A climate-aware built environment:
Integrating future weather data into building design today

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ABSTRACT

Building design practice relies on typical historical weather data. Because of climate change, this means that building designs are based on incorrect climates, resulting in wasted energy, shorter equipment lifetimes, higher cost and emissions, and vulnerability to extreme weather. Overestimating climate change can also lead to overdesign with higher costs and lower lifetimes. The solution to this is accurately understanding the variations in energy performance that future weather conditions will likely cause, and incorporating these considerations into building design.

Recently, Oak Ridge National Laboratory created future Typical Meteorological Year files under extreme climate change for all continental U.S. counties. For resilience and extreme temperature, Sandia National Laboratories created a stochastic heat and cold wave generator. Argonne National Laboratory developed dynamically downscaled chronological future weather data across North America. While needing broader geographic and climate scenario coverage, these products represent the three most important types of future weather data: 1) typical, 2) extreme, and 3) precise futures. When used appropriately, they form a comprehensive evaluation of future conditions necessary for planning and resilience.

This paper outlines barriers and progress towards deploying these novel tools and datasets. An evaluation of climate projection data utilization and barriers is conducted based on a literature review and stakeholder survey. Technical and market barriers to broader implementation, and recommendations to overcome them are discussed. Equitable and wide-scale incorporation of future climate data into building design represents a critical gap and important opportunity to spark transformation towards a climate-aware built environment.

Introduction

Climate adaptation[1] has thus far been small-scale, sector-specific, fragmented, focused on near term impacts, and lagging in lower income populations (IPCC 2022, UNEP 2022). While there has been progress overall in levels of adaptation, current rates of adaptation are not keeping pace with climate impacts and risks, meaning the adaptation gap is growing causing rising maladaptation. (IPCC 2023, Reckien et al. 2023). These impacts are disproportionately large for vulnerable and marginalized communities, including communities of color, low-income

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[1] Climate adaptation refers to changing "fundamental attributes of a social-ecological system" in anticipation of or as a reaction to climate change and its impacts (IPCC 2022).

communities, tribes and indigenous people (IPCC 2023). Many campuses, cities, and utilities have started developing adaptation plans and conducting vulnerability and impact assessments, which must be based on accurate data of future conditions.

The Executive Order on Tackling the Climate Crisis at Home and Abroad directs federal agencies to develop climate adaptation and resilience plans. It calls for the improvement of climate information products to help governments prepare and adapt to the impacts of climate change. Furthermore, many pieces of the $1.2 trillion Bipartisan Infrastructure Law are designed to make infrastructure more climate resilient (White House Fact Sheet 2021). Overall, clear climate adaptation goals exist, but to meet these goals, buildings must be designed for the climates in which they will exist.

Significant work remains to be done to translate adaptation goals and incentives into a climate-aware built environment. Here we define a climate-aware built environment as buildings designed for future conditions such that the likely hazards and changes in efficiency have been adequately analyzed using future weather datasets to evaluate building design response. This entails “correct application” of future weather data to the building design process. Here, future weather denotes atmospheric measures such as temperature, humidity, solar radiation, wind, and cloud cover on an hourly to sub-hourly time scale. This is different than future climate which is the mean behavior of weather variables and event patterns over 30 or more years. Currently, “correct application” requires detailed knowledge of climate models and how to downscale the needed information from them to form future weather data. A climate-aware built environment also requires understanding different types of future weather analysis, such as design for normal operations in future typical conditions, as well as preparation for resilience operations during extreme weather events (Villa et al. 2023). The significant complexity of using future weather data can therefore easily lead to incorrect practice such as applying future typical weather for extreme event resilience analysis or, conversely, designing normal operations to extreme conditions (i.e. oversizing for unlikely peak conditions). This complexity must be subsumed into an established set of actions that designers can take without expert knowledge concerning future weather data products to assure their designs are robust and efficient for future conditions. Requiring the use of future weather data through code and policy may enable more equitable outcomes, as many buildings in lower income communities may not be individually designed and optimized, and may instead be built to prescriptive standards.

Currently, decisions that rely on climate or weather data often use Typical Meteorological Year (TMY) datasets compiled from median monthly historical weather conditions extending back at least 14 years. TMY datasets are hourly weather files used in building energy modeling (BEM) programs like EnergyPlus, DOE-2.2, and IES Apache among others, for energy performance assessment and code compliance analysis. TMY3 are the most recent datasets released by the National Renewable Energy Laboratory using weather data from 1976-2005 or 1991-2005 (Wilcox and Marion 2008). More recently, the TMYx datasets include data through 2021 with locations worldwide (Lawrie and Crawley 2022). Using up-to-date historical information via TMYx is an improvement over TMY3 but future weather is needed; even using the most recent TMYx file, covering 2007-2021, a building designed in 2024 would miss 2022 and 2023 which were hotter than ten of the fourteen years over this period (based on global land average temperatures from NOAA).

