ANL/DIS-22/4

ComEd Climate Risk and Adaptation Outlook, Phase 1: Temperature, Heat Index, and Average Wind

Center for Climate Resilience and Decision Science

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ComEd Climate Risk and Adaptation Outlook, Phase 1: Temperature, Heat Index, and Average Wind

Prepared for ComEd by the Center for Climate Resilience and Decision Science at Argonne National Laboratory

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prepared for Commonwealth Edison

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ERRATA

After initial publication of this report the authors were made aware of some minor errors. These errors have been corrected in the present version.

Location	Error	Correction
Page 1	km^2 used twice in 2nd paragraph	Changed to “100 km-by-100 km” and “12 km-by-12 km”
Page 9	km^2 used twice in 2nd to last paragraph	Changed to “12 km-by-12 km” and “4 km-by-4 km”
Page 29	km^2 used once in 3rd paragraph	Changed to “4 km-by-4 km”

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ACRONYMS AND ABBREVIATIONS

Argonne	Argonne National Laboratory
C	Celsius
CAVA	Climate Adaption Vulnerability Assessment
CDD	Cooling degree days
CCVS	Climate Change Vulnerability Study
CEJA	Climate and Equitable Jobs Act
CMIP5	Coupled Model Intercomparison Project Phase 5
ComEd	Commonwealth Edison
CT	Central Time
DER	Distributed Energy Resources
E3	Energy+Environmental Economics
F	Fahrenheit
GCM	Global Climate Model
GHG	Greenhouse gas
HDD	Heating degree days
HVAC	Heating, ventilation, and air-conditioning
ICC	Illinois Commerce Commission
IPCC	Intergovernmental Panel on Climate Change
km	Kilometer
PV	Photovoltaic
RCP	Representative Concentration Pathway
SCE	Southern California Edison
Tmax	maximum temperature
Tmean	mean temperature
Tmin	minimum temperature
WRF	Weather Research and Forecasting

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EXECUTIVE SUMMARY

This *Climate Risk and Adaptation Outlook* report presents the research and findings of a joint venture between Commonwealth Edison (ComEd) and Argonne National Laboratory (Argonne) to evaluate future climate risks to ComEd's infrastructure and operations. ComEd recognizes that its position as the state of Illinois' largest electric utility, serving roughly 70% of the state's population, underscores the importance for communities across Illinois to consider climate risk as they plan for future conditions. Climate impacts, such as more severe heatwaves or more frequent flood events, can disrupt the generation, transmission, and distribution of electricity and create public health challenges. Taking a proactive approach to adapt to climate risks will help ensure that ComEd continues to serve its growing customer-base reliably and efficiently.

ComEd requires comprehensive understanding of projected future climate conditions in order to plan and implement a long-term adaptation strategy. Global climate models (GCMs), which translate climate and meteorological science into representations of projected future climate conditions, are an important tool in evaluating changes across broad regions (100 km-by-100 km). However, when planning for infrastructure and operations risks at the local or facility level, more detailed information is needed to evaluate impacts and develop strategies to mitigate these impacts. The research presented here draws upon the climate modeling and risk analysis expertise at the Center for Climate Resilience and Decision Science at Argonne, where climate scientists have dynamically downscaled three different GCMs to provide more local (12 km-by-12 km) projections of future climate.

Argonne projected future climate impacts for both medium-emissions (RCP4.5) and high-emissions (RCP8.5) climate scenarios for mid-century (2045-2054). The results presented here focus on projected climate conditions for ComEd's service territory under high-emissions, given the importance of ensuring critical infrastructure remains reliable under the more high-risk scenarios. Argonne explored three primary climate components that are of immediate interest to ComEd for infrastructure and operations planning: surface temperature, wind, and humidity (represented via heat index). Each of these climate variables can affect the ability to generate, transmit, and distribute electricity, and the loads that ComEd needs to serve. Hotter and more humid conditions, for instance, increase demand for space cooling while simultaneously reducing the distribution capacity of power lines. Changes to average wind speeds affect the generation capacity of wind turbines, while increases in maximum wind speeds can threaten transmission and distribution infrastructure.

Argonne's analysis shows that projected mid-century climate conditions for ComEd's service territory are likely to be substantially warmer and more humid than historical (1995-2004) conditions. Northern Illinois will experience higher average temperatures across all seasons, as well as more intense and prolonged heat waves during summer months, the effects of which will be amplified by higher humidity. In particular, temperatures during the "shoulder seasons" (late spring and early fall) are likely to be markedly warmer, producing longer periods without freeze or frost, which will likely increase the annual growing season. Simple measures of seasonal energy demand, such as cooling degree days, point to marked growth in demand for cooling, particularly during the spring and fall. Argonne's wind projections suggest that, on average, maximum winds will not increase beyond current maxima; on average, wind speeds are projected to be lower across three seasons (summer, fall, and winter), with the only seasonal increase occurring during the spring, which has historically been a period of subdued winds.

Importantly, these climatic changes will impact the generation and transmission of electricity, along with ComEd's distribution assets and their ability to maintain their current level of service. According to ComEd's analysis, a longer growing season will lead to greater vegetative coverage, which creates greater physicals risks to distribution infrastructure (e.g., downed power lines). Higher temperatures create a number of stress points within the system, such as overheating of lines and equipment, and may require the derating of transformers across the service territory. ComEd's assessment indicates that these climatic changes must be managed or they are likely to adversely affect the frequency and duration of service interruptions, thereby increasing the possibility of failing to meet service targets such as the System Average Interruption Duration Index. Moreover, while some assets and facilities are designed for conditions that are not currently projected for northern Illinois' mid-century climate (e.g., sustained ambient temperatures in excess of 35° Celsius), climate change will nevertheless increase the risk of extreme, unexpected weather events that may imperil energy infrastructure.

This *Climate Risk and Adaptation Outlook* serves as an important first step to inform ComEd's grid planning efforts, but Argonne and ComEd recognize that additional research beyond this report will be necessary to characterize future climate conditions more comprehensively throughout northern Illinois, to assess their impacts to grid assets and system operations, and to index effective adaptation options at an asset-level.[i] A more focused assessment and adaptation strategy will occur in Phase 2 of this project, which may include evaluations of the following:

- Impacts to convection and resulting probability of extreme storms;
- Impacts to flood risk, including frequency and severity (amount of inundation);
- Upstream risks to generators and transmission systems;
- Interactions with quiescent heat; and
- Load planning for peak demand impacts.

Critically, these analyses will be paired with an increased effort to work jointly with Illinois communities engage in shared learning and plan for future climate risks.

1 INTRODUCTION

Over the past several decades, the earth's climate has changed in ways that are significant for communities globally and the infrastructure systems that serve them. Climate change has increased the frequency and severity of extreme weather events, leading to more intense storms, heat waves, and droughts, as well as heavier rainfall events that can cause flooding, among many other types of changes. These climate impacts can damage or disrupt electric utility infrastructure and affect utility operations in ways that interrupt the reliable generation, transmission, and distribution of electricity that customers and communities require. However, by characterizing future climate conditions at regional and local scales, utilities can better assess their current and future climate risk exposure and implement proactive adaptation strategies to increase grid resilience and reliability for decades to come.

Commonwealth Edison (ComEd) is the largest electric utility in Illinois, serving more than four million customers with a service territory encompassing the City of Chicago and much of northern Illinois. In pursuit of its climate resilience goals, ComEd entered into an agreement with the [Center for Climate Resilience and Decision Science at Argonne National Laboratory](https://) in the spring of 2022 to begin forecasting future climate conditions for northern Illinois, and to consider the future climate risk exposure that ComEd's infrastructure and operations may face in the coming decades. These outcomes serve as the basis for adaptation planning that will enable ComEd to build a more resilient future for electricity delivery in Chicagoland and northern Illinois.

ComEd's proactive approach to climate resilience planning through closer study of future climate impacts across the region is also part of a broader effort to pursue a climate-conscious, clean-energy future. In 2021, the state of Illinois enacted the Climate and Equitable Jobs Act (CEJA) to combat the climate crisis. This new law charts a path to 40% renewable energy by 2030, 50% renewable energy by 2040, and 100% clean energy by 2050 —and ComEd will play a significant role for the region in achieving these goals.[ii,iii] CEJA also

Climate Equity

Illinois' Climate and Equitable Jobs Act (CEJA) expressly recognizes the needs of "communities disproportionately impacted by climate change." Climate equity encompasses the importance of ensuring that under-resourced communities have the resources that they need to adapt to climate-change impacts and to fully participate in the ongoing energy transformation. In this Phase 1 *Adaptation Outlook*, the key topics of climate equity relate to ambient heat and heat index, which disproportionately impacts denser urban areas where temperatures can be even more extreme because of the urban heat island effect. ComEd and Argonne anticipate that additional climate equity topics will emerge in the Phase 2 study within the topic areas of storms and flooding risk. While this initial assessment begins with the direct impact that climate change can have on the electrical grid, the work will not be complete until climate adaptation community partnerships are forged to ensure that northern Illinois communities have the knowledge, tools, and infrastructure that they need to adapt to climate change. This report joins climate reports from the City of Chicago and the State of Illinois in gathering information that will be essential to prepare for the climate-driven weather that the region will face by mid-century, and to better understand some of the extreme weather that we are already facing today.

requires ComEd to file a strategic Multi-Year Integrated Grid Plan with the Illinois Commerce Commission (ICC) that will chart the course for grid investments for the coming years. Argonne has worked with ComEd to inform this plan with a detailed first look at the future climate, the climate for which the grid will need to be prepared. Therefore, in response to changing climate conditions, as well as new state clean energy goals, broader technological trends like electrification, and a mandate to sustain best-in-class system performance, ComEd is pursuing a multi-faceted climate strategy informed by leading climate science and modeling.

The research presented in this report is the outcome of the first phase of a longer-term effort by ComEd to understand the impacts of climate change to its system and operations, and to devise strategies for adapting to climate-change impacts in northern Illinois. The goal of this phase is to begin to characterize some of the highest priority climate impacts that could have the greatest effect to ComEd's system; to discuss the implications of those impacts to physical infrastructure, operations, and governance considerations; and to lay out a roadmap for ComEd's ongoing analysis of climate risk.

This report is structured as follows: first, it discusses Argonne's approach to downscaled regional climate modeling, which projects local-scale, utility-relevant climate impacts across ComEd's service territory in northern Illinois. It then presents the results for the first phase of climate impact modeling, focusing on priority areas related to temperature, wind, and humidity. Concluding sections discuss the physical infrastructure, operational, and governance implications of these climate impacts, and they lay out a roadmap for future study and local-scale infrastructure modeling to inform ComEd's climate resilience and adaptation planning strategy.

2 CLIMATE SCIENCE OVERVIEW

Climate science investigates the structure and dynamics of earth's climate system to better understand how global, regional, and local climates are sustained, as well as how they evolve over time. Greenhouse gas (GHG) emissions—to which the electric power sector is a major contributor—are the key driver of global climate change. These gases trap heat energy in the atmosphere through the greenhouse effect, which introduces additional energy into the climate system, affecting its dynamics at a global scale. While numerous variables drive local climate conditions, the climate risk landscape is closely tied to past and future GHG emissions and subsequent concentration of these gases in the earth's atmosphere.

