

Climate Change Weather Files: A Comparison of Future Weather Generators for Building Simulation

Corona-Henriques, V.; Monge-Barrio, A.; Idzikowski, I.; Martin, O.; Ruiz-Juncos, L.

Abstract— Considering the increasing pace of GHG emissions and expected climate changes over the 21st century, the demand for reliable future climate projections continues to grow. This research highlights the importance of incorporating future weather projections into building simulations to ensure long-term occupant comfort and optimize building performance towards decarbonization by 2050.

This study reviews and assesses statistical weather generators (WGs) used to create future weather files for evaluating building performance. The analysis examines these WGs based on format, cost, Global Climate Models (GCMs), downscaling methods, resolution, emissions scenarios, output year, and ease of use. From this review, three WGs were selected to apply in a case study: CCWorldWeatherGen (CCWWG), Meteonorm (M), and Future Weather Generator (FWG). These tools were chosen for their robust climate models and ability to simulate different emissions scenarios. The study focuses on two locations with distinct climates, Chicago (USA, 5A) and Madrid (Spain, 3B), under two emissions pathways— high-emission pathway and middle-of-the-road scenario— projected for 2050 and 2080.

A comparative analysis of the weather generated data emphasizes key climate variables relevant to buildings, such as temperature, radiation, heating and cooling degree days, and comfort hours. These weather files are used as inputs for energy demand simulations to evaluate how future climate conditions will affect a small office building, which is modelled according to local building codes.

Results show an overall increase in total energy demand, with variations by scenario. In middle-of-the-road scenarios, demand rises by 5-10% in 2050 and goes up to 12% in 2080. Under high-emissions scenarios, the increase ranges from 5-14% in 2050 and up to 18% in 2080. In Madrid, heating demand declines at least 14% in middle-of-the-road scenarios by 2050 and up to 42% in high-emissions scenarios by 2080. Meanwhile, cooling demand rises by at least 43% by 2050 and up to 117% by 2080. In Chicago, heating demand decreases at least 9% by 2050 and up to 35% by 2080. However, cooling demand increases at least by 26% by 2050 and up to 131% by 2080.

These findings emphasize the need to integrate future weather analysis into building design to enhance resilience, energy efficiency, and sustainability in a changing climate.

Keywords— Weather Generator, Emissions Scenario, Future Weather Files, Climate Projection, Climate Resilience.

I. INTRODUCTION

APPROACHING the study of atmospheric sciences from different perspectives allows us to understand the impacts of climate change on extreme weather phenomena. Climatology and meteorology are two terms that represent different but complementary approaches to understanding the atmosphere. In general, meteorology focuses on atmospheric elements and the state of the atmosphere at a specific time, whereas climatology is dedicated to studying the average conditions of the atmosphere and its elements. [1]

While weather forecasting aims to predict atmospheric conditions over the next few hours or days, climate projections describe how the climate might respond over the coming decades to different greenhouse gas (GHG) emission scenarios and socio-economic developments. These projections involve many assumptions and carry uncertainty—especially for longer timeframes—because of the complex nature of the climate system. The concept of chaos theory, often explained through the “butterfly effect,” shows how small changes in current measurements can lead to large differences in long-term predictions. [2]

To interpret this historical data, it is essential to understand Earth’s carbon cycle. This biogeochemical process, active since the formation of the Solar System, moves carbon between the atmosphere, oceans, biosphere, and land. Chemical reactions between CO₂ and minerals lead to the formation of carbonates, which are transported to the oceans and eventually buried as sediment. Over long timescales, these sediments are recycled through volcanic activity, releasing CO₂ back into the atmosphere. This cycle has helped regulate Earth’s CO₂ levels over millions of years. [3] [4]

The current rise in CO₂, although natural, has been expedite by human activities and is expected to lead to sea-level rise, more frequent extreme weather, and changes in ecosystems. It is the combination of natural processes and human influence that is reshaping the climate, making it urgent to understand and reduce our impact. Model results suggest that global warming in this century could exceed the temperatures of the Last Glacial Maximum and even the warmest periods of the Holocene, taking the

climate system into conditions outside human experience. [5]

Climate change is already affecting key parts of society, such as health, food production, water supply, transportation, energy, and biodiversity. These impacts are expected to become more disruptive in the coming decades. Recent evidence shows with high confidence that the climate is warming and that is linked to an increase in extreme events, like heatwaves and heavy rainfall. While the risk of other events like floods or droughts will vary by location, the general trend is toward more intense extremes as temperatures rise. [6]

A stable climate depends on a balance between the energy the Earth receives from the Sun and the energy it emits back into space. Over the last century, this balance has been disrupted by the increase in GHGs from human activities. This extra energy trapped in the system is responsible for the enhanced greenhouse effect. Natural factors like volcanoes or changes in solar activity cannot explain the size and timing of the changes we now observe. Climate forcing refers to changes in the Earth's energy balance. Radiative Forcing (RF) is the standard way of measuring this, a positive RF leads to warming; negative RF leads to cooling. RF helps scientists understand how different factors influence global temperatures. Data from 1750 to 2011 shows changes in RF from various agents and includes uncertainty estimates. [5]

To understand how the climate system behaves and to predict its future, scientists use climate models. These models—often called General Circulation Models (GCMs)—solve equations to simulate how water vapor, CO₂, heat, and Earth's rotation interact. Developed by teams of scientists and programmers, their results help create climate projections based on different scenarios. Early models handled different components separately, but today's models are more complex and combine systems like the atmosphere and oceans. They divide the Earth into 3D grid cells to capture regional differences. However, some small-scale processes still must be simplified. With better computing power, model resolution and accuracy have increased, but running these models still requires powerful supercomputers. [7]

The World Climate Research Program (WCRP) is an international collaborative group of scientists and modeling experts whose primary goal is to develop and oversee the Coupled Model Intercomparison Project (CMIP). [5]

CMIP's goal is to improve our understanding of past, present, and future climate changes using a common modelling framework. This includes studying natural variability, responses to radiative forcing, and model performance. CMIP organizes and coordinates experiments involving multiple climate models and their climate responses under different future scenarios based on possible human development paths. [8]

These scenarios show different ways the future might unfold. They are not predictions, but useful tools for

studying the possible effects of changes in emissions and for evaluating risks and planning responses. The scenario-based approach has changed over the years—from focusing mainly on climate to focusing more on how societies may develop, while still looking at climate outcomes.