TMY datasets represent neither present nor future conditions because Earth's climate is rapidly changing, and they do not represent extremes because they are derived from median conditions. As cooling needs are expected to increase in the future, using TMY datasets will cause the predicted energy savings for cooling energy efficiency measures to be underestimated, undermining potential investments in energy efficiency. The potential for extreme temperature leading to thermally dangerous conditions is also underestimated. Designing buildings based on historical weather data is also likely to lead to increased carbon emissions, and health, comfort, and safety issues for residents. On the other hand, using improper future weather data may also overestimate climate change impacts (by for example, oversizing HVAC systems) leading to higher costs and higher embodied and operational carbon emissions. The solution for this is accurately understanding the variations in energy performance that climate change will likely cause and incorporating these considerations into building design.

As future weather extremes become more frequent and intense (IPCC 2021), the rate of temperature extreme increase is predicted to exceed the rate of mean temperature increase (Miller et al. 2008), meaning that in addition to shifts in typical climatic conditions, it will become more important to prepare for the increasing intensity, duration and frequency of extreme events, especially in disinvested communities bearing the brunt of these impacts. On average globally, historic 50-year heat wave events are already happening every 10 years and are projected to occur every 4 years if 2.0°C of warming is reached (IPCC 2021). The peak temperature of these events will increase on average by 2.6°C with 2.0°C of warming, which is likely to lead to equipment failures and increasing heat stroke deaths.

Coordination is needed between the producers of climate projection data, the users of weather data, and the codes and standards bodies to ensure that future weather data are well-suited for building design applications, that building professionals have the tools and resources required to use them, and that they are accessible to lower income communities most affected by climate change. Equitable and wide-scale incorporation of future climate considerations in our building decisions represents a critical gap and potentially highly impactful opportunity to spark a transformation towards a climate-adapted and resilient built environment.

Here we conduct a review of recent progress in developing novel tools and datasets that address the problem of designing buildings for the appropriate future climate conditions. To evaluate the current state of future weather data utilization and barriers to broader use, we have conducted a brief review of the literature, including three recently developed tools from DOE national labs, and engaged in stakeholder conversations. We used these methods to form the basis for a broader survey of architecture and energy modeler stakeholders to identify technical and market barriers to broader implementation and recommendations to overcome these barriers.

Review of the current state of future weather data implementation

Overall, there are a wide range of datasets available and increasingly being used that provide future climate and weather information. Few jurisdictions have formalized guidelines, incentives or mandates institutionalizing the use of this data. Here we review the current policy landscape around implementing these datasets.

In the UK, future weather data files have been made available for energy modelers. The CIBSE (Chartered Institution of Building Services Engineers) publishes future weather files using the UKCIP09 climate change scenarios, with files for three time periods, 2011-2040, 2041-

2070, and 2071-2100 with options for a high, medium, and low emissions scenarios available for purchase on the CIBSE website. They also have datasets representing years with hot summers, to represent a year with three scenarios of intensity and duration of heat events to allow for the consideration of plausible warmer-than-average conditions. This dataset covers 14 sites across the UK and is available in multiple file types including EnergyPlus Weather Files (EPW) and Excel®. The Greater London Authority requires that for London, modeling efforts use weather data files that account for both future climate and the urban heat island effect, and follow the CIBSE TM49 Design summer years for London (2014) guidance. The UK government's Department for Business, Energy & Industrial Strategy has published recommendations for the use of this data through the National Calculation Methodology modelling guide, which provides guidance on how to carry out energy calculations for buildings using approved software and methodologies and lays out the procedure for demonstrating compliance with building regulations (UK NMC 2021).

In Canada, the Pacific Climate Impacts Consortium (Ek et al. 2018) and the National Research Council of Canada (Abhishek and Lacasse 2022) offer two types of future weather data at various locations across Canada that are freely available.