A wide body of research, drawing upon meteorology, oceanography, physics, chemistry, environmental science, and other related fields, has explored how different environmental factors influence the global climate. Ice cores, gathered by drilling deeply into Antarctic ice sheets, provide a record of the climate from thousands of years ago, along with the factors influencing the climate, such as the presence of aerosols (e.g., dust, ash, pollen, trace elements) and atmospheric gases.[iv] Using ice cores, the scientific community has identified a clear link between GHG concentrations and global climate.[v]

In its Fifth Assessment Report (2014), the Intergovernmental Panel on Climate Change (IPCC) defines the representative concentration pathways (RCPs), which are scenarios of future emission concentrations in the atmosphere that are aligned to different climate futures.[vi] All of these scenarios are considered possible depending on humanity's global efficacy in curbing GHG emissions in the years to come. The RCPs use assumptions relating to national policy decisions and individual behaviors that will either decrease, stabilize, or increase future GHG emissions concentrations. RCP8.5 is the "high emissions" scenario, often described also as the "business-as-usual" scenario, and suggests that if humanity does not take dramatic actions to curb emissions from current practices, the temperature will continue to rise throughout the end of the 21st century, leading to more extreme changes in climate over that time period. As the highest-GHG-concentration scenario, RCP8.5 could lead to the most consequential impacts for the infrastructure sector; therefore, from an enterprise risk-planning perspective, embedding RCP8.5 risks into futures planning is the more conservative emissions scenario for characterizing climate risk. RCP4.5 is a lower emissions scenario that assumes that emissions

IPCC

The IPCC is an intergovernmental body of the United Nations responsible for advancing knowledge on climate change. It provides objective and comprehensive scientific information on climate change, including the natural, political, and economic impacts and risks as well as possible response options. It does not conduct original research nor monitor climate change, but rather undertakes a periodic, systematic review of all relevant published literature. Thousands of scientists and other experts volunteer to review the data and compile key findings into "Assessment Reports" for policymakers and the general public. This has been described as the biggest peer review process in the scientific community.

Climate vs. Weather

Weather refers to short-term atmospheric conditions while climate is the weather of a specific region averaged over a long period of time. Climate change refers to long-term changes.

will peak around the year 2040 and then decline as the world transitions away from carbon-based fuels towards renewable energy sources and takes other similar mitigation actions (these assumptions are more aligned with the United Nations Paris Agreement established in 2015). Many factors will influence future atmospheric concentrations of GHGs, and the resulting realized climate scenario, including renewable-energy technology advancements, governmental and organizational policy decisions, consumer behavior, and the pace of modernization in developing countries. While substantial differences exist in projected end-of-century climate conditions between RCP4.5 and RCP8.5, Argonne's research has found the two scenarios do not differ excessively at mid-century.

To understand how these emission scenarios will translate into future climate conditions, scientists construct computer models of the earth's climate system that incorporate future GHG concentrations, among diverse other factors, to project how the climate system will evolve. Global climate models (GCMs) are complex mathematical representations of the major climate system components (atmosphere, land surface, ocean, sea ice, etc.), and their interactions. The goal of most GCMs is to examine how climatic conditions will change over time given one or more GHG concentration scenarios (e.g., RCP8.5). Climate models are computationally intensive simulations because as they step through time, they model the complex interactions of these coupled systems, effectively recomputing the entire state of the global climate with each time step (e.g., every 3 hours for the next 50 years). Dozens of agencies and organizations across the world have developed GCMs to investigate how the effects of climate change will unfold in the coming decades.

Given the drivers of climate change and the local-scale impacts that it is causing, climate scientists are increasingly working with engineers and social scientists to better characterize how changing climatic conditions will impact critical infrastructure systems and the communities that rely on them. However, doing so requires more location-specific information about future climate impacts than GCMs are able to produce. For example, GCMs typically provide analysis results that can be visualized and mapped across a region as gridded outputs that have cell sizes on the order of 100 km-by-100 km. However, local climate trends can be highly variable across such large areas (northern Illinois, for example, is about 200 km wide, or about two GCM grid cells), making it difficult to project local-scale impacts to infrastructure systems, such as ComEd's local and regional power systems. In response to this, climate scientists and modelers have developed techniques to "downscale" GCM projections. These downscaled results translate GCM results into much higher resolution projections (~10 km), which better characterize the local variability in how climate impacts will manifest in the future, making it possible for infrastructure owners and operators to better explore how these "neighborhood-scale" projected impacts will affect individual assets, facilities, or systems. The Argonne team of climate scientists has dynamically downscaled three widely used GCMs, producing highly local representations of climatic changes under multiple modeling scenarios. The three GCMs that the team used to inform this downscaling have varying sensitivities to atmospheric carbon concentrations. By selecting models that cover a plausible range, the team is better able to quantify and account for climate model uncertainty in its projections of future local impacts. Taken together, this modeling process provides a more reliable and more granular representation of the variability in climate conditions that ComEd will face across its service territory over the coming decades.

3 MODELING UTILITY-RELEVANT CLIMATE IMPACTS

Argonne's approach to downscaling employs a regional climate model of North America that dynamically downscales GCM results to achieve higher-resolution, local-scale climate projections at a 12-km-by-12-km scale. This approach characterizes ComEd's service territory with many smaller individual grid cells, offering a tremendous increase in resolution over the 100-km-by-100-km resolution of GCMs. This high resolution better aligns with the scale of decision-making that utilities face, enabling climate scientists and engineers to better understand how climate impacts will vary across the system and identify those parts of the system that are most vulnerable to changing conditions. In addition to enhanced model resolution, Argonne ran its regional climate models under two emissions scenarios and with an ensemble of three GCMs, which provides better quantification of modeling uncertainty.

Argonne's regional climate modeling employs the Weather Research and Forecasting (WRF) model, developed by the [National Center for Atmospheric Research](), which is scaled to model regional climate over North America. By modeling a smaller, sub-global spatial domain, Argonne gains substantial efficiencies in computing, allowing for modeling at much higher spatial resolution. Relevant to this study, Argonne scientists ran the WRF model for 10 years of projected time at mid-century (2045-2054), conducting separate runs using input data (i.e., boundary conditions) from three GCMs (the University Center for Atmospheric Research's Community Climate System Model, the Hadley Centre's Global Environmental Model, and the National Oceanic and Atmospheric Administration's Geophysical Fluid Dynamics Laboratory climate model) from the Coupled Model Intercomparison Project Phase 5 (CMIP5) data repository. While the outcomes of this study focus on an RCP8.5 emission scenario, Argonne has also conducted simulations based on the RCP4.5 emission scenario.

Dynamical vs. Statistical Downscaling

There are two main approaches to downscale climate model outputs: statistical and dynamical downscaling. For statistical downscaling, a statistical relationship is developed between historic climate data and the output of the climate model used for the same historical period. The relationship is then used to generate future climate data. Dynamical downscaling uses higher resolution regional climate models with GCMs as boundary conditions to reproduce local climate conditions. Argonne uses this approach for this study.
(See Copernicus Climate Change Service – Global Impacts)

Regional climate modeling begins by conducting validation studies in which the regional climate model is run for a historical, or baseline, time period (a process called "backcasting"), in order to assess the ability of the regional climate model to reproduce climate trends similar to historical or observed climate. In this instance, Argonne used a baseline period of 1995-2004 for backcasting, which is consistent with both the historical GCM data in the CMIP5 data repository, and the 30-year historical weather period that ComEd uses for grid planning. This information is then used to run the model over future time periods to project future climate. For more detailed information on Argonne's regional climate modeling, see Wang et al. (2015),[vii] Wang & Kotamarthi (2014),[viii] and Zobel et al. (2018).[ix]

For the first phase of climate modeling conducted in this study, Argonne consulted with ComEd engineering and planning staff to collaboratively identify climate impacts that are most likely to stress system assets. Climate vulnerability and adaptation studies conducted by peer utilities, such as those from Con Edison,[x] Southern California Edison,[xi] and Pacific Gas and Electric,[xii] were useful benchmarks to help prioritize the first set of climate variables to be analyzed (for reference, see the table on climate sensitivities of the grid in section 12). Broadly, ComEd and Argonne identified future temperature, average wind, and humidity as being of immediate interest to ComEd from the perspective of infrastructure impacts and load forecasting. Further discussions with ComEd staff identified the following specific local climate impact variables relevant to climate resilience and clean energy planning:

1. **Surface Temperature** levels affect the performance of various electrical grid components. Higher temperatures could cause a reduction of the electric transmission capacity in power lines, loss of strength in conductors, an increase in conductor sag resulting in reduced clearances, a reduction of connector life/integrity, degradation of insulation, acceleration of the aging of various components, and damage to the equipment attached to conductors.[xiii] Northern Illinois is already subject to temperature extremes that pose serious challenges to the design and operation electrical grid components. Thus, identifying future temperature conditions will prove valuable when planning a climate-driven grid adaptation strategy.

   For surface temperature, mid-century is defined as the 10-year period between 2045-2054 and the historical reference is the 10-year period between 1995-2004. Relevant temperature information includes:

   - Change in *mean, maximum, and minimum* temperatures, both on a *seasonal* and *annual* basis at mid-century, as compared with the historical baseline period.
   - Changes in number of heating degree days (HDD) and cooling degree days (CDD) at mid-century with respect to the historical baseline.
   - Changes in growing season as represented by the change in the number of both frost-free days and freeze-free days at mid-century as compared with the historical baseline period, on an annual and seasonal basis.
   - Changes in the number of days per year exceeding threshold temperatures relevant to infrastructure design, load, maintenance, and operations. Important temperature threshold values include:
     - Count of days per year with a 24-hour average temperature exceeding 30° Celsius (C).
     - Count of days per year with a maximum temperature exceeding 40°C.
     - 1-in-10-year lengthiest sequential daily average where no day averages less than 30°C (count of days in a row; average temperature for entire sequence).
     - Characterization of warmer nights using seasonal maximum overnight averages by decade.
     - Frequency of days with threshold temperatures over time, up to a 10-year event, for baseline period and mid-century. Intervening decades will be interpolated.

2. **Wind** information is important to ComEd for two primary reasons: (1) high winds can cause power outages by snapping utility poles and downing power lines, and (2) changing average wind patterns will impact the adequacy of renewable generation under different scenarios.[xiv] Understanding changes in future wind patterns will allow ComEd to strategically harden critical power lines and plan for changing generation mixes. Relevant wind information includes:
   - Change in *maximum* and *mean* seasonal average wind speed, frequency, and direction at mid-century, compared with the historical baseline.
   - Change in frequency of observed 90-mile-per-hour wind speeds at mid-century, compared with the historical baseline.
3. **Humidity** influences human comfort and safety in combination with temperature, which creates a need for cooling and increases electricity demand. Relevant humidity information includes:
   - Heat index at mid-century across the ComEd service territory, compared with the historical baseline.
   - The combined impact of heat and humidity on soil moisture at mid-century across the ComEd service territory, compared with the historical baseline.