CMIP's evolution—through phases like CMIP3, CMIP5, and CMIP6—has led to increasingly sophisticated frameworks for emissions scenarios.

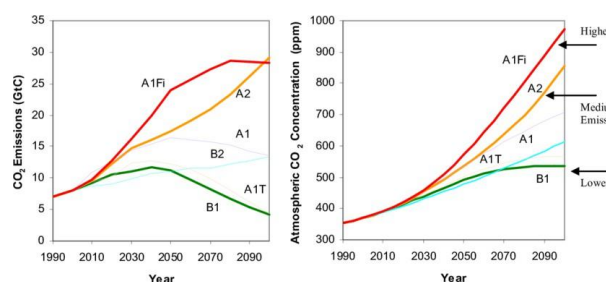


Fig. 1. CMIP3 – Special Report on Emissions Scenarios (IPCC)

A. CMIP3 – SRES Scenarios

The SRES scenarios used in CMIP3 are based on four narrative storylines (A1, A2, B1, B2), each describing different global development paths in terms of population growth, economic activity, and technology. These scenarios do not include climate policy and are purely emission driven. The main differences lie in whether the world becomes more globalized or regionalized, and whether growth is fast or uneven. They were the first widely used framework for projecting future emissions and their impact on climate.

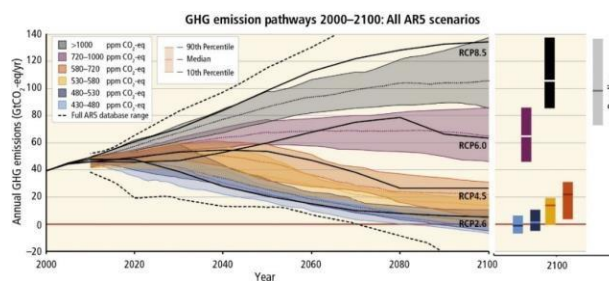


Fig. 2. CMIP5 – Representative Concentration Pathways (IPCC)

B. CMIP5 – RCP Scenarios

CMIP5 introduced the Representative Concentration Pathways (RCPs), which focuses on future levels of radiative forcing by 2100 rather than socioeconomic storylines. The four RCPs (2.6, 4.5, 6.0, 8.5) represent different greenhouse gas concentration levels and associated warming outcomes, ranging from strong mitigation (RCP2.6) to high emissions without policy

action (RCP8.5). This marked a shift from emissions scenarios to concentration-driven climate modeling.

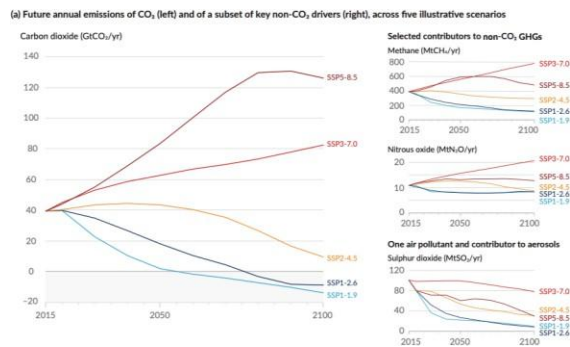


Fig. 3. CMIP6 – Socio-Economic Pathways (IPCC)

C. CMIP6 – SSP Scenarios

CMIP6 combines updated socioeconomic pathways (SSPs) with climate targets similar to the RCPs, offering a more flexible and integrated framework. Each SSP describes different development trends (e.g., sustainability, inequality, regional rivalry) and can be linked to different climate policy goals. This approach allows a broader exploration of how societal choices affect both emissions and the ability to mitigate or adapt to climate change.

These emissions scenarios reflect different futures, from strong mitigation to fossil-fuelled growth, and serve as inputs for GCMs to generate a range of climate projections. However, GCMs operate at coarse spatial scales (often >100 km), making them insufficient for local analysis. Therefore, downscaling techniques—either dynamical (via regional climate models) or statistical—are applied to adapt global outputs to local conditions.

In the context of building performance, these downscaled projections help simulate future heating and cooling demands under varying climate conditions. This study contributes to understanding how WG tools handle these inputs and support climate-resilient design. While projections involve uncertainty, they remain essential for long-term planning and adaptation.

II. COMPARATIVE ANALYSIS OF TOOLS

1. WEATHER GENERATORS (WG)

Weather generators are the statistical models that can simulate a series of meteorological variables from empirical data. These are typically based on a daily time step, which often is an effective resolution for impact studies, but sub-daily scale weather generators can also be used. There are primarily two main types of weather generators: statistical and stochastic models.

Despite stochastic weather generators offering greater realism, statistical WGs are gaining traction due to their computational efficiency, lower data requirements, and simpler structure. These factors make them more practical for many applications, especially those requiring rapid

data generation or operating with limited resources. While advancements in statistical modelling enhance their capabilities, stochastic models remain valuable for specific applications demanding high accuracy and the simulation of extreme events. (See Table I)

Table II explores the technical capabilities of the current available tools for climate projection, while Table III does a qualitative assessment of the selected tools for the following experiment.

TABLE I
EXAMPLE VARIABLES AND UNITS

	Statistical	Stochastic
Concept	Based on empirical relationships: These models use statistical relationships between weather variables to generate daily values.	Based on probabilistic models: These models simulate weather variables as random processes, following statistical distributions that capture the observed patterns in historical data.
Pros	Computational efficiency: Relatively fast and easy to run compared to stochastic models. Data requirements: Typically require less data than stochastic models.	High level of realism: Can accurately reproduce the statistical properties of observed weather data, including extreme events. Theoretical foundation: Based on sound statistical and probabilistic principles.
Cons	Difficulty in simulating extremes: Often struggles to reproduce extreme weather events. Oversimplification: May oversimplify the underlying physical processes of weather generation.	Computational intensity: Requires significant computational resources, especially for long-term simulations. Model complexity: Can be challenging to develop and implement, requiring specialized expertise.

