scale and make predictions at a smaller scale, such as the resolution for building energy simulation. There are several ways to do this. In climate science, dynamical downscaling uses the lower resolution climate models, GCM, as boundary conditions to rerun numerical simulations at high resolution and over a limited geographic area of interest. The result is a regional climate model (RCM) that better resolves small-scale climate processes, but is computationally expensive. A second method is using a stochastic weather generator, which is computationally cheap but may not give meteorologically consistent results. A third option is statistical downscaling, where mathematical equations approximate the relationship between large scale and small-scale climate variables. This has been the method of choice to develop future weather files for building performance simulations.[13,14]

The sidebar, *Climate Change Related Sources*, lists some sources for climate change related weather data, visualizations, and future weather files.

Predicting Future Energy Use

The case study presented here demonstrates the use of future weather files in building simulation to explore the impact of climate change on building energy performance for two selected building types and three locations.[15] This study assumes constant building design parameters throughout the period of analysis, and does not take into account improvements to system efficiencies, which are likely to occur. Therefore, our results provide an upper bound on future energy use.

Climate Change Related Sources

Data

Global

Data Distribution Centre	www.ipcc-data.org

Visualization

Global

Climate Time Machine	climate.nasa.gov/interactives/climate-time-machine
Panoply	www.giss.nasa.gov/tools/panoply/download
Climate Inspector	gisclimatechange.ucar.edu/inspector
Climate Reanalyzer	cci-reanalyzer.org/about

United States

Climate Mapper	https://climatetoolbox.org/tool/climate-mapper
Climate Explorer	https://crt-climate-explorer.nemac.org

California/Nevada

Cal-Adapt	cal-adapt.org/data/loca

New York

Climate Data Grapher	www.nyclimatescience.org

Future Weather Files

Global

CCWorldWeatherGenerator	www.energy.soton.ac.uk/ccworldweathergen
Weather Shift	weathershift.com

United Kingdom

Data Distribution Centre	www.ipcc-data.org
CCWeatherGen	www.energy.soton.ac.uk/ccweathergen
CIBSE Weather Data Sets	www.cibse.org/weatherdata