Argonne's analysis of these climate variables, presented in the next section, has provided ComEd with critical information needed to begin planning for direct impacts to ComEd's operations, such as risks to infrastructure and changes in demand, as well as upstream impacts to generation and transmission resources. Nevertheless, important climate considerations remain to be investigated. In particular, the 12 km-by-12 km climate model employed in this analysis, while of higher spatial resolution than GCMs, does not fully model the physics that shape convective storms and their impacts, such as localized but severe winds and heavy rains. Therefore, the associated risks to ComEd's infrastructure and operations, such as outages caused by extreme winds and other storm impacts, are not fully accounted for in this analysis. Argonne is currently processing a 4 km-by-4 km downscaled climate model that will better incorporate convective processes for use in grid-level modeling and analysis. Evaluating the impact of climate change on convective forces in northern Illinois will be a key aspect of future work conducted jointly by Argonne and ComEd.

Flooding is another critical risk to ComEd operations and infrastructure, and one identified by peer utilities as a risk that is likely to grow with climate change. A dedicated flood analysis, along with an assessment of changes to seasonal, monthly, and daily precipitation levels in northern Illinois, will be an important component of future climate risk analyses for ComEd.

4 CLIMATE CHANGE IN NORTHERN ILLINOIS

ComEd's service territory in northern Illinois already experiences extreme weather events that pose challenges to the utility's ability to plan, build, manage and operate the electrical distribution grid. In general, the results of Argonne's climate modeling indicate that by mid-century, the frequency and intensity of extreme weather events in ComEd's service territory will increase. ComEd will face hotter and longer summers with more consistent and extreme high temperatures, and warmer winters. Similarly, changes in humidity will equate to higher mid-century heat indexes, which can have physiological effects on individuals' capacity to cope with extreme heat, increasing the potential for public health and safety issues. Maintaining reliable service during heat waves is of critical importance, as evidenced by the deadly heat wave that afflicted the Chicago region in 1995. Given that higher temperatures also decrease the capacity of transmission and distribution lines, planning for infrastructure and operations investments to cope with increasing demand and decreasing relative capacity is paramount.

Argonne's climate modeling points to a small decrease in wind speeds for most parts of the region, which will both reduce a natural mechanism for cooling the body while also lowering potential wind generation capacity. However, projections of wind impacts vary considerably by season. Wind speeds are projected to decrease by 1.5% and 3% for winter, summer, and fall, whereas they are projected to increase by nearly 4% in the spring. These are not major changes, however they will impact generation capacity; in particular, the lowering of wind speeds over the summer months means a reduction in capacity during the season in which demand is likely to peak. On the other hand, although this analysis does not fully account for convection, which can lead to extreme rain and wind events, the results of this analysis do not point to a systemic increase in wind speeds that might imperil ComEd's distribution assets; however, a more detailed analysis of wind extremes is needed to confirm this.

Taken together, the Argonne team's temperature, wind, and heat index projections for northern Illinois' mid-century climate underscore the need to plan and prepare for the impacts of significantly warmer temperatures on grid capacity and demand. Rising average temperatures will increase indoor space cooling needs over the spring, summer, and fall, which will place greater demand on regional generation and transmission infrastructure, as well as ComEd's distribution grid. Simple correlates of energy demand, such as HDDs and CDDs, shows a marked decrease in heating demand and an increase in cooling demand, particularly for the border seasons. In particular, the team's results show an increase in the high temperatures experienced over extended periods (i.e., multiple days in a row). Multi-day events increase the burden on space cooling as the thermal mass in structures becomes increasingly heated. Brick buildings, which normally provide a measure of comfort on hotter days, become difficult to cool during multi-day events. The combined impact of these heating events will be an increase in average cooling demand. As ComEd's service territory experiences more frequent periods of extreme heat, increased electricity needs must be met to avoid the more serious public health risks associated with heatwaves.

5 TEMPERATURE: MEAN, MINIMUM, AND MAXIMUM

Argonne's climate modeling projects that by mid-century, ComEd could expect higher minimum, higher average, and higher maximum temperatures across its entire northern Illinois service territory as compared with baseline temperatures. Mid-century temperature projections were generated using aggregated data from the three regional climate model simulations based on the 10-year period between 2045-2054, assuming an RCP8.5 emissions scenario.

Argonne calculated monthly, seasonal, and annual values of daily average, maximum, and minimum temperatures based upon the regional climate model outcomes for northern Illinois and ComEd's service territory (see Figure 1). For example, to calculate the summertime maximum daily temperature, the team took the maximum projected temperature for each day in June, July and August, from each of the three GCM-based model runs, for each of the 10 years in the mid-century (2045-2054) time period, and calculated the average value. A similar calculation was made for the single baseline time period from 1995-2004 in order to calculate the difference between future projections and historical trends. Average and minimum daily temperatures were calculated in a similar fashion, as were annual (i.e., not seasonal) values. These values represent seasonal and annual *averages*, however the region will experience days in the future that are both hotter and colder due to natural variability in day-to-day weather. Nonetheless, these values are useful to understand the general magnitude and direction of changes in the future. Figure 2 shows the annual changes in temperature for each modeled grid cell within ComEd's service territory, while Figure 3 depicts seasonal changes. Figure 4 summarizes changes in service territory-wide temperatures on a monthly basis

Finally, Argonne also evaluated the percentage of time in which modeled daily average temperatures exceed a given threshold temperature (e.g., how often, relatively, are average daily temperatures projected to exceed 25 °C). This information, presented in Figure 5, allows for an exploration of the way in which daily temperatures will shift with a changing climate, throughout all possible temperatures, including at the extremes (very hot and very cold). Argonne's results depict a noticeable shift upwards in the relative amount of time in which a given temperature threshold is exceeded, with the greatest change at the minima and smallest change at the maxima.

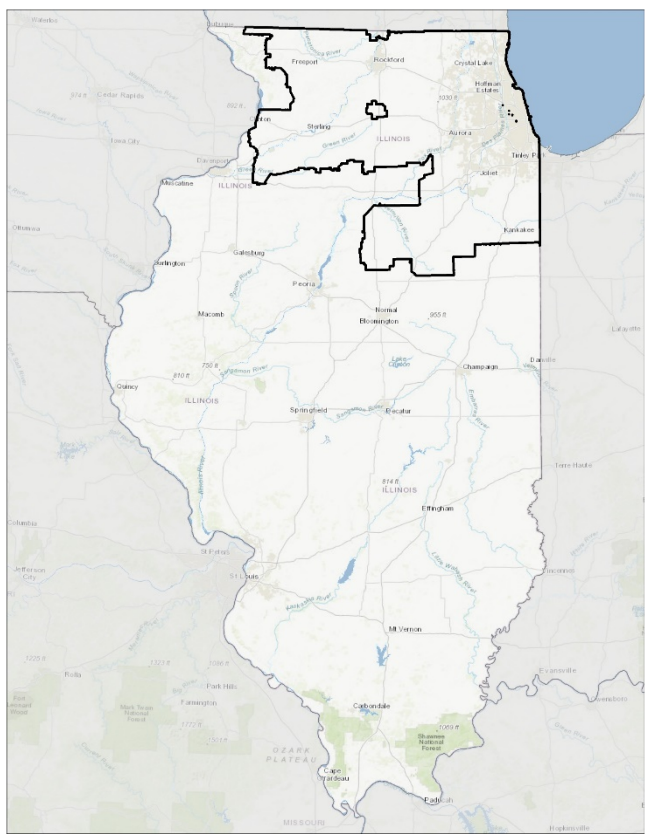


FIGURE 1 ComEd's service territory, which encompasses much of northern Illinois, including the greater Chicago region.

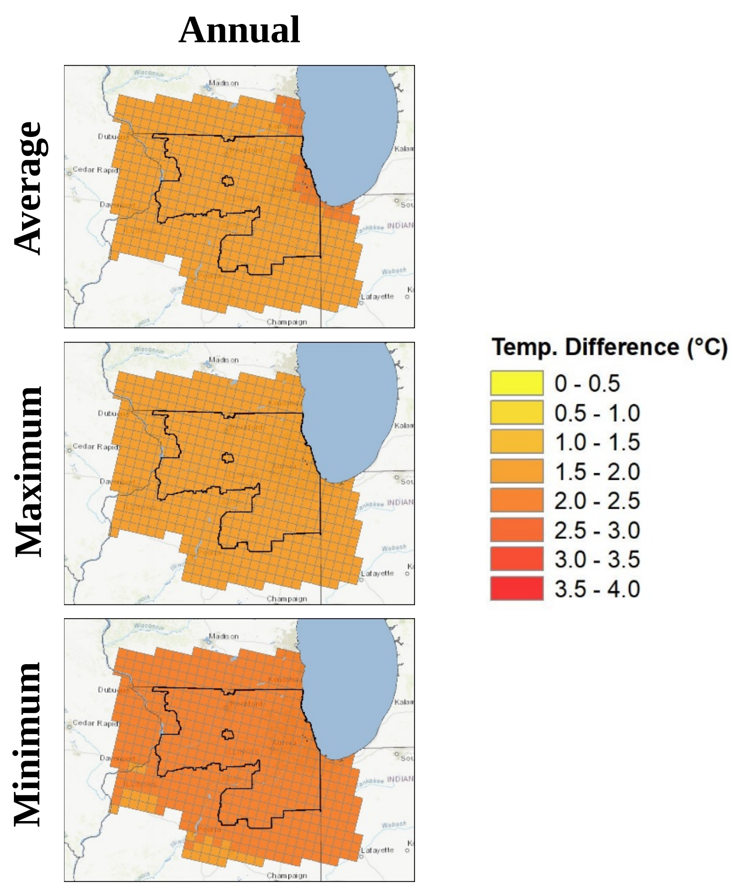


FIGURE 2 Change in annual average, minimum, and maximum temperatures from the baseline period to mid-century.