TABLE II
TECHNICAL CHARACTERISTICS COMPARATIVE TABLE OF WG (2024)

	Meteonorm	CC World Weather Generator	Weather Shift	Future Weather Generator	Re-Climate	SimClim	Climate Data for Building Performance Simulation (CDBPS)	epwshiftr
Type	Statistical/Stochastic	Statistical	Statistical	Statistical	Statistical	Statistical	Statistical	Statistical
Tool Format	Software	Excel Based	Online	Software	JavaScript	Software	Software Integrated	CRAN
Cost	675 € first license, 350 € additional license	Free	First Scenario \$285 Each Additional Scenario \$200	Free	Free	30\$ monthly for students, 6997\$ per year for businesses	895 € for 1 user for 1 year (without taxes)	Free
Global Climate Model (GCM)	CMIP5	HadCM3	CMIP5	CMIP6	Weather Logistics' statistical model (A) from Copernicus (B)	CMIP6	HadCM3	CMIP6
Resolution	100x100km	417km x 278 km	100x100km	25x25km	–	25x25km	417km x 278 km	25x25km
Downscaling Method	Statistical and Interpolation between local weather stations and GCM	Morphing	Morphing	Bilinear interpolation, nearest point, or averaging four points.	Statistical	Bilinear interpolation method	Morphing	Morphing
Regional Climate Model (RCM)	No RCM	For UK UKCIP02	Uses an Ensemble of various RCM for their 259 Cities	RCM for Portugal	No RCM	Depends on country	No RCM	No RCM
Resolution	–	5x5km	Unknown resolution of the models	–	–	–	–	–
Initial conditions	GCM Statistical and Interpolation with Local Weather Stations	EPW File	EPW File	EPW File	CSV	CSV	EPW	EPW
Historical Baseline Period	1961-1990 and 2000-2019	1983–2004	1976-2005	1985-2014	2017-2021	1991-2020	1980-2023	Depends on the EPW
Emissions scenarios	RCP (Representative Concentration Pathways)	SRES (Special Report on Emissions Scenarios)	RCP (Representative Concentration Pathways)	SSP (Shared Socioeconomic Pathways)	Climate Forecast Hazards	SSP (Shared Socioeconomic Pathways)	SRES (Special Report on Emissions Scenarios)	SSP (Shared Socioeconomic Pathways)
Downscaled Final Resolution	8km (Worldwide) 3km (Europe)	295 km x 278 km	Unknown resolution of the models	6km	5km	1km	Unknown	1°x1°
Format Output	EPW, TMY2, and many others	EPW or TMY2	EPW	EPW and CSV	GeoJSON and CSV	PDF, Word, CSV, or Excel	EPW	EPW
Years Output	2020-2050 2050-2080 2080-2100	2020 (2011-2040) 2050 (2041-2070) 2080 (2071-2100)	2020, 2030, 2040, 2050, 2060, 2070, 2080, 2090	2050, 2080	Up to 2040	Yearly until 2100	Not Specified	Not Specified

TABLE III
TECHNICAL CHARACTERISTICS COMPARATIVE TABLE OF WG (2024)

	CC World Weather Generator	Meteonorm	Future Weather Generator
Installation difficulty (1-3)	3	1	2
Usage difficulty (1-3)	1	2	1
Features	• Excell based and free to use. • Can generate future weather data from any location (only needs the input .EPW file). • Output format compatible with other software (.EPW or .TMY).	• Software is self-contained, has all their own data. • Wide range of output formats compatible with other software • User friendly interface. • Data is considered as “reliable” because it is based on a combination of ground-based measurements and satellite data. • Can calculate more than 30 climatic parameters. • Allows you to select a specific year (intervals of 10 years) and scenario for calculation.	• Open-source and free to use. • Model can be considered as the most up to date (CMIP6) and uses the latest emissions scenarios (SSP). • Can generate future weather data from any location (only needs the input .EPW file). • Output format compatible with other software (includes .STAT file). • Fixed problems with parameters (Snow depth, Extreme periods, Present Weather Observation, Present Weather Code, Liquid Precipitation Depth) to morph data from the GCM.
Limitations	• Model can be considered as too coarse (CMIP3). • For the software to work, the user must download the data from the IPCC data center. Process can take time. • Focuses solely in the A2 from SRES scenarios. Averages scenarios A2a, A2b, and A2c to obtain A2. • Problems with certain parameters (Snow depth, Extreme periods, Present Weather Observation, Present Weather Code, Liquid Precipitation Depth) may cause inaccuracies with energy simulation. • Limited Support and Updates (since 2017). • The tool averages the four nearest location points for morphing. • Generates 3 future time slices and one is “outdated” (2020).	• Cost. • Model can be considered as too coarse (CMIP5). (Update of the platform is coming soon with CMIP6 and SSP scenarios). • Doesn’t allow for input files. • Data accuracy may decrease in regions with sparse weather station coverage or complex terrains.	• Installation requires basic Java knowledge. • The software calculates only two time slices 2050 and 2080. • Software doesn’t allow to select a specific year nor scenario but rather calculates both years for all scenarios.

2. BUILDING SIMULATION TEST

a. Building and Climate

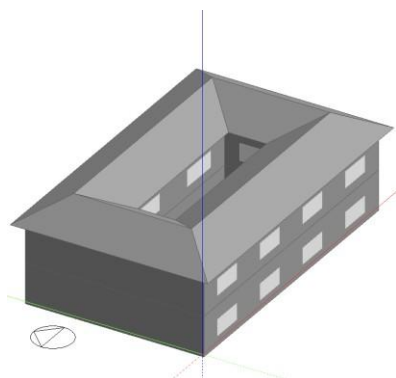


Fig. 4. Design Builder – Courtyard Model

This study investigates the impact of climate conditions on building energy performance using different weather generators (WGs). Two locations, Madrid and Chicago, were chosen to represent distinct climates: Madrid (hot, dry) in Climate Zone 3B and Chicago (cold, temperate) in Climate Zone 5A, classified according to their corresponding ASHRAE Climate Zone. These cities were selected to analyze a broad range of climatic conditions, ensuring comprehensive insights into energy demand variations across climates.