In the US, most state codes and standards, and utility efficiency programs use TMY3 data (NYSERDA 2020). California, however, has started using TMYx files spanning 1998-2017 for their 2022 Building Energy Efficiency Standards (known as Title 24), facilitated by the fact that California develops its own set of codes. These are available for 97 locations in various file types including EPW and free to download from the California Measurement Advisory Council page (CALMAC 2024). For some utility incentive calculations, California investor-owned utilities use "trended" TMYx files, which incorporate the recent observed long-term warming trends and are used in BEM and energy savings calculations for efficiency programs (Huang 2020; NYSERDA 2020). The New York State Energy Research and Development Authority (NYSERDA) has commissioned studies and conducted analysis (e.g. NYSERDA 2020; Brown et al. 2023) but still uses TMY3 in its codes and standards, which are based on IECC, and utility programs. The University of Minnesota Climate Adaptation Partnership is in the process of generating dynamically downscaled climate projections at ~3 mile resolution through 2100 for Minnesota and is working with weather data users to maximize implementation (Laxo et al. 2023).

Several other businesses provide future weather data or climate analytics for infrastructure for a fee including WeatherShift® (Dickinson and Brannon 2016), Meteonorm® (Remund et al. 2020), CCWorldWeatherGen® (Jentsch et al. 2013), Jupiter Climate Score® (Jupiter Intelligence 2024), and cove.tool (cove.tool 2024). Of these resources, only WeatherShift explicitly addresses providing future weather files for building energy simulation. Meteonorm is focused on radiation data. Jupiter offers climate risk mitigation across corporate assets as a service. Cove.tool provides sustainability consulting for the built-environment with future conditions as an option for analysis. One study shows significant differences in outcomes when analyzing residential buildings in Italy using WeatherShift, Meteonorm, and CCWorldWeatherGen (UK tool) (Tootkaboni 2021). Differences are expected given the uncertainty of the future, yet this underscores the need for correct use of files and methods to gain a complete perspective of future conditions.

Review of the technical complexities and barriers to using future weather data

Spatial and temporal resolution of future weather data

Future weather files have become readily available. A multitude of climate projections generated by Global Climate Models (GCMs) are already available, but the majority of GCMs in the latest Coupled Model Intercomparison Project (CMIP Phase 6) are coarser than 1° (~110 km), are intended to understand global scale climate, and can have large uncertainties and biases particularly in future extreme event projections. To be useful for local impact analysis, GCM projections need to be downscaled.

GCM projections can be downscaled using statistical or dynamical downscaling. Statistical downscaling is empirically-based, using statistical relationships between global climate from GCMs and local historical climate observations and is computationally efficient. However, the statistical relationships between large-scale simulated climate and local observed climate are expected to change with a changing climate, meaning that higher radiative forcing scenarios are less likely to be accurate (Rastogi, Kao, Ashfaq 2022). Dynamical downscaling uses physics-based regional climate models to simulate local atmospheric processes at higher resolutions, capturing detailed features and generating the expected changes in extreme weather but demanding significant computational resources. Both require bias corrections and are influenced by the choice of observational data and GCMs used (Rastogi, Kao, Ashfaq 2022; Bhanage et al. 2023), which affects the accuracy of downscaled projections.

Downscaling involves statistical inference where the best information about historical patterns and future projections are blended to give a best guess for future weather conditions. Such inferences can only be accurate if the weather variable being downscaled is accurately projected by a GCM. Variables like surface temperature are somewhat reliable but others such as cloud cover have wide variations across GCMs. There can be even less accuracy at preserving correlations between variables such as temperature and humidity. There are difficult tradeoffs between using results from a single GCM which have a closer tie to physical behavior of the climate system or ensembles of GCMs which represent a broader range of the uncertainty associated with physics of the climate system. Downscaling is therefore an active field of research.

The most frequently used approach for producing future weather files for buildings is “morphing” current weather data, proposed by Belcher, Hacker, and Powell (2005) and used widely (e.g. Dickinson and Brannon 2016; Jiang et al. 2019; Zhai and Helman 2019). Morphing entails scaling and shifting TMY data to fit them to future climate conditions projected by GCMs. Morphed future TMY files can be purchased from several of the tools previously mentioned. This method however is unlikely to accurately account for the changes in extreme weather, and falls short in modeling the relationships between different weather variables (Muehleisen et al. 2020).

More recently, work at Sandia National Laboratories (Villa et al. 2022; 2023a) for example, has also been focused on downscaling extreme events. Such work can involve statistical or dynamic downscaling. First, current frequency, duration and intensity (FDI) of an extreme weather event is characterized. For statistical downscaling, the extreme event FDI is correlated to an accurately predicted GCM variable.

Existing high spatial resolution downscaled projections are largely only available at the daily temporal scale which is sufficient for most climate impact analyses. BEM tools like EnergyPlus, however, require hourly data because buildings have highly variable usage schedules and their thermal dynamics are sensitive to the short-term variations of weather conditions. Furthermore, building energy modelers require this data to be in formats that can be read by energy modeling software (e.g. EPW).