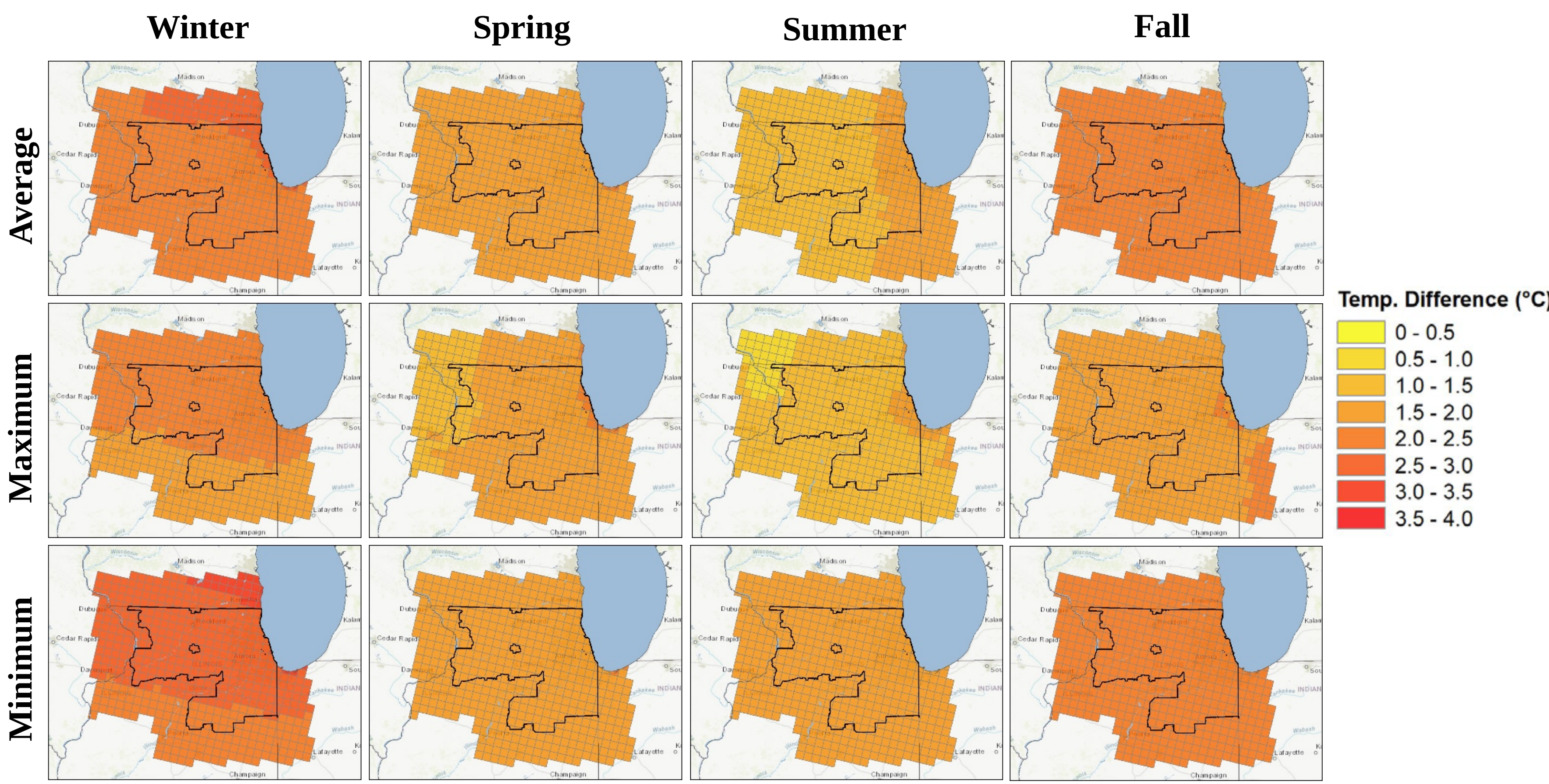
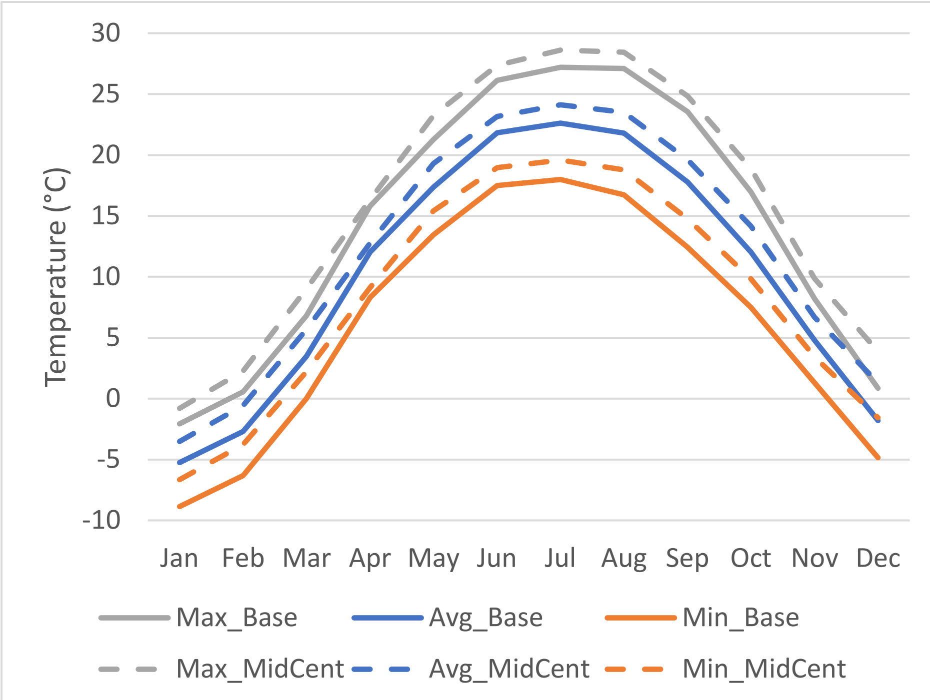
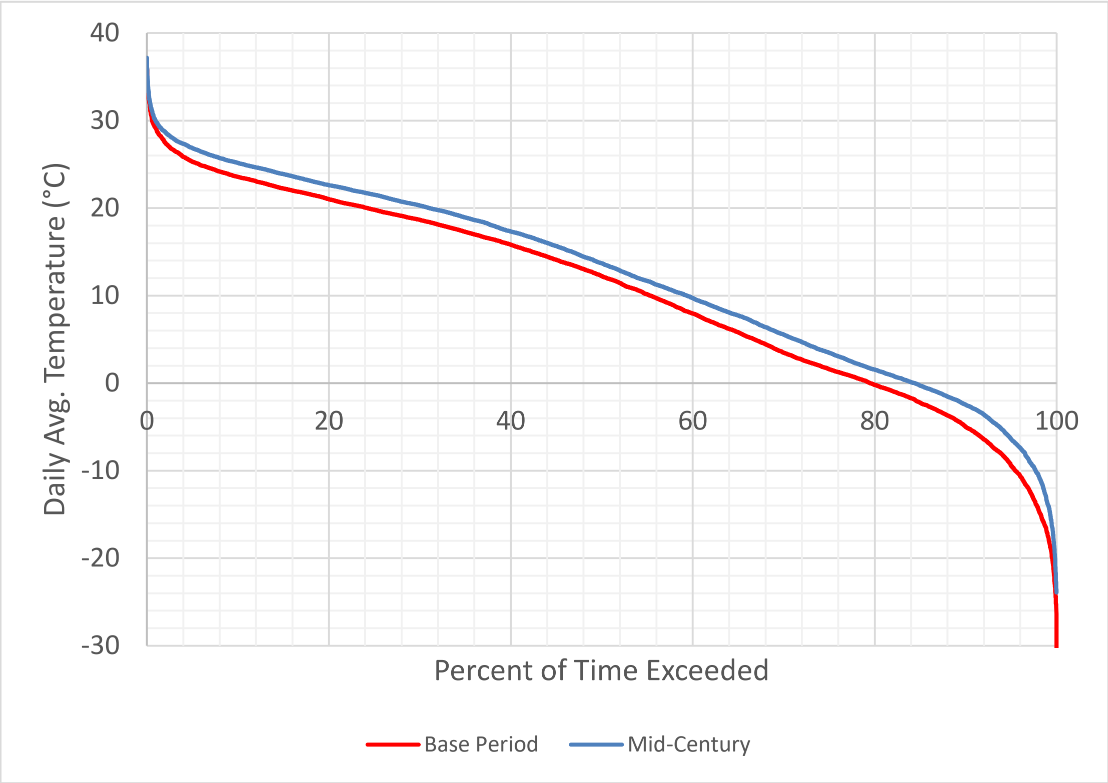


FIGURE 3 Change in seasonal average, minimum, and maximum temperatures from the baseline period to mid-century.



Month	Base Period			Mid-Century		
	Avg. of averages	Avg. of minima	Avg. of maxima	Avg. of averages	Avg. of minima	Avg. of maxima
Jan	-5.3	-8.9	-2.1	-3.5	-6.7	-0.8
Feb	-2.7	-6.3	0.6	-0.6	-3.8	2.3
Mar	3.5	0.0	6.8	5.7	2.2	9.0
Apr	12.0	8.3	15.8	12.8	9.1	16.4
May	17.4	13.5	21.3	19.3	15.4	23.2
Jun	21.8	17.5	26.1	23.2	19.0	27.4
Jul	22.6	18.0	27.2	24.1	19.6	28.6
Aug	21.8	16.7	27.1	23.5	18.8	28.5
Sep	17.8	12.4	23.6	19.6	14.8	24.9
Oct	12.0	7.5	17.0	14.2	9.8	18.9
Nov	4.8	1.3	8.2	6.7	3.4	9.9
Dec	-1.8	-4.8	0.9	1.3	-1.6	3.9

FIGURE 4 Comparison of monthly averages, minimum, and maximum temperatures for the baseline and mid-century periods.



Daily Avg. Temp (°C)	Percent Time Exceeded		Days Exceeded Per Year	
	Base Period	Mid-Century	Base Period	Mid-Century
-30	99.98		365	
-25	99.92		365	
-20	99.51	99.82	363	364
-15	98.24	99.29	359	362
-10	95.44	97.68	348	357
-5	90.03	93.72	329	342
0	79.49	84.37	290	308
5	66.80	71.28	244	260
10	55.30	59.35	202	217
15	42.36	46.73	155	171
20	24.24	31.03	88	113
25	5.75	10.63	21	39
30	0.58	0.95	2	3
35	0.04	0.06	0.15	0.23
40				

FIGURE 5 Percent of time that daily average temperatures exceeded a given threshold for the baseline and mid-century periods.

6 HEATING AND COOLING DEGREE DAYS

Degree days are measures of how cold or warm a location is by comparing the mean (the average of the high and low) outdoor temperatures to a standard base temperature, usually 65° Fahrenheit (F) (18.33°C) in the United States. The more extreme the outside temperature (i.e., excessively hot or cold), the higher the number of degree days, which generally results in higher levels of energy use for space heating or cooling. HDDs are a measure of how cold the temperature was on a given day or during a period of days, which shapes the need for a certain amount of heating. For example, a day with a mean temperature of 40°F has 25 HDD (e.g., 65°F - 40°F = 25 HDD). Two such cold days in a row have a total of 50 HDD for the 2-day period. When added up across weeks, months, seasons or even a year, total HDD provide an estimate of building heating demand, which, depending on building efficiency and fuel type, is a key variable in the capacity requirements of the electrical distribution system. Likewise, CDDs are a measure of how hot the temperature was on a given day or during a period of days. A day with a mean temperature of 80°F has 15 CDD (e.g., 80 – 65 = 15 CDD). A mean temperature of 83°F for the following day would equate to 18 CDD, with the total CDD for the two days being 33 CDD.[xv]

HDD and CDD are useful measurements for evaluating aggregate building energy demand over both short- and long-term horizons; ComEd's annual system peak demand, for instance, usually occurs on the hottest day of the year, when the extreme temperature produces a high number of CDD for that day. Evaluating projected changes in HDD and CDD over seasonal and annual timescales provides a key input that allows ComEd's capacity planners to analyze how different weather scenarios will impact system peak demand and the distribution resources needed to meet these loads. While demand over the summer has historically been the most taxing on ComEd's distribution resources, the potential for a broad adoption of heat pumps and electric heat sources might offset decreasing numbers of HDD in future years (i.e., reduced demand for heating due to a warmer climate) and cause winter peak demand to be of greater concern for capacity planning.