The study uses a two-story office building model, referred to as the "courtyard model," with a total area of 575 m². It incorporates typical office building load profiles for lighting, occupancy, and office equipment based on location-specific building codes. In Madrid, the building follows Spain's Código Técnico de la Edificación (CTE), with a masonry facade and specific insulation standards. For Chicago, the building adheres to ASHRAE 90.1 2019, using a metallic frame and insulation requirements specific to the cold climate. These regulatory standards influence the building's energy demand calculations for heating and cooling.

b. Climate KPIs

The simulation focused on temperature, radiation, cooling degree days (CDD), heating degree days (HDD), and comfort hours as key performance indicators (KPIs). These parameters were chosen for their direct impact on energy performance and human comfort under changing climate conditions. The weather data for both cities was sourced from One Building EPW files, with selected timeframes ensuring the data's temporal relevance.

c. Tools and Emissions Scenarios

To assess future climate scenarios, the study used three WGs: CCWorldWeatherGenerator [9], Meteonorm [10], and Future Weather Generator [11]. These tools generated EPW files reflecting different emissions scenarios: A2 (SRES), RCP 4.5 (middle-of-the-road), RCP 5.8 (business-as-usual), and SSP 2-4.5 (middle-of-the-road), SSP 5-8.5 (business-as-usual). By simulating these scenarios, the

study aimed to evaluate the impact of future climate conditions on energy demand.

d. Baseline

Baseline energy performance was calculated by simulating heating and cooling demands for both Madrid and Chicago. The simulation results were compared with ASHRAE benchmark data for similar climate zones. For Madrid, the simulation showed a heating demand of 16.80 kWh/m² and cooling demand of 55.59 kWh/m², while for Chicago, heating demand was 29.48 kWh/m², and cooling demand was 69.78 kWh/m².

e. Madrid Results and Analysis

The analysis of future climate projections for Madrid reveals significant changes in temperature, solar radiation, and energy demand for office buildings by mid- and late century. (See Annex 1) Under various emissions scenarios—including CCWWG A2, M -RCP 4.5/8.5, and FWG SSP 2-4.5/5-8.5—average annual temperatures are projected to increase by 15% to 23% by 2050, rising from the current baseline of 14.5°C to as high as 17.8°C. By 2080, this increase could reach 42%, with average temperatures climbing to 20.5°C under the SSP 5-8.5 scenario. Maximum temperatures are expected to rise by up to 16% by 2050 and 27% by 2080, potentially reaching 44.4°C. Although the rise in minimum temperature is less extreme, it has critical implications, including the disappearance of sub-zero winter temperatures, with increases from -2.0°C to 1.6°C by 2080 under high-emission scenarios.

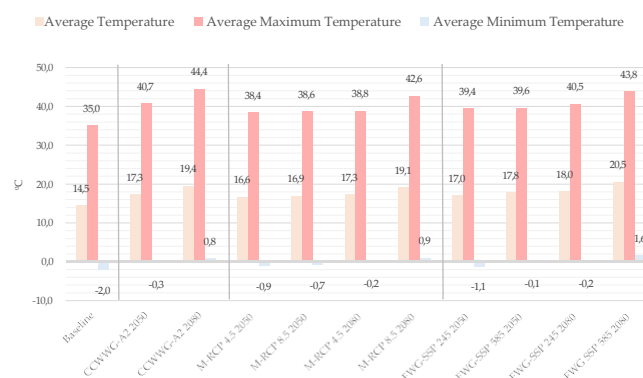


Fig. 5. Madrid – Temperature Projection

In addition to temperature shifts, solar radiation patterns are projected to change, with annual cumulative horizontal solar radiation increasing by up to 11% by 2050 and 12% by 2080. This is coupled with a marked decline in diffuse solar radiation—down by over 34%—indicating more intense direct sunlight and greater potential for solar heat gain. Degree day analysis supports these projections, showing a substantial reduction in HDD and a dramatic rise CDD. By 2080, HDD could drop by 76% under the SSP 5-8.5 scenario, while CDD may increase by 183%, pointing to a significant rise in cooling energy requirements. These findings underscore a clear trend toward higher cooling demands and reduced heating needs, with the most severe impacts associated with high-emission scenarios.

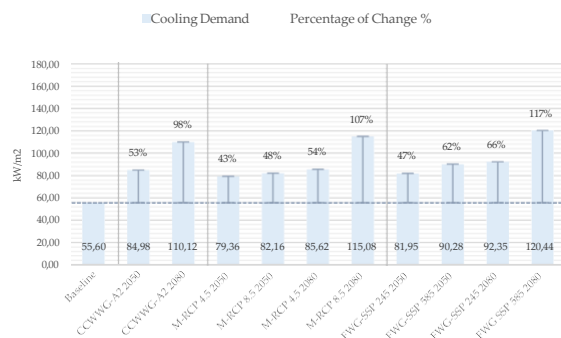


Fig. 6. Madrid – Cooling Demand

The projected energy demand reflects the climatic shift, with particularly sharp increases in cooling requirements. By 2050, cooling energy demand is expected to rise by 43% to 62%, increasing from a baseline of 55.60 kWh/m² to values between 79.36 kWh/m² (RCP 4.5) and 90.28 kWh/m² (SSP 5-8.5). This upward trend intensifies by 2080, with projected increases ranging from 53% to 117%, reaching up to 120.44 kWh/m² under SSP 5-8.5. Even under moderate scenarios, cooling demands remain significantly elevated, indicating increased energy loads during warmer months and a heightened need for efficient cooling strategies.