Uncertainties, risks, and scenario selections

Future weather data, unlike historical data, covers a spectrum of potential scenarios, not merely averages, and requires the consideration of risk and uncertainty. Using projection data in building planning will therefore require risk and uncertainty analysis that is unconventional for the built environment. Such types of analysis are not new but have only been economical for industries that have high consequences and replicability. For example, the transportation industry undertakes risk analysis for motor vehicle accidents including crashing actual cars to know the safety performance. Such testing is feasible because a single car design will be used to build millions of cars. Such testing is economically infeasible at a full building scale.

In addition, buildings are typically in use for much longer periods than the equipment in them. For example, a heat pump that has an expected lifespan of 20 years may only need to use present weather data or a single future weather dataset. On the other hand, a new building intended to last many decades could undergo a performance evaluation that includes weather data for the present, 20, 40, and 60 years into the future. Understanding how to integrate these different timescales is challenging.

Predicting Earth’s climate will always include uncertainty, in part due to the uncertainty in anthropogenic greenhouse gas emissions in the future. Most GCMs use Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs) to outline possible futures. SSPs are socioeconomic narratives capturing five plausible combinations of varying levels of mitigation and adaptation based on variables like population, GDP, technology and equality to define potential emissions pathways (e.g. Riahi et al. 2017). RCPs use potential emissions pathways to illustrate how four levels of greenhouse gas concentration trajectories would impact the global climate through 2100. Together RCPs and SSPs define a range of plausible climate futures used to develop climate projections assessed by the IPCC (2013). For building applications, a major outstanding uncertainty around incorporating future weather data is the question of which scenario to use as the basis for design. Zeng and others (2023a) note that some studies have used emissions scenarios that are “unattainable” and recommend using different emissions scenarios based on the specific application.

There is also a lack of standardization in applying future weather data to building design. Without standardized methods, any designer that does decide to consider climate change must navigate issues well beyond their expertise, such as how accurate a future weather file based on an ensemble of CMIP6 models is in comparison to a future weather file derived from a single CMIP5 GCM. The details of the downscaling method are hard to understand and at times are not transparent.

Finally, competing design criteria and a larger and more uncertain range of design conditions will lead to a significant increase in the number of BEM runs required. For example, air-conditioning design may be conducted via a fTMY set of files across several GCMs for present and 20 years into the future. The design could then be optimized for best performance during the entire lifetime of the equipment. This could be accompanied by a stochastic study of thermal resilience for occupants given worst case conditions that involves several thousand runs considering increased FDI of heat waves (Villa et al. 2024). Such an approach avoids overdesign to unlikely extreme events by using fTMY while assuring occupant safety during worst case future conditions. These increases in runs will require a switch from BEM being used to create a narrative of how energy can be saved to a complex intercomparison of several metrics with overlapping uncertainty variables. The lack of simplicity of such presentations of data may overwhelm decisionmakers and lead to avoidance of further investment in BEM analysis using future weather data.

Review of progress towards technical solutions

To address these complexities, Oak Ridge, Sandia, and Argonne National Laboratories (ORNL, SNL, ANL, respectively) have recently created data and tools to facilitate the utilization of future weather data for projecting energy use, equipment sizing, and resilience analysis.

Future weather data

Recent efforts to address these data gaps have been enabled in part by advances in high-performance computing (e.g. Bass and New 2020; New et al. 2018). Most recently, the future typical meteorological year (fTMY) has been created (Chowdhury et al. 2023a) and is publicly and freely available for download (Chowdhury et al. 2023b; Chowdhury et al. 2023c). These fTMY files are statistically downscaled from six different IPCC climate models to 1 km grids in the EPW format, with hourly data for nearly every county in the US. Files were created for the six 20-year time periods between 1980-2100 using the worst-case climate scenarios, RCP8.5 and SSP5. The projections are less likely to be accurate in the window farthest in the future because statistical climate relationships will change as climate dynamics change. Moreover, ANL has released a dynamically downscaled future weather dataset under RCP4.5 and RCP8.5 for the centroid of each Public Use Microdata Area in the US. It comprises weather data spanning two future 10-year periods (2045–2054 and 2085–2094), encompassing both typical and extreme weather conditions. This dataset can also be downloaded for free (Zeng et al. 2023b).