Argonne calculated seasonal and annual HDD and CDD for the baseline (1995-2004) and mid-century time-periods (2045-2054), and then evaluated and mapped the change in seasonal HDD and CDD between these two time-periods (see Figures 6-10). This analysis reveals significant projected decreases in HDD across ComEd's service area by mid-century, with noticeable variation between southern and northern areas. Similarly, the team finds a noticeable increase in CDD by mid-century. These changes to historical HDD and CDD metrics will be used by ComEd's engineers to conduct weather-normalization analysis within the capacity planning process. Seasonal changes in HDD and CDD can inform the analysis of new technologies that customers may use to reduce GHG emissions, notably heat pumps and the need for long-duration energy storage.

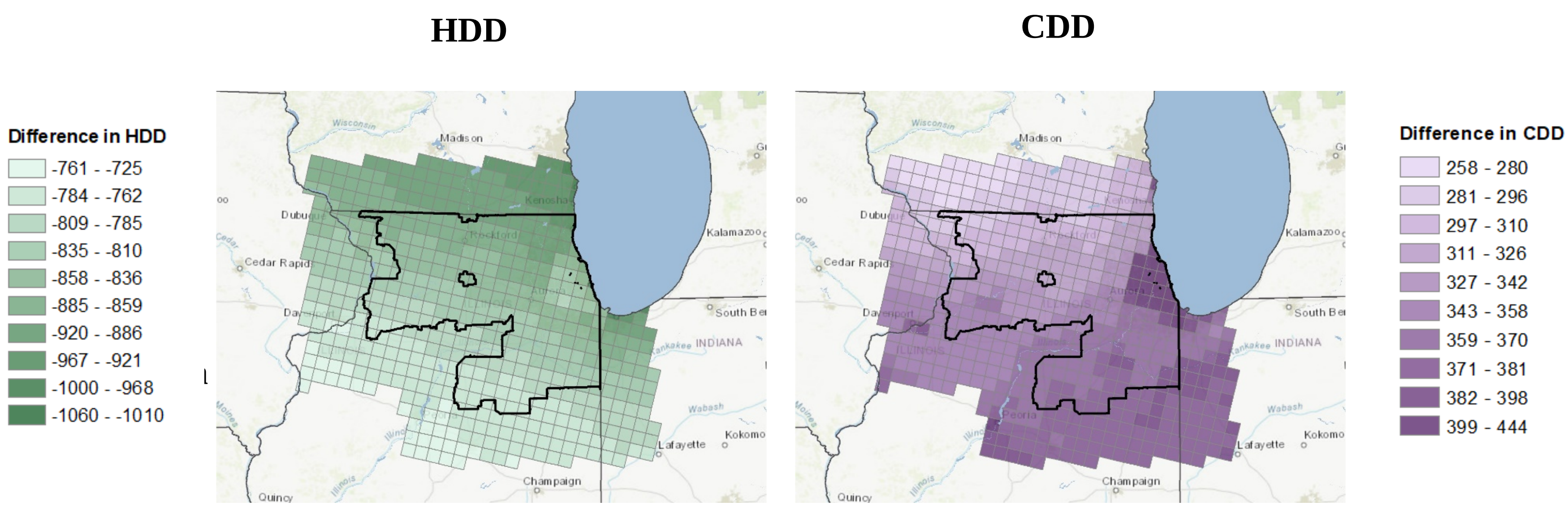


FIGURE 6 Change in the annual count of HDDs and CDDs between the baseline and mid-century periods.

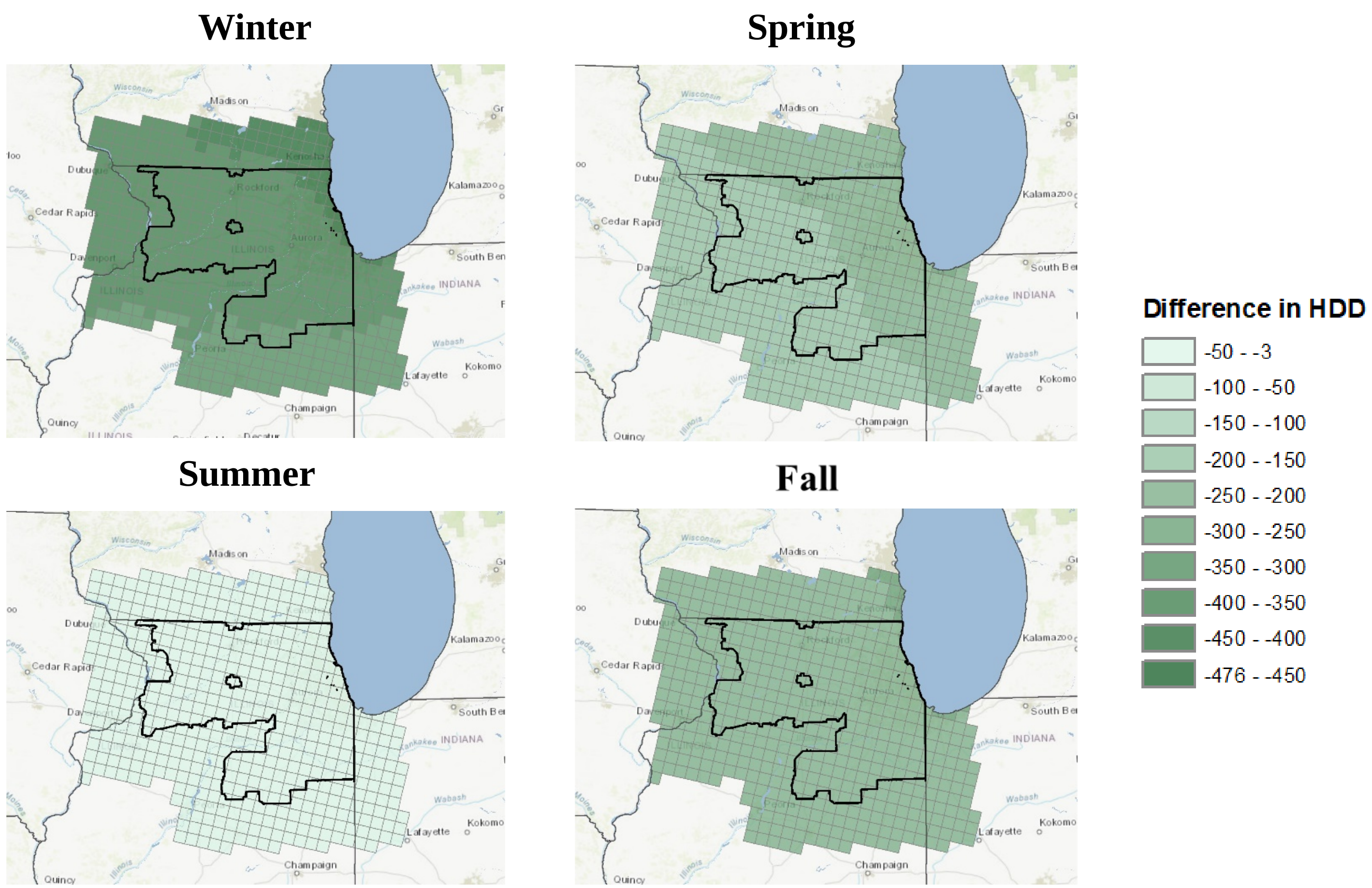


FIGURE 7 Change in the seasonal count of HDDs between the baseline and mid-century periods.

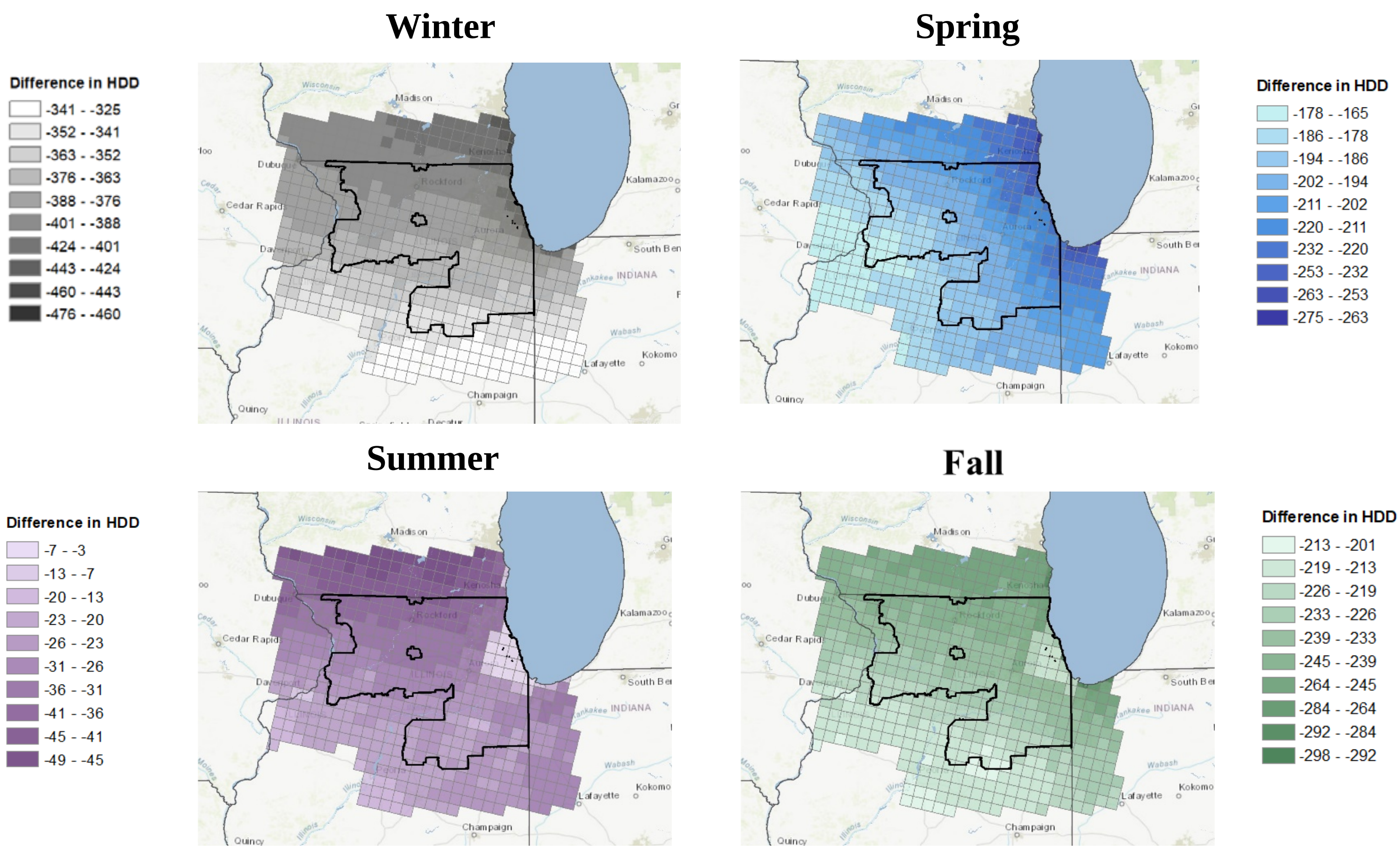


FIGURE 8 Change in the seasonal count of HDDs (varying scale) between the baseline and mid-century periods.