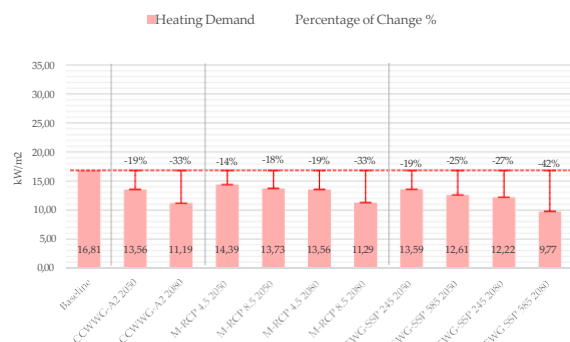


Fig. 7. Madrid – Heating Demand

In contrast, heating energy demand is anticipated to decline, consistent with rising minimum temperatures and reduced heating degree days. By 2050, heating demand may drop by 14% to 25%, reaching between 14.39 kWh/m² (RCP 4.5) and 12.61 kWh/m² (SSP 5-8.5). By 2080, this reduction could deepen to 42%, with the lowest value recorded at 9.77 kWh/m² under the high-emission SSP 5-8.5 scenario.

Overall, total annual energy demand is expected to increase modestly by 5–7% by 2050, and by 6–13% by 2080, primarily driven by the surge in cooling energy use. These shifts underscore the critical importance of adapting building design and operational strategies to mitigate the impacts of climate change and ensure long-term occupant comfort and energy efficiency.

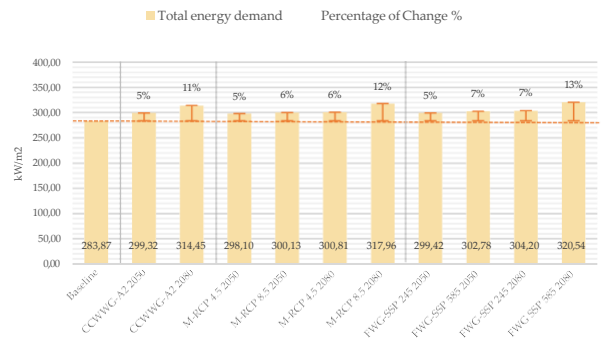


Fig. 8. Madrid – Total Energy Demand

f. Chicago Results and Analysis

The future climate of Chicago projects drastic increases in temperature, solar radiation, and building energy loads during mid- and late century. (See Annex 2) The mean annual temperatures are likely to increase by 6% to 32% by 2050, from a baseline of 11.4°C to 12.1°C to 15.1°C. By 2080, under the SSP 5-8.5 scenario, mean temperatures are expected to go up by up to 54% to 17.5°C. Maximum temperatures in summer are also expected to rise, though less severely—from 32°C to 32.1°C (RCP 4.5) and 36.5°C (SRES A2) by 2050 (0.3% to 14% increase), and 40.9°C by 2080, a 28% increase. The winter minimum temperatures are projected to rise more notably, from -18°C to between -13.2°C and -11.1°C by 2050 (27% to 38% rises), and as high as -7.9°C by 2080 (a 56% rise under FWG), suggesting a reduction in cold extreme days.

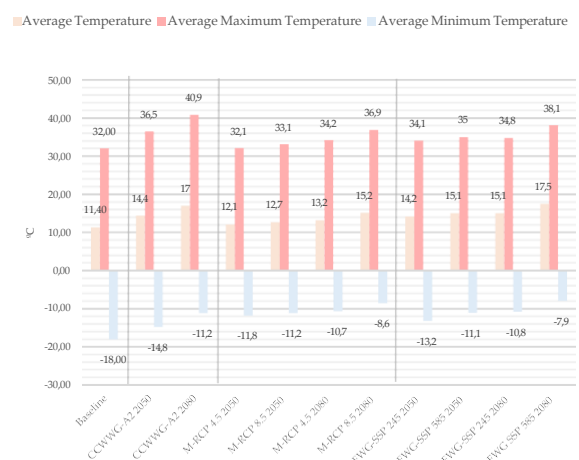


Fig. 9. Chicago – Temperature Projection

Patterns of solar radiation are also likely to change. Cumulative horizontal solar irradiation is projected to increase from a baseline of 1377.24 kWh/m² to 1380.72 kWh/m² (SSP 2-4.5) to 1434.99 kWh/m² (RCP 8.5) by 2050—an increase of 0.3% to 4%. By 2080, it could be 1444.34 kWh/m² (an increase of 5%). Diffuse horizontal solar radiation trends vary, with SRES A2 projecting a decrease of 6% in 2050 and as much as 9% by 2080. FWG scenarios predict decreases of 0.6–2% in 2050 and 1–3% in 2080. In contrast, Meteonorm RCP 4.5 predicts increases of 3% by 2050 and 2% by 2080. These changes mean greater direct

solar gain and less atmospheric scattering, which will affect daylighting and passive solar heating strategies.

Degree day and comfort hour computations underscore the importance of these climatic shifts. HDD will decrease from a reference of 1458 days to 1322 (RCP 4.5) and 825 (SSP 5-8.5) in 2050—a decrease of 9% to 43%. By 2080, HDD can go down by as high as 59%, to 599 days (SSP 2-4.5). In contrast to CDD, which are expected to rise sharply, from 691 days to 1172 (SRES A2) to 1208 (RCP 4.5) by 2050—a rise of 70% to 75%. By 2080, CDD could rise to 1621 days (SRES A2), a rise of 135%. Comfort hour analysis shows that the percentage of hours below comfort thresholds decreases from 73% to 70–64% by 2050, while hours above comfort thresholds will more than double—from 12% to between 14% and 23%. By 2080, it could rise to 30% (SRES A2), emphasizing the growing importance of cooling measures, building envelope optimization, and thermal adaptation.