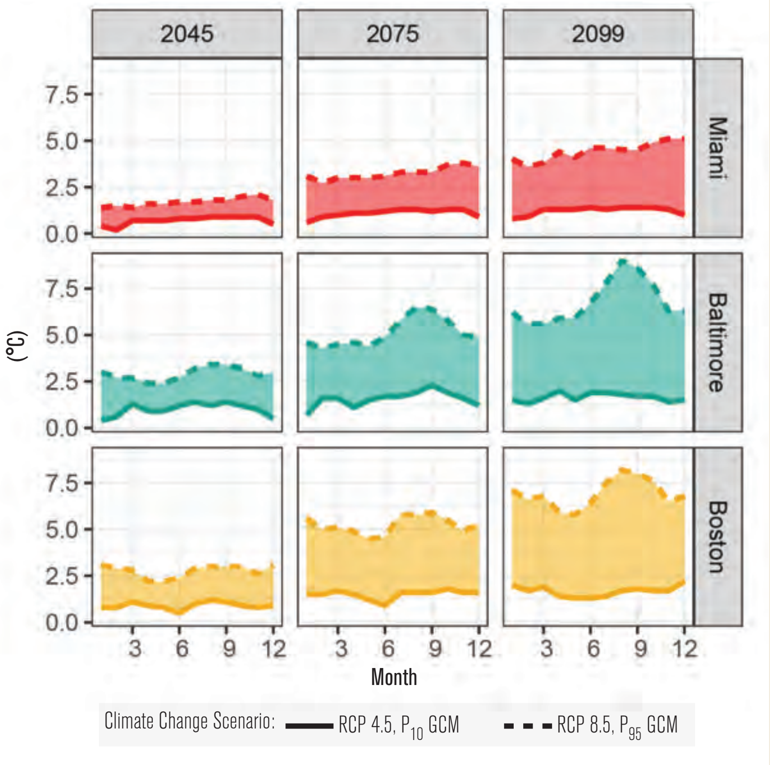
Methodology

We compared the simulation results from a present day weather file (third generation typical meteorological year, TMY3) and three future periods, ending in 2045, 2075, and 2099, which we obtained from Weather Shift.[16] We bounded uncertainty in climate change by using multiple emissions scenarios and an ensemble of GCM. Weather Shift ranks GCM results by the projected mean daily temperature increase in order to ascribe a warming percentile to each GCM. This describes the probability of a particular mean daily temperature increase. For example, the 50th percentile (P50) GCM means half of the GCMs in the ensemble predicted a lower temperature increase. The combination of RCP 4.5

and 10th percentile (P_{10}) warming forms the lower bound and RCP 8.5 and the 95th percentile (P_{95}) form the upper bound. These were the ranges available from Weather Shift for study locations. We considered three locations: Miami, Baltimore, and Boston, located in ASHRAE Climate Zones 1A, 4A, and 5A respectively.

We used the U.S. Department of Energy (DOE)'s commercial reference building energy models for this analysis, and considered two of their building typologies: midrise apartment and medium office. The envelope and equipment parameters in both models come from ASHRAE Standard 90.1-2004, *Energy Standard for Buildings Except Low-Rise Residential Buildings* and Standard 62.1-2004, *Ventilation for Acceptable Indoor Air Quality,* which were contemporary standards at the times the DOE models were developed. Therefore, we can consider our results most applicable to existing buildings of this vintage. The energy model sizes the heating and cooling systems based on the present-day ASHRAE 99.6% and 0.4% design days for each location. We compared the annual building energy consumption, which we calculated in EnergyPlus v. 8.6.0.

FIGURE 3 Change in mean monthly temperature relative to the present varies seasonally and by location.



Results and Discussion

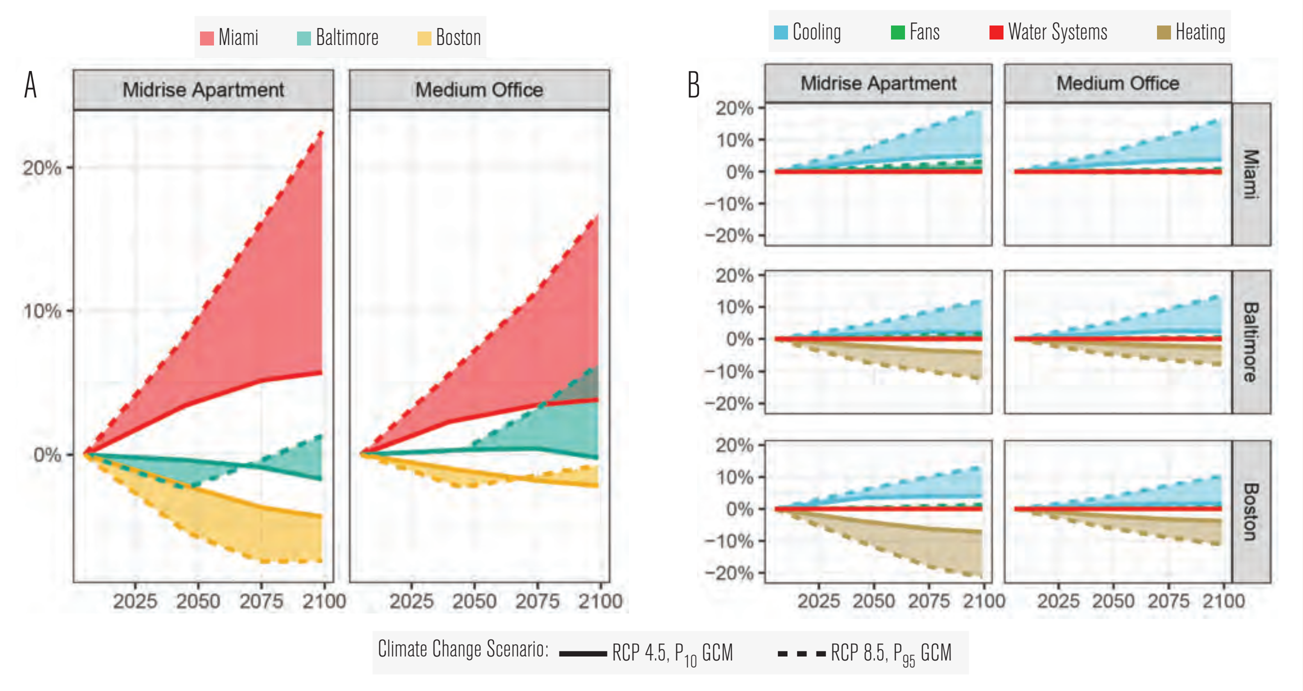
Figure 3 shows the change in mean monthly temperature relative to the present for each time period. In Miami, the average monthly temperature change is nearly uniform throughout the year, while in Baltimore and Boston temperature change is greatest in the summer. Climate models take into account energy and transport processes in the atmosphere and oceans. These processes could have seasonal and geographic dependencies. Some examples could include incoming solar radiation, land surface properties, and atmospheric circulation. Uncertainty in mean monthly temperature increases with future time-period.