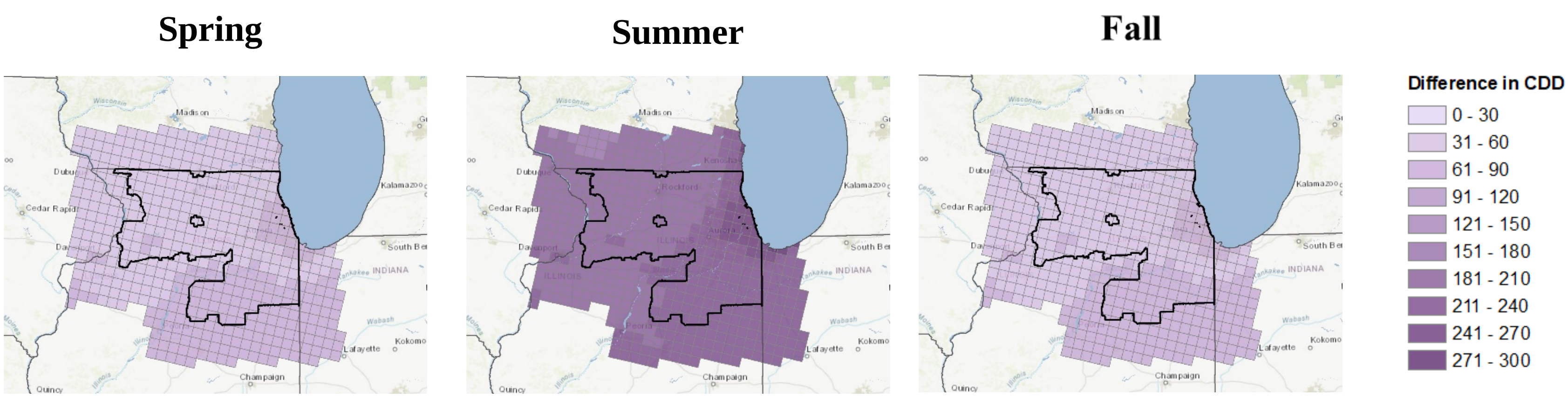


FIGURE 9 Change in the seasonal count of CDDs between the baseline and mid-century periods.

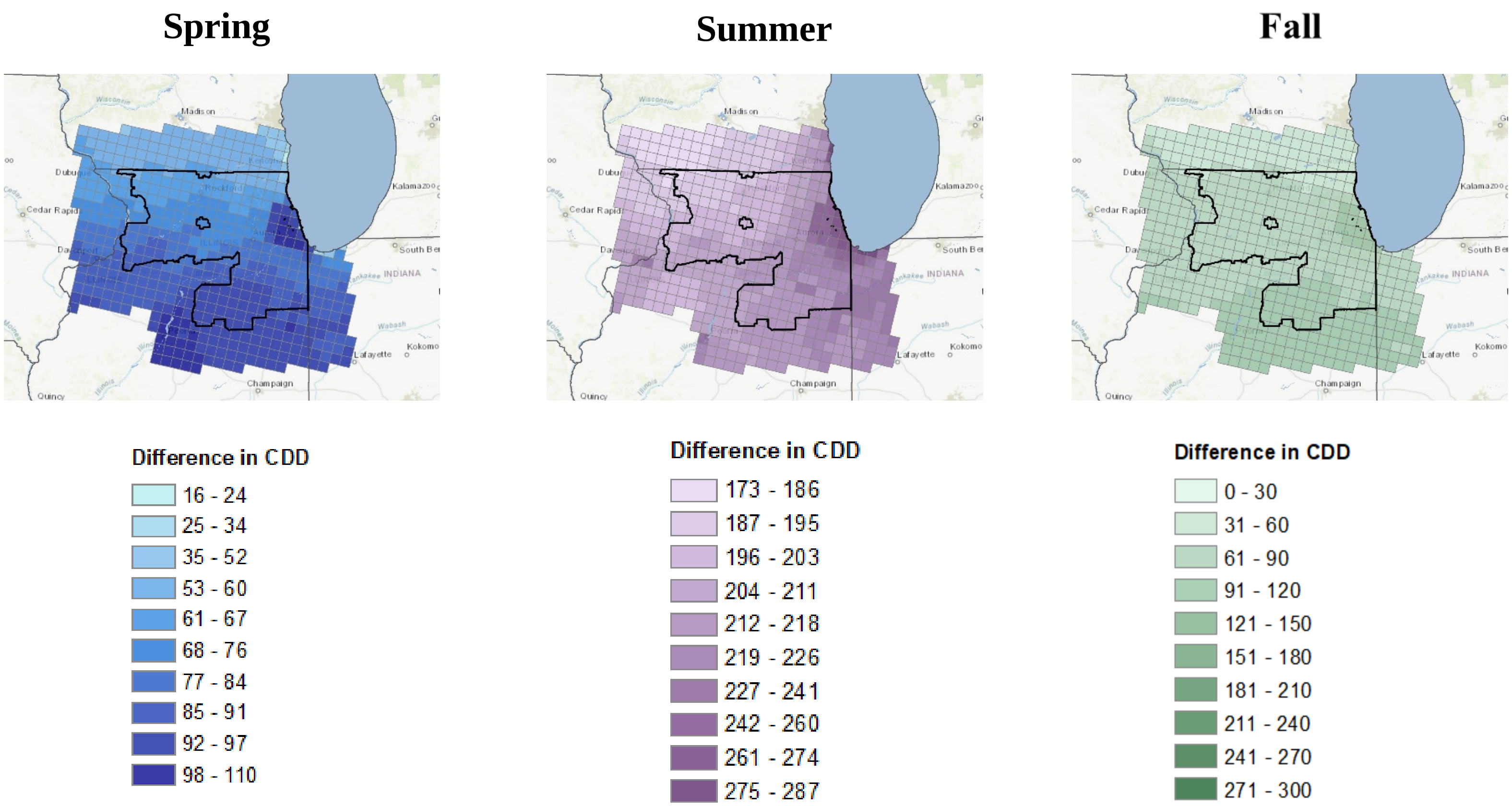


FIGURE 10 Change in the seasonal count of CDDs (varying scale) between the baseline and mid-century periods.

7 AVERAGE TEMPERATURE FOR CONSECUTIVE DAYS

Extended periods of extreme heat can be a major stressor to communities and the infrastructure that serves them, placing additional demands on power generation and transmission. Service reliability during these periods is crucial, given that overexposure to extreme heat is a significant public health threat. Using the daily average temperature information that the regional climate models produced for northern Illinois, Argonne analysts can evaluate how climate change will alter the severity of extended periods of extreme heat.

Argonne identified the hottest consecutive average temperatures for a given number of days (*n* of 2 days, 4 days, and 7 days) based on daily average temperatures. For example, Argonne identified the two consecutive days in 1995 in which the sum of the daily average temperatures was highest, and then divided this value by the number of days (2) to calculate the hottest 2-day period in 1995. This process was repeated across all years in the base period (1995-2004) and mid-century (2045-2054) data, producing ten unique 2-day average temperatures for each decadal time-period.

Analysts then repeated this same method to find the hottest 4- and 7-day consecutive average temperatures. The results provide insight into how climate change will alter periods of extended heat. Specifically, the team observes consistently higher average temperatures over multiple days by mid-century, suggesting heat waves will increase in both intensity and duration.

TABLE 1 Average temperature of the hottest consecutive n (2, 4, or 7) days' daily average temperature. Value depicted is the ensemble mean for the base period and mid-century.

Number of consecutive days	Avg. Consecutive Daily Avg. Temp (°C)	
	Base Period	Mid-Century
2	29.22	30.45
4	27.94	29.14
7	26.60	27.97

Disproportionate Impacts of Heat Waves

In July 1995, the Chicago area experienced 4 days of exceptionally high temperatures, with daily maximum temperatures exceeding 94°F (34°C) and a peak heat index of 124°F (51°C). This wave of heat was amplified by an urban heat island effect that kept temperatures high throughout the night, resulting in 525 deaths in Chicago and hundreds more across the upper Midwest. These impacts were felt most acutely among more vulnerable groups, including the elderly, persons of color, and lower income households. Since this event, many structural changes have reduced the region's vulnerability to heat waves, such as wider proliferation of air conditioning, the opening of cooling centers, and the implementation of preparedness and emergency response protocols. However, ComEd recognizes that climate change will increase the risk of extreme heat and heat waves, which continue to have unequal impacts on lower-income households and the elderly. Climate risk analyses, including this study, are an important first step towards understanding northern Illinois' future climate and preparing for more extended heat waves. This work will equip ComEd with the information needed to ensure its operations remain resilient in the face of longer and more intense heat waves.

8 DAYTIME AND NIGHTTIME TEMPERATURE DIFFERENCES

Argonne's climate model steps through time in 3-hour intervals which results in eight temperature values for each 24-hour period. To logically articulate differences in daytime and nighttime temperatures, Argonne shifted the traditional calendar day of midnight to midnight, to 9:00 AM Central Time (CT) to 6:00 AM CT the next morning in order to capture all daytime and nighttime values within the same 24-hour period. Therefore, daytime is defined as the 9:00 AM CT, 12:00 PM CT, 3:00 PM CT, and 6:00 PM CT values; nighttime is defined as the 9:00 PM CT, 12:00 AM CT, 3:00 AM CT, and 6:00 AM CT values. For example:

Day Value – 9:00 AM CT	24-hour Interval OR "Day"
Day Value – 12:00 PM CT	
Day Value – 3:00 PM CT	
Day Value – 6:00 PM CT	
Night Value – 9:00 PM CT	
Night Value – 12:00 AM CT	
Night Value – 3:00 AM CT	
Night Value – 6:00 AM CT	

Daytime and nighttime temperature values are averaged over each respective 12-hour period for both the baseline (1995-2004) and mid-century RCP8.5 (2045-2054) models. Each temperature average is then grouped by its corresponding season to produce seasonal daytime and nighttime averages for both time periods at the 12-km grid level. Analysts then calculated the difference between mid-century seasonal daytime/nighttime temperatures and those of the baseline period.

While seasonal daytime temperatures increase across all parts of ComEd's service area and across every season, Argonne's analysis reveals that the largest increase in daytime temperatures occurs during the winter, in particular along the northern portion of ComEd's service area. Conversely, projections of seasonal daytime temperatures show the least amount of increase over warmer months. Similar patterns emerge in the difference between seasonal nighttime temperatures for the mid-century and baseline periods, with fall and winter seasons depicting noticeably larger increases in nighttime average temperatures than spring and summer. These temperature changes also exhibit what appears to be a heat island effect, occurring within the Chicago region. Here, one would expect the urban land use and lack of vegetative cover to produce higher temperatures, particularly in the daytime and during seasons that are historically warmer.

Argonne also evaluated the percentage of time in which modeled daytime/nighttime temperatures exceed a given threshold temperature (e.g., how often, relatively, are nighttime temperatures projected to exceed 25°C). Modeled results depict a noticeable upwards shift in the percentage of time exceeding a given temperature, similar to those patterns exhibited across daily average temperatures.