Bass et al. (2022) used the fTMY files to quantify energy use and emissions changes associated with climate change for Maricopa County, Arizona. Using the Automatic Building Energy Modeling (AutoBEM) software suite (New et al. 2018) to simulate the energy profiles of individual buildings, and the individual building characteristic data from LightBox[2], the authors simulated 1.5 million buildings for the four twenty-year time slices from 2020-2100. Energy use, cost, and emissions were compared to running the same simulation using TMY3, showing that RCP-8.5 and SSP-5 would result in a projected annual building energy cost increase of $1.2 billion and annual CO_2 emission increase of 3 million tons county-wide. Using a new visualization tool users can interact with this data and see each individual existing building and its associated projection (Bass et al. 2022).

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[2] LightBox is a platform for commercial building data.

Accounting for future extremes

To help design and prepare for increases in FDI of future weather extremes, SNL has created the multi-scenario extreme weather simulator (MEWS; Villa et al. 2022; 2023a). This new tool uses statistical approaches to analyze historical weather data to characterize the FDI of heat waves and cold snaps, and then uses IPCC projections to shift the IDF of the historical events to produce projected extreme weather as EPW files (Villa et al. 2022; 2023a).

The resulting shifted distributions from MEWS can be used directly in BEM to produce informed risk assessments. Scenario-based resilience analysis can use the peak temperature increase above the NOAA daily climate norms average temperature to create a year of data with one or more worst case heat waves, cold snaps, or for stochastic methods. The duration distribution output by MEWS can also be used to estimate a maximum duration event. These hot and cold extreme events can then be used to analyze building performance with and without air-conditioning to evaluate thermal resilience for worst case future 10- or 50-year heat events. Even less probable events can also be analyzed, although the accuracy of such remote extreme events is questionable. Several different risk levels could be assessed for a single study this way if a range of outcomes is desired.

Sampling of the distributions to run thousands of evaluations of BEM performance under probable future scenarios in a Monte-Carlo study is a second use case. This approach is computationally expensive but provides all BEM outputs as statistical distributions that enable application of risk and uncertainty evaluations for energy performance and resilience metrics. Several studies have been conducted with this stochastic approach (Villa et al. 2023c, Villa et al., 2024). Such results give as comprehensive a view into future performance as possible. Even so, understanding the results and methods of MEWS can be a barrier to its use.

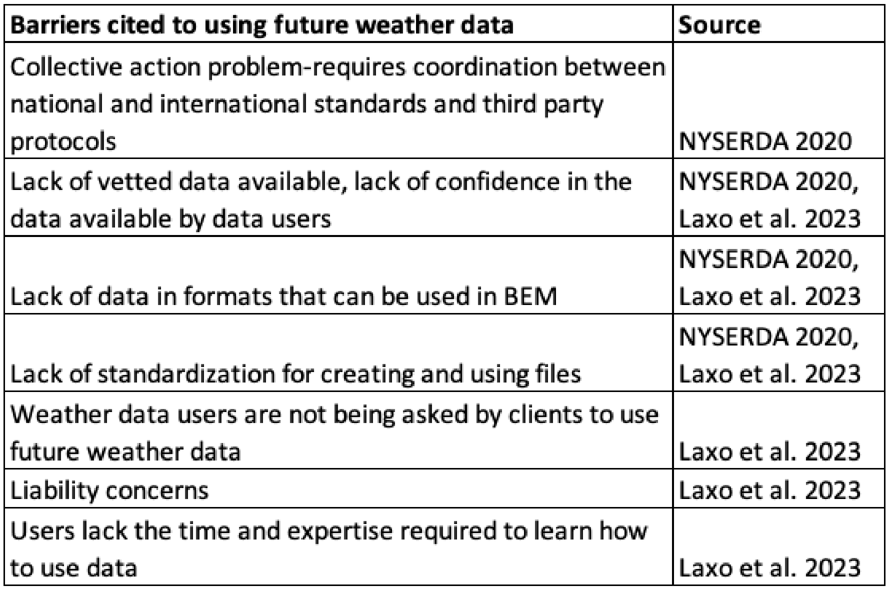
Efforts to construct state-of-the-art, accurate future weather files using dynamical downscaling, and a combination of dynamical and statistical downscaling for multiple RCP-SSPs are underway by ANL and ORNL, and is an active field of current research. Future work could help validate the statistical methods used in MEWS (Villa et al. 2022) and the fTMY (Chowdhury et al. 2023a) to show that they are sufficiently similar to results using dynamic downscaling. Overall, further research and development on future weather data tools and product, alongside engagement with weather-data-users, is needed to make the results more accessible without compromising accuracy.