Figure 4a compares the percent change in total energy consumption relative to the present by building type and location, and then *Figure 4b* is similar but breaks it down further by end use. The bands represent the range of emission scenarios and warming percentiles, as described earlier. As expected, climate change most significantly affects heating and cooling end use consumption, along with a slight change in fan energy use. The changes in end use energy consumption (*Figure 4b*) help explain the trends in total energy consumption (*Figure 4a*), elaborated on below. *Figure 3* also shows that for the midrise apartment in Baltimore and the medium office in Boston, there is an inflection point where the upper and lower bound climate change scenarios cross, which can be better understood by comparing the percent change in end use energy consumption shown in *Figure 4b*.

In Miami, where cooling energy dominates, total energy consumption increases for both building types, though the range of uncertainty is higher for the midrise apartment. Differences between the two building types likely relates to the interaction between hourly weather changes and the building's internal gains schedule. For example, greater variation in evening temperatures would have a larger effect on the midrise apartment than a medium office.

Miami will continue to be a cooling dominated climate under both the lower and upper bound climate change scenarios.

FIGURE 4 Change in (a) total energy consumption and (b) end use energy consumption varies by building location and type.



Baltimore is a mixed climate and the predictions are more complicated, showing that changes in internal gains due to building type have a more significant impact on the relative changes in total energy consumption. In the midrise apartment in Baltimore, the decrease in heating energy consumption associated with a warming climate offsets the increase in cooling energy consumption. As a result, total energy consumption initially decreases relative to the present (i.e., reduction in heating is greater than increase in cooling). However, around approximately 2080, the net effect of increased cooling with warming temperatures results in total energy consumption now increasing in the upper bound climate change scenario. For the medium office in Baltimore, with its higher internal loads and cooling loads, total energy consumption increases more significantly and earlier, starting approximately in 2050. An important takeaway from this analysis is that mechanical systems sized in the present may not be sufficient to meet future demand (cooling equipment) or may operate at partial load efficiencies (heating equipment).

Boston is a heating dominated climate, so the net impact is a decrease in total energy consumption for both building types, but particularly for the apartment compared to the office building. The difference between the two building types due to differences in internal loads is also visible. For the medium office, in the upper bound climate change scenario, total energy consumption begins to increase around 2070, though it remains below that of the present through 2100. For the midrise apartment, this inflection occurs later, beyond 2100.

Summary and Conclusions

Building design professionals are accustomed to their role in climate change mitigation. However, scientific literature shows that even if the most aggressive mitigation measures are successful, we can expect climate-related changes, such as increasing temperatures, over the next 30 years. These changes can adversely affect building performance. Furthermore, increasing energy use to adapt to climate change negates mitigation efforts. Building design professionals can use models and methods from climate scientists to predict future weather conditions and handle uncertainty in emissions and the atmospheric response. The case study demonstrates that climate change impacts will vary by building type and location. Future weather files are already available and offer designers a way to assess the impact of climate change on their building designs.

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