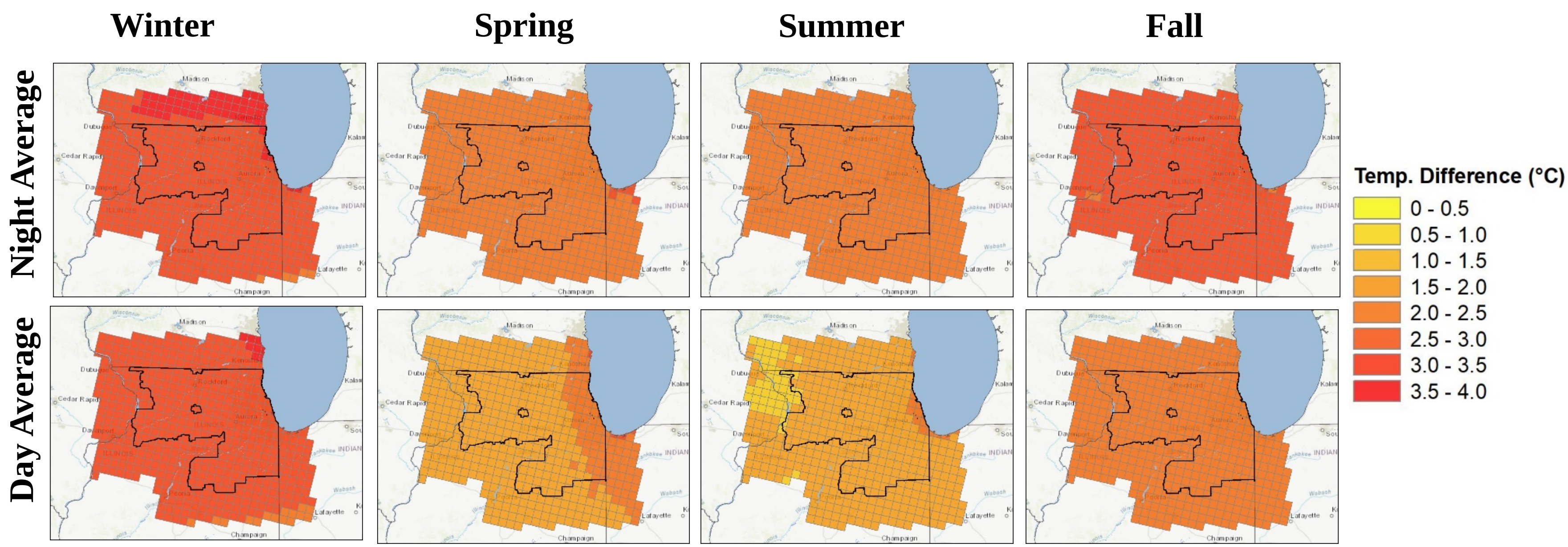


FIGURE 11 Change in the average seasonal daytime/nighttime average temperatures between the baseline and mid-century periods.

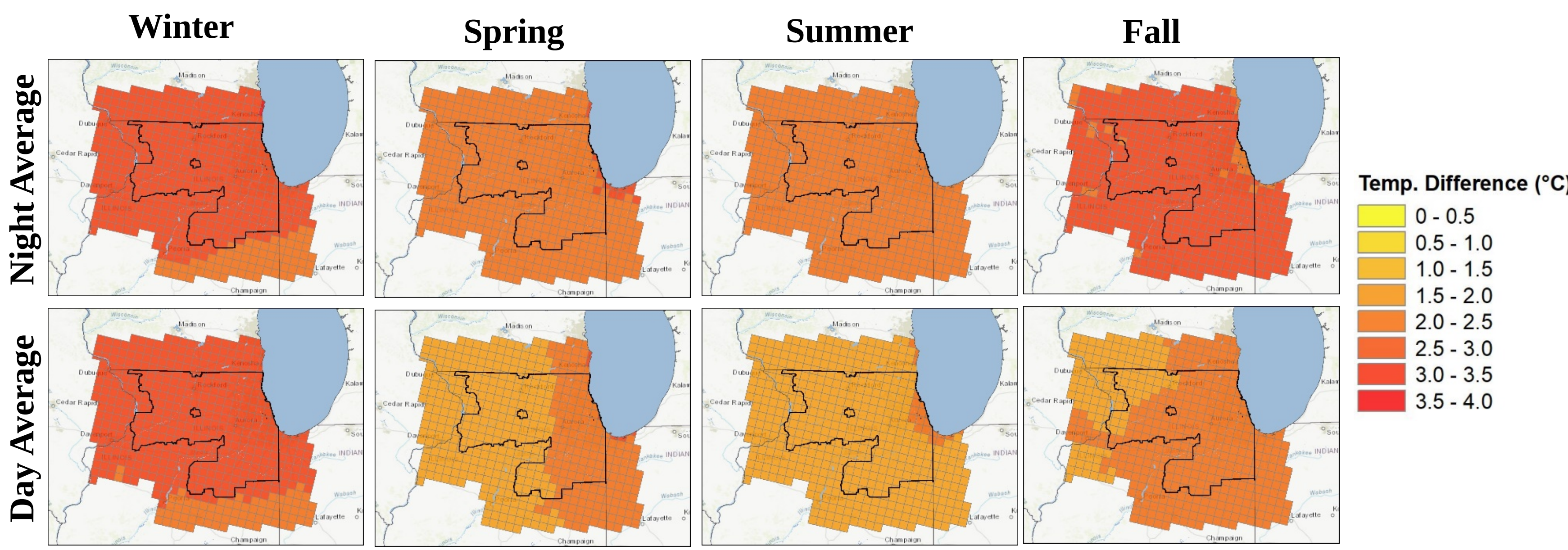


FIGURE 12 Change in the average seasonal daytime/nighttime maximum temperatures between the baseline and mid-century periods.

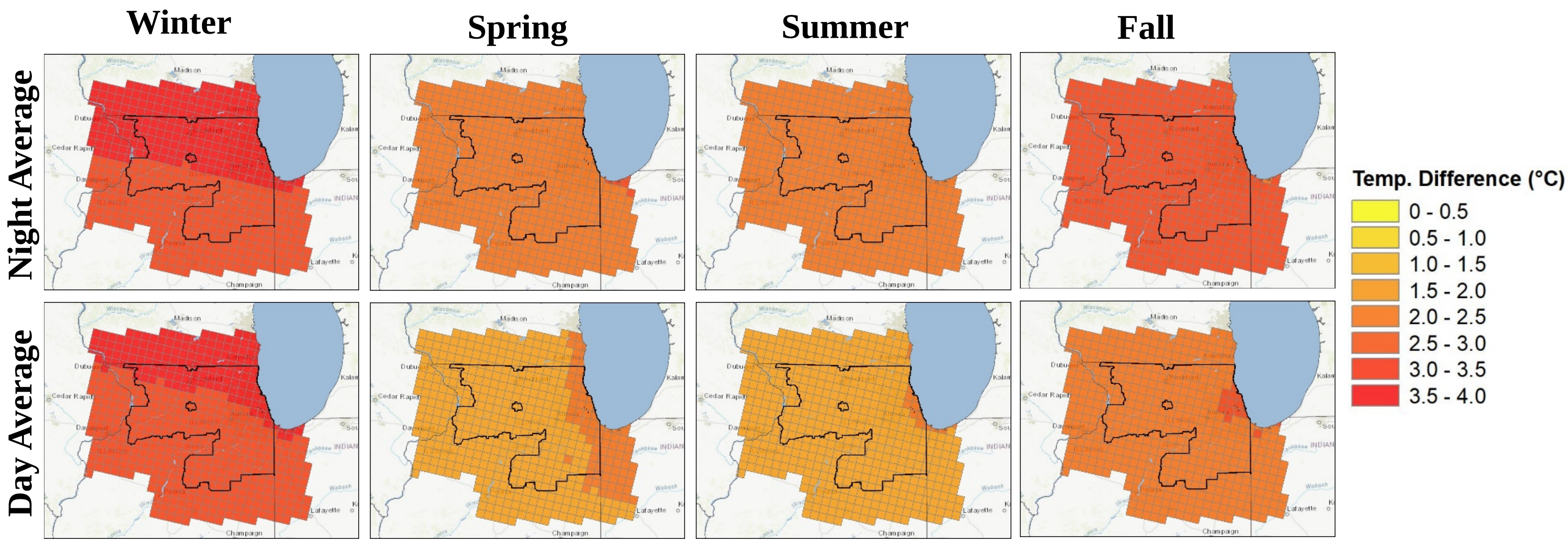
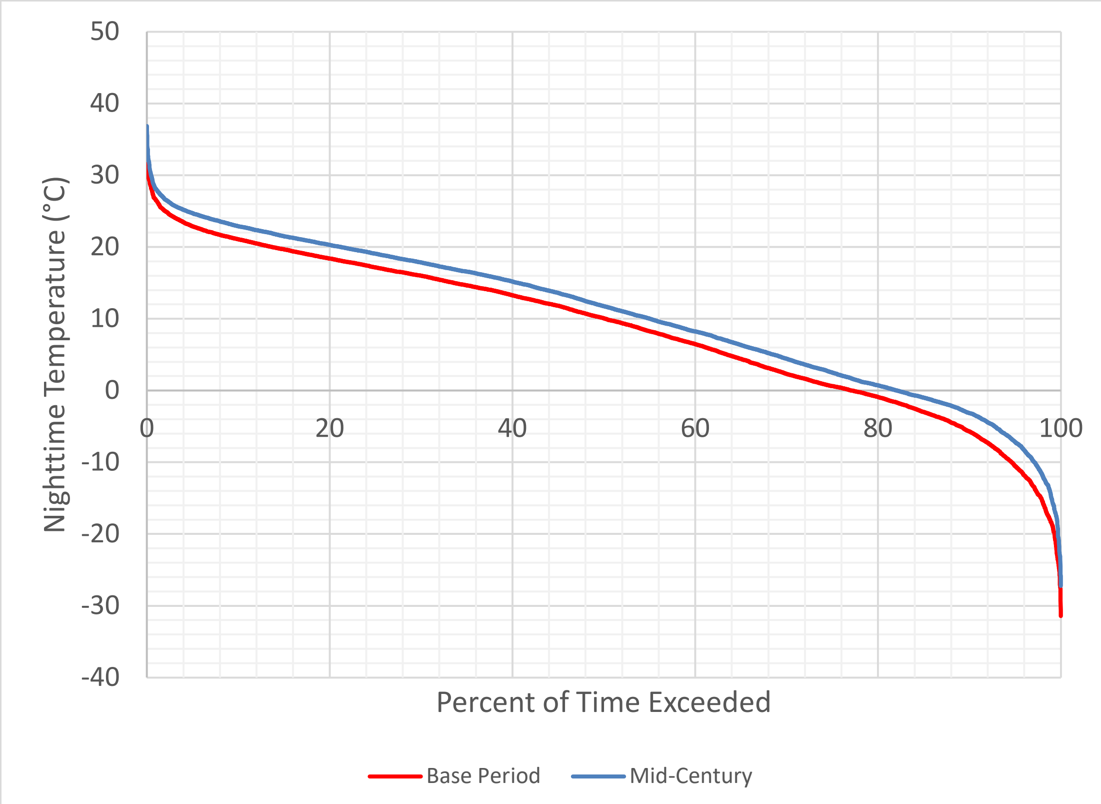
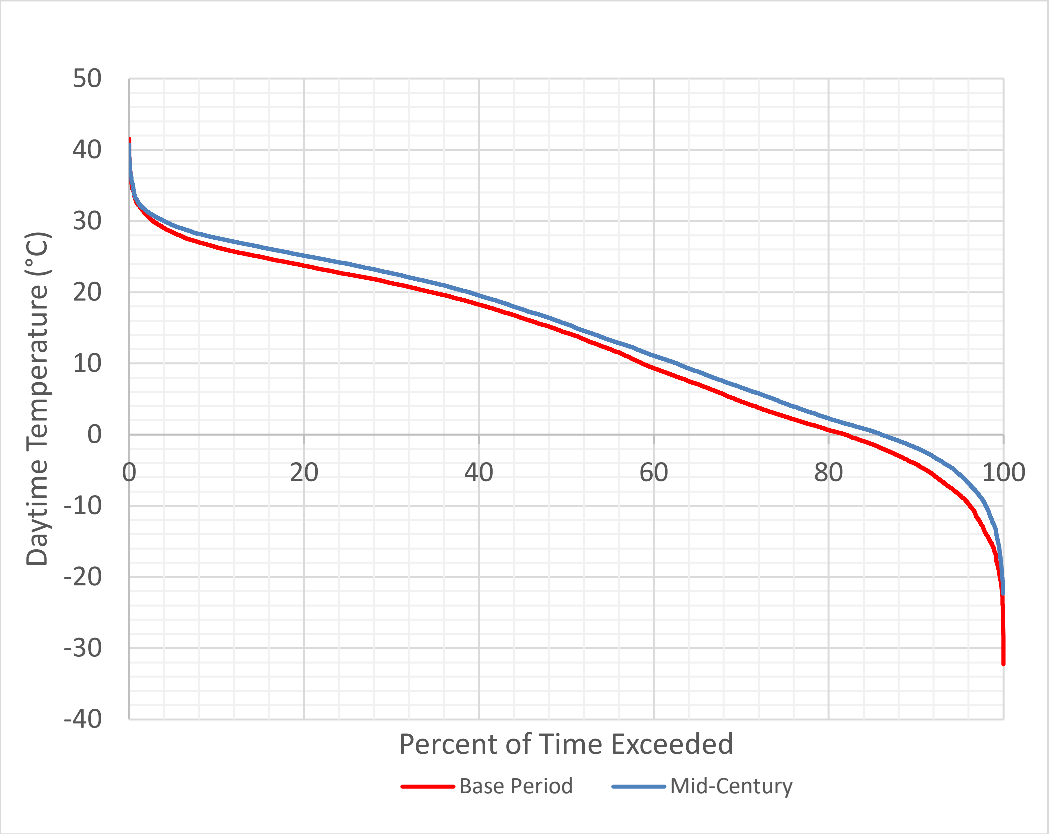