Understanding Barriers to Real-World Use of Future Weather Data

While future weather data tools have made significant progress, barriers still exist for building owners and managers who want to use this data. Coordination is needed between industry users and dataset developers/modelers to ensure that 1) the future climate and weather tools discussed here are well suited for integration into the field, and 2) the non-technical barriers to deploying and implementing tools and datasets are overcome. This must culminate in building codes, ratings, and standards using future weather files in ways that are useful for avoiding undue risk. In the UK this has already started by incorporation of future weather files as a part of building design criteria. Without such standardization, or a requirement from the building owner, the majority of BEM analysis will not consider future conditions.

A handful of efforts to formally survey US industry users of weather data for buildings have been conducted. ANL has held an internal stakeholder meeting. University of Minnesota with the architecture firm HGA conducted focus groups and online surveys of 144 architecture and engineering professionals, planners, and sustainability specialists from the US, UK and Canada to characterize the data needs and barriers of building architect and engineering professionals (Laxo et al. 2023). NYSERDA conducted stakeholder interviews with six people from NYSERDA, four people from private data/software companies (WeatherShift, White Box Technologies, and Bentley Systems), two from the California Energy Commission, and one person from academia. The main barriers identified by these surveys are summarized in Table 1. Interestingly, the additional cost associated with having to conduct additional analysis was not included as a main barrier.

Table 1. Main barriers to using future weather data in building design.



Barriers cited to using future weather data	Source
Collective action problem-requires coordination between national and international standards and third party protocols	NYSERDA 2020
Lack of vetted data available, lack of confidence in the data available by data users	NYSERDA 2020, Laxo et al. 2023
Lack of data in formats that can be used in BEM	NYSERDA 2020, Laxo et al. 2023
Lack of standardization for creating and using files	NYSERDA 2020, Laxo et al. 2023
Weather data users are not being asked by clients to use future weather data	Laxo et al. 2023
Liability concerns	Laxo et al. 2023
Users lack the time and expertise required to learn how to use data	Laxo et al. 2023

The most recently developed tools and datasets from ORNL, ANL and SNL have worked to reduce these barriers by creating accurate data in the formats needed for BEM. Here we build on the findings of prior surveys and stakeholder interviews, and update them based on the new tools and datasets, to develop new insight into the barriers and data needs that will directly inform ongoing work at the national labs.

Future and Extreme Weather Data Survey - Methods

We conducted an online survey within the building energy sector. The survey was disseminated at the SimBuild conference, through LinkedIn, and via emails to stakeholders from Daniel Villa and Dr. Muehleisen’s research group. Submissions were anonymous and no identifiable information was collected. Every question was optional. The survey included 12 multiple choice questions, and two write-in questions. Three multiple choice questions allowed respondents to write in other responses, which were categorized and included in the figures with “Write in:” (Figures 1 and 2).

Results and Discussion

The survey had 67 respondents from a range of organization types (Figures 1 and 2 are color coded according to organization type). About half of respondents already use future weather data (Table 2). Fewer respondents use extreme weather data (26%), but a larger fraction (66%) would like to. Figures 1-3 summarize the survey results, with the survey question, as written in the survey, in the figure headings.

Table 2: Uptake of weather data among respondents. Total responses for the future weather question was 67, and 38 for the extreme weather question.

Response:	**Do you already use future weather data in your work?**	**Do you already use extreme weather data in your work?**
Yes	54%	26%
No, but I would like to	43%	66%
No, and I am not interested in doing so at this time	3%	8%