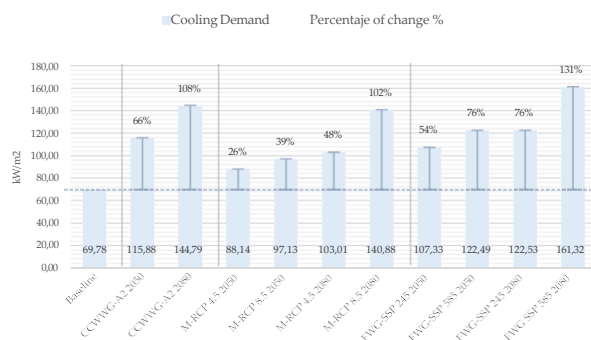


Fig. 10. Chicago – Cooling Demand

The projected energy demand reflects these climatic shifts, with a particularly sharp rise in cooling requirements. By 2050, cooling energy demand per square meter is expected to increase by 26% to 76%, from a baseline of 69.78 kWh/m² to values between 88.14 kWh/m² (RCP 4.5) and 122.53 kWh/m² (SSP 5-8.5). This upward trend intensifies by 2080, with projected increases reaching 131% and cooling demand rising to 161.32 kWh/m² under SSP 5-8.5. These increases will place greater pressure on energy infrastructure and operational budgets, particularly during peak summer periods.

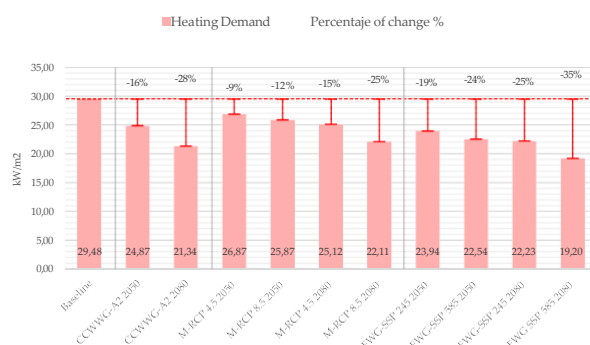


Fig. 11. Chicago – Heating Demand

Conversely, heating energy demand is projected to decline, consistent with milder winters and fewer heating

degree days. By 2050, heating demand may decrease by 9% to 24%, from 29.48 kWh/m² to values between 26.87 kWh/m² (RCP 4.5) and 22.54 kWh/m² (SSP 5-8.5). By 2080, this reduction may deepen to 35%, with heating needs falling to 19.20 kWh/m² under high-emission scenarios.

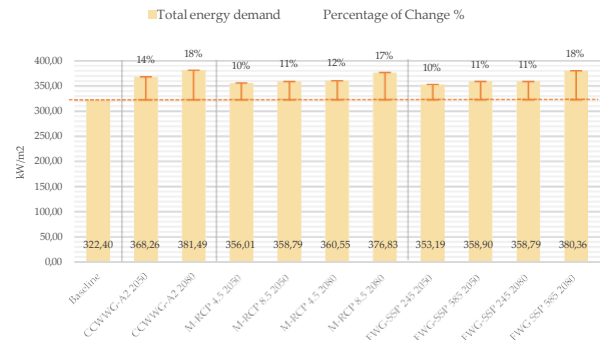


Fig. 12. Chicago– Total Energy Demand

Total annual energy demand is projected to increase modestly. By 2050, total demand may rise by 10% to 14%, from 322.40 kWh/m² to 356.01 kWh/m² (RCP 4.5) and up to 368.26 kWh/m² (SRES A2). By 2080, further increases of 11% to 18% are expected, with the highest projection reaching 381.49 kWh/m² under SRES A2. These increases are primarily driven by the surge in cooling demand and signal a fundamental shift in energy usage patterns.

These projections for Chicago highlight a clear trend toward increased cooling requirements, reduced heating needs, and overall higher energy demands under future climate scenarios. The findings emphasize the critical importance of adaptive building design, energy-efficient systems, and climate-resilient operational strategies to ensure occupant comfort and long-term performance in a warming climate.

III. ANALYSIS

This study compares the methodologies and climate projections of three weather generators—Meteonorm, CCWorldWeatherGen, and Future Weather Generator—with the aim of assessing their impact on building energy performance and occupant comfort under different emissions scenarios. All models indicate a general trend of rising temperatures, increasing radiation levels, and shifting heating and cooling demands, though the magnitude of these changes varies depending on the chosen emission pathway and weather generator. Notably, Future Weather Generator under SSP 5-8.5 and CCWorldWeatherGen under A2 show the most extreme increases in temperature across all parameters—average, minimum, and maximum—suggesting heightened energy demands for cooling and greater potential for thermal discomfort in inadequately ventilated or shaded buildings. In contrast, Meteonorm under RCP 4.5 and Future Weather Generator under SSP 2-4.5 reflect more moderate changes, indicating milder impacts.

Radiation trends follow a similar pattern. Meteonorm's RCP 8.5 scenario projects the most significant increase in cumulative and direct solar radiation, which may support passive heating strategies but also presents risks of overheating, particularly in warmer seasons. CCWorldWeatherGen offers moderate projections in this category, while Future Weather Generator under SSP 2-4.5 shows the lowest impact. These shifts in radiation levels also correspond with a reduction in diffuse radiation, increasing the share of direct radiation, which may benefit solar gain strategies but simultaneously raise the risk of occupant discomfort and overheating without proper shading systems or enhanced ventilation strategies.

The analysis of cooling and heating degree days highlights a strong transition toward cooling-dominant energy profiles. Across both locations, there is a clear increase in CDD and a decline in HDD, underscoring the need for adaptive HVAC systems capable of handling higher cooling loads while maintaining efficiency. This pattern is most evident under Future Weather Generator's SSP 5-8.5 scenario, while Meteonorm continues to present the lowest impact projections, though still indicating a substantial shift. These findings also align with trends in comfort hours, where increases in hours above the comfort threshold suggest rising discomfort levels and greater dependence on mechanical cooling, while a reduction in hours below the threshold confirms a warming trend.

Energy demand projections reflect all these climatic shifts. Future Weather Generator consistently shows the highest increase in total energy demand, especially under SSP 5-8.5, with estimated rises of 5–10% by 2050 due to climate change alone. Meteonorm's results are more conservative but remain reliable due to its robust methodology, which incorporates satellite and ground-based measurements, sophisticated interpolation models, and adjustments for local conditions. Despite producing milder outputs, Meteonorm is theoretically strong and highly applicable across diverse geographical contexts.