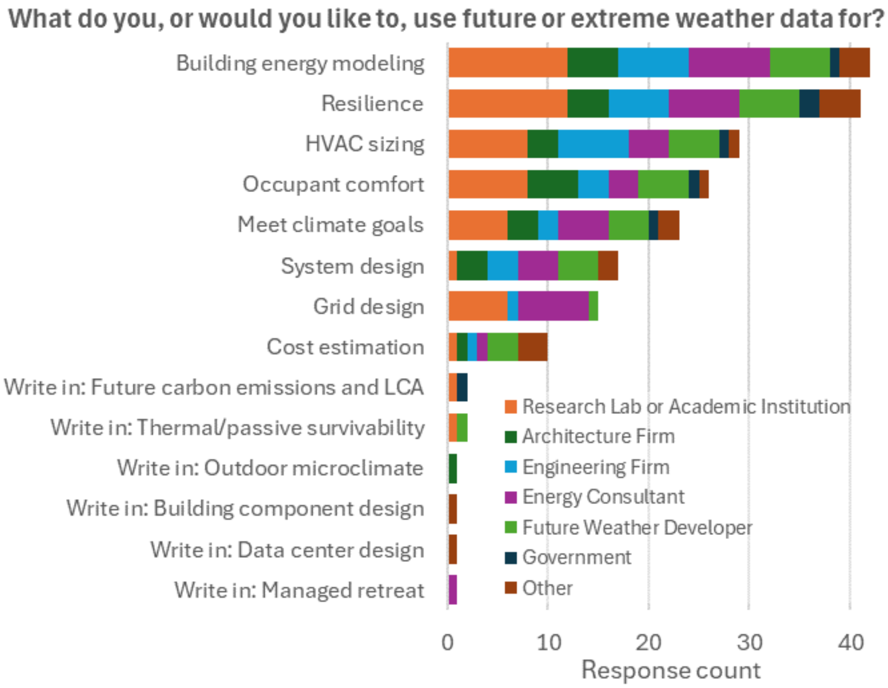


Figure 1: Use cases for future and exreme weather data by organization type. Respondents could select multiple options.

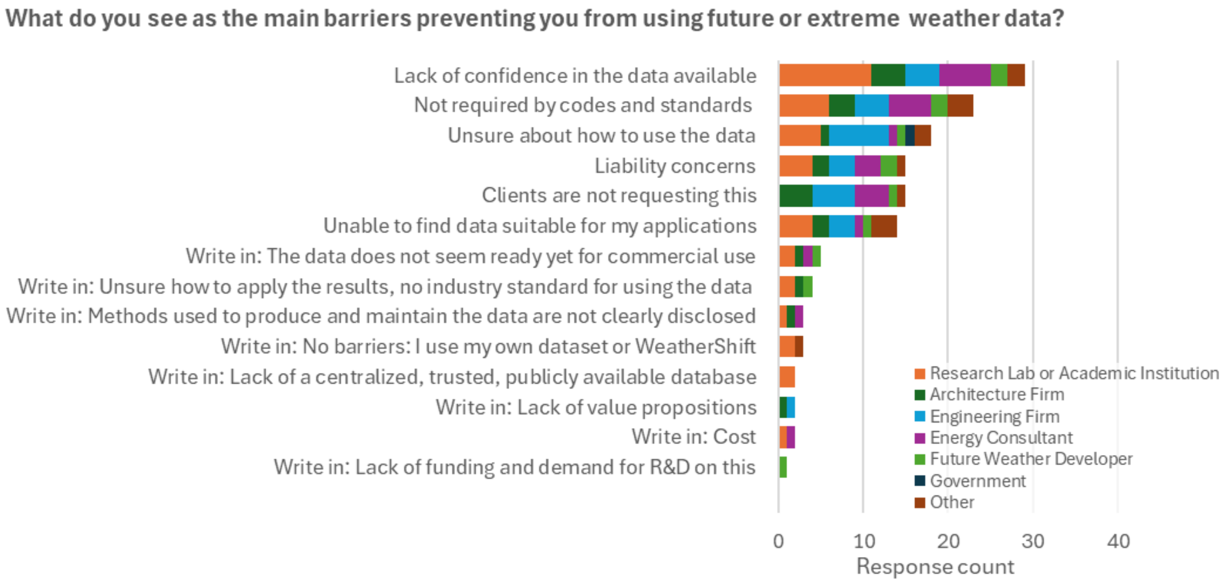


Figure 2: Barriers to broader use by organization type. Respondents could select multiple options.

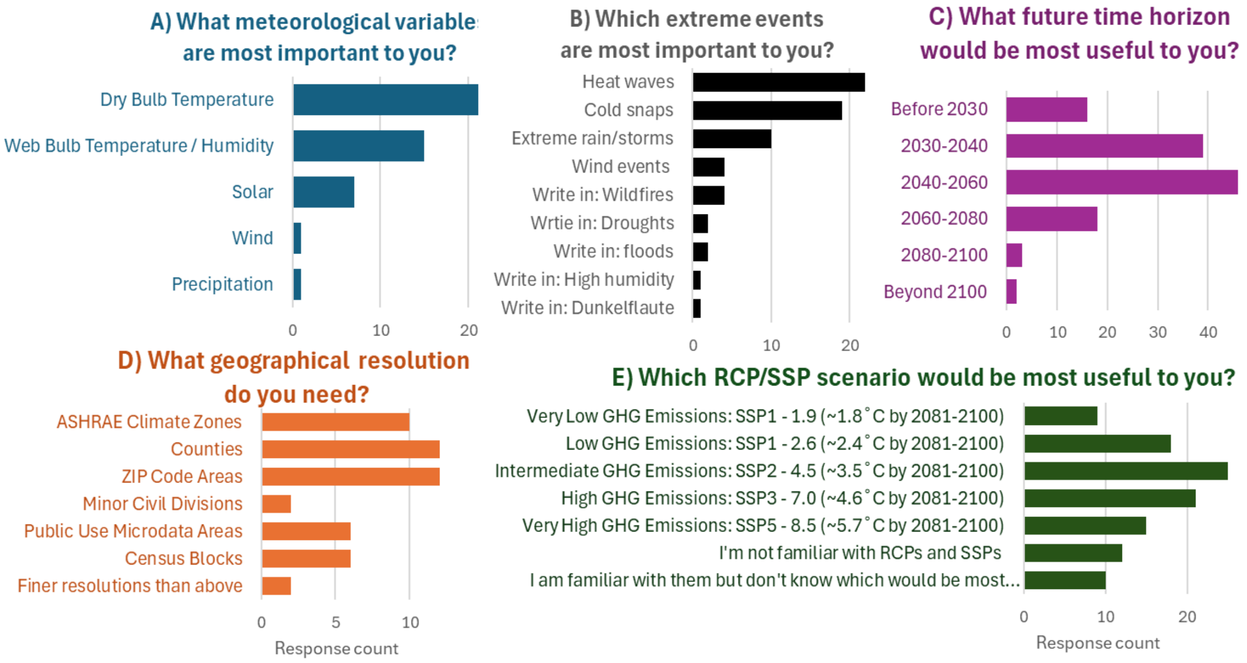


Figure 3: Future and extreme weather data format preferences.

These responses can help pinpoint needed areas for increasing usability of future weather data tools. First, most respondents find temperature extremes most important, while comparatively less are interested in extreme precipitation and wind (Figure 3B). Figure 3A similarly shows almost no respondents indicated that precipitation or wind variables are important to them. Second, respondents are generally much less interested in future weather data beyond year 2060 (Figure 3C) or, third, at spatial resolutions finer than ZIP code level (Figure

3D). Notably, many of the respondents would even be satisfied with data at the ASHRAE climate zone level.

A final survey question asked “Should the use of future or extreme weather files be incorporated into codes, standards, and/or certifications?”, to which 67% of respondents answered “yes”, 15% responded “no”, and 17% responded "other”. The write in comments following “other” largely fell into the following categories: (1) the respondent does not feel experienced enough with future weather data to comment, (2) they would like to see voluntary guidelines (e.g. above code certifications), and (3) that we need a better understanding of how these data can and cannot be used before setting policy around them. Overall, most respondents would like to see future weather data incorporated into codes, standards, and/or certifications, and wrote in an array of thoughts on what this would look like.

Multiple respondents wrote that a central source like DOE providing (1) trusted data and/or (2) guidance on how to use it would make an important contribution. One respondent wrote, “the most important step going forward is to give modelers a guideline for doing a range of different analysis types using future weather.” In response to the question about barriers another wrote in, “I would like a 1-4 hour course on the data files available, their pros and cons and how to correctly apply them and how not to apply them.”

Deployment of these tools will require stakeholder education, especially in the absence of a requirement by codes or standards. A central barrier to better use of future weather data appears to be a bilateral lack of confidence, where future weather producers do not fully trust data users to be able to navigate the complex decision-making process required, and a top barrier reported in our survey to using the data is a “lack of confidence in the data available” (Figure 2). Further research and development on future weather data tools is needed to make the tools more accessible without compromising accuracy, along with coordination between data developers and users (as well as policymakers) to address this bilateral lack of confidence.

Conclusions

We have examined three recently developed data tools that produce different kinds of future weather data. The EPW files from these tools have different use cases and each method has different assumptions built in (e.g. how interannual variability is accounted for, which GCMs, RCMs, downscaling, and observations are selected, and which point within a grid is selected as the representative location for each grid) all of which must be clearly communicated by the developers, and weighed by the users. Accounting for this spatial, temporal, and climate model variability is difficult and can result in significant differences in outcomes (e.g. Rastogi, Kao, Ashfaq 2022; Zhai and Helman 2019). The outcome and impact of these tools and datasets, like all tools, depend on how they are used or misused. Ensuring that the correct tools are used in the correct ways, and empowering weather-data-users to be able to make these decisions, requires coordination across future weather developers, end users, and policymakers. To this end, this stakeholder survey showed that many BEM practitioners currently use future weather for design and would like to use it for extreme event analysis. The majority of survey respondents would like future or extreme weather files to be incorporated into codes, standards, and/or certifications. The top three barriers to broader use were a “lack of confidence in the data available”, “not required by codes and standards” and “unsure about how to use the data”. To overcome these barriers, standardized guidance, training, and trust building between users and developers, and potentially standards and policy requiring their use, are needed. This literature review, stakeholder engagement and survey have sought to move these issues forward, towards achieving a climate-aware built environment.

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