Future Weather Generator stands out for its use of updated CMIP6 data, finer spatial resolution, and preservation of variables such as snow depth, rainwater collection, and surface moisture indicators—making it particularly suitable for advanced building simulations. It also supports various interpolation techniques and generates both typical and extreme weather periods, providing a comprehensive tool for performance analysis under future conditions.

Conversely, CCWorldWeatherGen uses a morphing approach based on GCM data, which, while simpler and less precise, remains accessible for users with limited computational resources. Its medium-high scenario A2 allows for broadly realistic projections, making it a practical tool for early-stage assessments or educational use.

Despite their strengths, all three weather generators show limitations in modelling complex variables like wind, precipitation, and extreme weather events. These

phenomena are influenced by numerous dynamic and localized factors that are difficult to capture in generalized statistical models. As such, more specialized tools are recommended when these variables play a significant role in building design. Nonetheless, each generator provides valuable insights into future climatic impacts on buildings, and the choice of tool depends largely on the user's goals, expertise, and required level of detail. Ultimately, the findings emphasize the urgent need for energy-efficient, flexible, and low-carbon design strategies to adapt buildings to the realities of climate change

IV. CONCLUSION

This investigation highlights the critical impact of climate change on building energy performance and occupant comfort. As greenhouse gas emissions rise, temperatures increase and weather patterns shift, leading to higher energy demands across all emissions scenarios.

The study aimed to assess all available – to the date – weather generators in terms of their technical capabilities to aid the decision-making process when considering climate projections.

By comparing three weather generation tools—CCWorldWeatherGen, Meteonorm, and Future Weather Generator—the study shows that while all models predict similar trends, the extent of projected impacts varies based on emissions scenarios and methodological approaches.

TABLE IV
USE-CASE WEATHER GENERATOR

	CCWWG	M	FWG
Low Resolution Weather Analysis	x	x	x
High Resolution Weather Analysis		x	x
Energy Simulation		x*	x
Adaptation Strategies			x

*Data provided for energy simulation would be from RCPs and would require an update to the SSPs

High-emissions scenarios (SRES A2, RCP 8.5, SSP 5-8.5) show the greatest increases in total energy demand—up to 18%—with significant shifts in cooling and heating loads. Even mid-range scenarios (RCP 4.5, SSP 2-4.5), which assume some mitigation, indicate a 5–14% rise. The Future Weather Generator, using the latest CMIP6 data, produces the most severe projections but also offers the most advanced simulation capabilities. Meteonorm, while based on older CMIP5 data, applies a robust methodology that yields conservative yet impactful estimates. CCWorldWeatherGen, though less detailed, provides a broad overview using CMIP3 and SRES A2.

Overall, the results indicate a 5–18% increase in total energy demand, varying by emissions scenario and time horizon. Middle-of-the-road scenarios show a 5–10% rise by 2050, reaching up to 12% by 2080, while high-emissions scenarios result in a 5–14% increase by 2050 and up to 18% by 2080. This rise is primarily driven by a significant surge in cooling demand—at least 43% in Madrid and 26% in Chicago by 2050, reaching 117% and 131% respectively by 2080. Meanwhile, heating demand declines, with reductions of at least 14% in Madrid and 9% in Chicago by

2050, and up to 42% and 35% respectively by 2080 under high-emissions conditions. This underscores the urgent need for adaptive, energy-efficient building design and the integration of future weather files in planning processes. As urbanization accelerates and cities become major GHG emitters, the construction industry must lead in adopting low-carbon strategies.

Given the rapid pace of anthropogenic warming, reducing carbon emissions is essential. The building sector holds a key ethical and practical responsibility to mitigate climate change by designing resilient, efficient, and future-ready buildings.

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APPENDIX 1:
TABLE V
MADRID RESULTS

			CC World Weather Generator				Meteonorm								Future Weather Generator							
			2050		2080		2050				2080				2050				2080			
			A2	% Change	A2	% Change	RCP 4.5	% Change	RCP 8.5	% Change	RCP 4.5	% Change	RCP 8.5	% Change	SSP 245	% Change	SSP 585	% Change	SSP 245	% Change	SSP 585	% Change
Average Temperature	°C	14.50	17.30	19.31%	19.40	33.79%	16.60	14.48%	16.90	16.55%	17.30	19.31%	19.10	31.72%	17.00	17.24%	17.80	22.76%	18.00	24.14%	20.50	41.38%
Average Maximum Temperature	°C	35.00	40.70	16.29%	44.40	26.86%	38.40	9.71%	38.60	10.29%	38.80	10.86%	42.60	21.71%	39.40	12.57%	39.60	13.14%	40.50	15.71%	43.80	25.14%
Average Minimum Temperature	°C	-2.00	-0.30	-85.00%	0.80	-140.00%	-0.90	-55.00%	-0.70	-65.00%	-0.20	-90.00%	0.90	-145.00%	-1.10	-45.00%	-0.10	-95.00%	-0.20	-90.00%	1.60	-180.0%
Annual Accumulative horizontal radiation	kWh/m ²	1624.6	1702.6	4.80%	1752.3	7.86%	1799.0	10.73%	1796.6	10.59%	1803.8	11.03%	1816.1	11.79%	1701.6	4.74%	1687.8	3.89%	1709.2	5.21%	1733.5	6.70%
Percentage of diffuse horizontal solar radiation	%	45.10%	41.00%	-9.09%	37.50%	-16.85%	29.50%	-34.59%	29.40%	-34.81%	28.90%	-35.92%	28.50%	-36.81%	41.30%	-8.43%	42.30%	-6.21%	40.80%	-9.53%	39.20%	-13.08%
Heating Degree Days	10°C Base	489.00	282.00	-42.33%	171.00	-65.03%	373.00	-23.72%	355.00	-27.40%	307.00	-37.22%	214.00	-56.24%	344.00	-29.65%	246.00	-49.69%	245.00	-49.90%	116.00	-76.28%
Cooling Degree Days	18°C Base	683.00	1255.0	83.75%	1717.0	151.39%	1163.0	70.28%	1225.0	79.36%	1272.0	86.24%	1708.0	150.07%	1204.0	76.28%	1313.0	92.24%	1392.0	103.81%	1933.0	183.0%
Below Comfort Hours	%	74.40%	63.90%	-14.11%	56.30%	-24.33%	61.40%	-17.47%	62.90%	-15.46%	58.50%	-21.37%	55.90%	-24.87%	60.00%	-19.35%	60.70%	-18.41%	56.50%	-24.06%	52.40%	-29.57%
Above Comfort Hours	%	12.30%	22.20%	80.49%	29.10%	136.59%	23.10%	87.80%	22.40%	82.11%	25.10%	104.07%	29.50%	139.84%	24.10%	95.93%	24.10%	95.93%	27.60%	124.39%	33.60%	173.1%
Comfort hours	%	13.30%	13.80%	3.76%	14.60%	9.77%	15.50%	16.54%	14.70%	10.53%	16.30%	22.56%	14.70%	10.53%	15.90%	19.55%	15.20%	14.29%	15.90%	19.55%	14.00%	5.26%
Cooling	kWh/m ²	55.60	84.98	52.84%	110.12	98.06%	79.36	42.74%	82.16	47.77%	85.62	54.00%	115.08	106.99%	81.95	47.40%	90.28	62.38%	92.35	66.10%	120.44	116.6%
Heating	kWh/m ²	16.81	13.56	-19.31%	11.19	-33.40%	14.39	-14.41%	13.73	-18.33%	13.56	-19.34%	11.29	-32.85%	13.59	-19.16%	12.61	-24.98%	12.22	-27.27%	9.77	-41.84%
Total	kWh/m ²	283.87	299.32	5.44%	314.45	11.77%	298.10	5.01%	300.13	5.73%	300.81	5.97%	317.96	12.01%	299.42	5.48%	302.78	6.66%	304.20	7.16%	320.54	12.92%

APPENDIX 2: TABLE VI
CHICAGO RESULTS

			CC World Weather Generator				Meteonorm								Future Weather Generator							
			2050		2080		2050				2080				2050				2080			
			A2	% Change	A2	% Change	RCP 4.5	% Change	RCP 8.5	% Change	RCP 4.5	% Change	RCP 8.5	% Change	SSP 245	% Change	SSP 585	% Change	SSP 245	% Change	SSP 585	% Change
Average Temperature	°C	11.4	14.4	26.32%	17.0	49.12%	12.1	6.14%	12.7	11.40%	13.2	15.79%	15.2	33.33%	14.2	24.56%	15.1	32.46%	15.1	32.46%	17.5	53.51%
Average Maximum Temperature	°C	32	36.5	14.06%	40.9	27.81%	32.1	0.31%	33.1	3.44%	34.2	6.88%	36.9	15.31%	34.1	6.56%	35	9.38%	34.8	8.75%	38.1	19.06%
Average Minimum Temperature	°C	-18	-14.8	-17.78%	-11.2	-37.78%	-11.8	-34.44%	-11.2	-37.78%	-10.7	-40.56%	-8.6	-52.22%	-13.2	-26.67%	-11.1	-38.33%	-10.8	-40.00%	-7.9	-56.11%
Annual Accumulative horizontal radiation	kWh/m²	1377.2	1411.9	2.52%	1425.1	3.47%	1423.6	3.37%	1434.9	4.19%	1443.9	4.85%	1444.3	4.87%	1380.3	0.25%	1382.7	0.40%	1384.6	0.53%	1385.6	0.61%
Percentage of diffuse horizontal solar radiation	%	45.50%	43.00%	-5.49%	41.50%	-8.79%	46.80%	2.86%	45.50%	0.00%	46.60%	2.42%	44.10%	-3.08%	45.20%	-0.66%	44.80%	-1.54%	45.00%	-1.10%	44.30%	-2.64%
Heating Degree Days	10°C Base	1458.0	1105.0	-24.21%	812.0	-44.31%	1322.0	-9.33%	1247.0	-14.47%	1177.0	-19.27%	920.00	-36.90%	945.00	-35.19%	825.00	-43.42%	829.00	-43.14%	599.00	-58.92%
Cooling Degree Days	18°C Base	691.00	1172.0	69.61%	1621.0	134.6%	743.00	7.53%	830.00	20.12%	927.00	34.15%	1273.0	84.23%	966.00	39.80%	1117.0	61.65%	1102.0	59.48%	1535.0	122.14%
Below Comfort Hours	%	72.60%	64.70%	-10.88%	56.30%	-22.45%	70.20%	-3.31%	68.40%	-5.79%	67.50%	-7.02%	63.20%	-12.95%	64.00%	-11.85%	64.50%	-11.16%	60.90%	-16.12%	58.60%	-19.28%
Above Comfort Hours	%	11.70%	23.40%	100.00%	29.10%	148.72%	13.80%	17.95%	15.50%	32.48%	17.50%	49.57%	23.90%	104.27%	20.40%	74.36%	22.80%	94.87%	24.10%	105.98%	29.60%	152.99%
Comfort hours	%	15.71%	11.90%	-24.25%	14.60%	-7.07%	16.00%	1.85%	16.00%	1.85%	15.00%	-4.52%	13.00%	-17.25%	15.60%	-0.70%	12.70%	-19.16%	14.90%	-5.16%	11.80%	-24.89%
Cooling	kWh/m²	69.78	115.88	66.07%	144.79	107.50%	88.14	26.31%	97.13	39.20%	103.01	47.62%	140.87	101.89%	107.32	53.81%	122.49	75.54%	122.52	75.59%	161.32	131.18%
Heating	kWh/m²	29.48	24.87	-15.64%	21.34	-27.61%	26.87	-8.87%	25.87	-12.25%	25.12	-14.80%	22.11	-24.99%	23.94	-18.79%	22.54	-23.54%	22.23	-24.61%	19.20	-34.87%
Total	kWh/m²	322.26	368.26	14.22%	381.49	18.33%	356.01	10.42%	358.79	11.29%	360.55	11.83%	376.83	16.88%	353.19	9.55%	358.90	11.32%	358.79	11.29%	380.36	17.98%