FIGURE 13 Change in the average seasonal daytime/nighttime minimum temperatures between the baseline and mid-century periods.



Nighttime Avg. Temp. (°C)	Percent Time Exceeded		Days Exceeded Per Year	
	Baseline	Mid-Century	Baseline	Mid-Century
-30	99.98		365	
-25	99.83	99.97	364	365
-20	99.31	99.69	362	364
-15	97.84	98.96	357	361
-10	94.63	97.10	345	354
-5	88.99	92.79	325	339
0	77.06	82.06	281	300
5	63.47	68.57	232	250
10	50.16	55.04	183	201
15	33.58	40.58	123	148
20	13.68	21.24	50	78
25	2.02	4.37	7	16
30	0.16	0.46	1	2
35		0.04		0.16
40				

FIGURE 14 Percent of time that average nighttime temperatures exceeded a given threshold for the baseline and mid-century periods.



Daytime Avg. Temp. (°C)	Percent Time Exceeded		Days Exceeded Per Year	
	Baseline	Mid-Century	Baseline	Mid-Century
-30	99.99		365	
-25	99.93	99.99	365	365
-20	99.59	99.86	364	364
-15	98.47	99.35	359	363
-10	96.15	97.95	351	358
-5	91.22	94.41	333	345
0	81.94	86.02	299	314
5	69.27	73.73	253	269
10	58.67	62.66	214	229
15	48.43	51.07	177	186
20	34.60	38.84	126	142
25	14.94	20.62	55	75
30	2.72	4.02	10	15
35	0.29	0.42	1	2
40	0.02	0.01	0.06	0.05

FIGURE 15 Percent of time that average daytime temperatures exceeded a given threshold for the baseline and mid-century periods.

9 COMPARING NORTHERN ILLINOIS TO OTHER REGIONS

To visualize how conditions are changing across ComEd's service territory, it is useful to compare projected mid-century temperatures in northern Illinois to other regions that currently experience temperatures that ComEd expects by mid-century. ComEd may use this information to create or participate in peer learning opportunities with utilities currently operating in ComEd's projected mid-century conditions to understand the specifications, design criteria, and standards deployed in those regions.

This analysis identifies regions in the central and eastern United States that could provide information as modern analogs of projected mid-century temperatures. Argonne compared mean conditions projected for the mid-century period (2045-2054) to recent historical data, on both an annual and seasonal basis. Argonne subset the mid-century data to the season of interest and then calculated the annual mean for each year from 2045-2054, combining data from all three model runs for maximum temperature (Tmax), minimum temperature (Tmin), and mean temperature (Tmean). Argonne then averaged these annual values to produce a single value for each Tmax, Tmin, and Tmean for the mid-century period for each season. The team recorded the standard deviation for the interannual means for use during the mapping process.

Argonne used monthly data from the PRISM dataset for modern observed climate. PRISM is a national gridded (approximately 4 km-by-4 km) dataset that extends from 1895 to the present.[xvi] For this analysis, Argonne used a time period from 2012-2021 to identify modern analog regions. Argonne extracted monthly PRISM data for Tmean, Tmin, and Tmax, and calculated an average annual value for each year across each seasons. These annual values were then aggregated into a single mean value for the 2012-2021 period. Argonne also extracted the average daily maximum heat index for summer months in the PRISM data to identify analog regions based on heat and humidity over the warmest months of the year.

To identify modern analog regions, Argonne calculated the difference between the projected mid-century mean values and the modern PRISM means. When mapped, a zero (0) value indicates that the recent climate at that location is the same as what ComEd's service territory is projected to experience at mid-century. Argonne then mapped a range of two standard deviations of the interannual mean at mid-century to illustrate adjacent regions that currently experience temperatures slightly warmer or cooler than what is projected across ComEd's region at mid-century. In the resultant maps, negative values (blue on map) indicate areas where modern temperatures are slightly cooler than the projected mid-century temperature and positive values (red on map) indicate areas where modern temperatures are slightly warmer than the projected mid-century temperature.

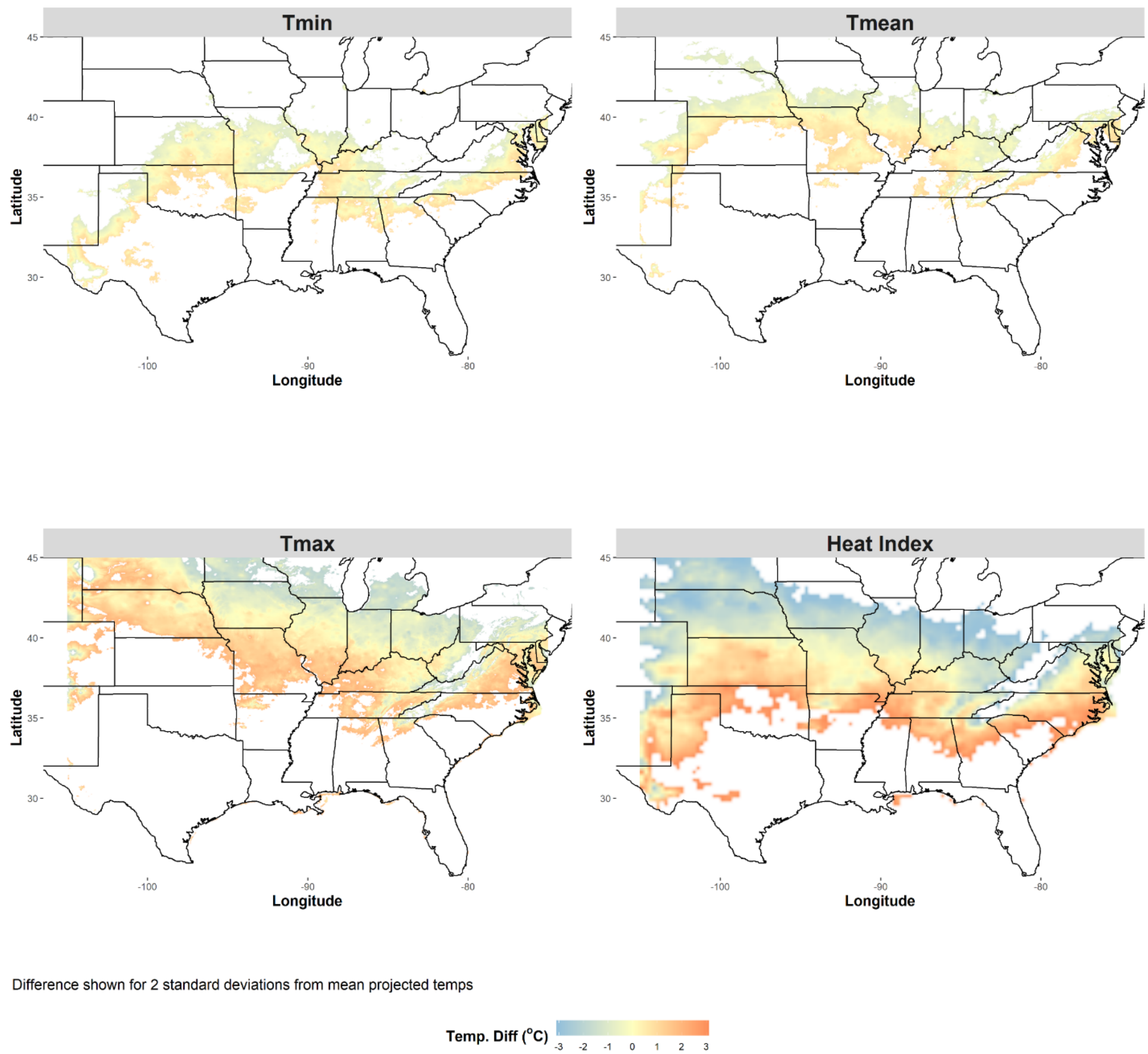


FIGURE 16 Modern annual analog regions for northern Illinois' mid-century climate. Maps depict analog regions based on projected average annual minimum (Tmin), mean (Tmean), and maximum (Tmax) temperatures, as well as the average maximum heat index for the summer months. Each map illustrates the difference between the respective mid-century temperature value and modern (2012-2021) observed temperatures.

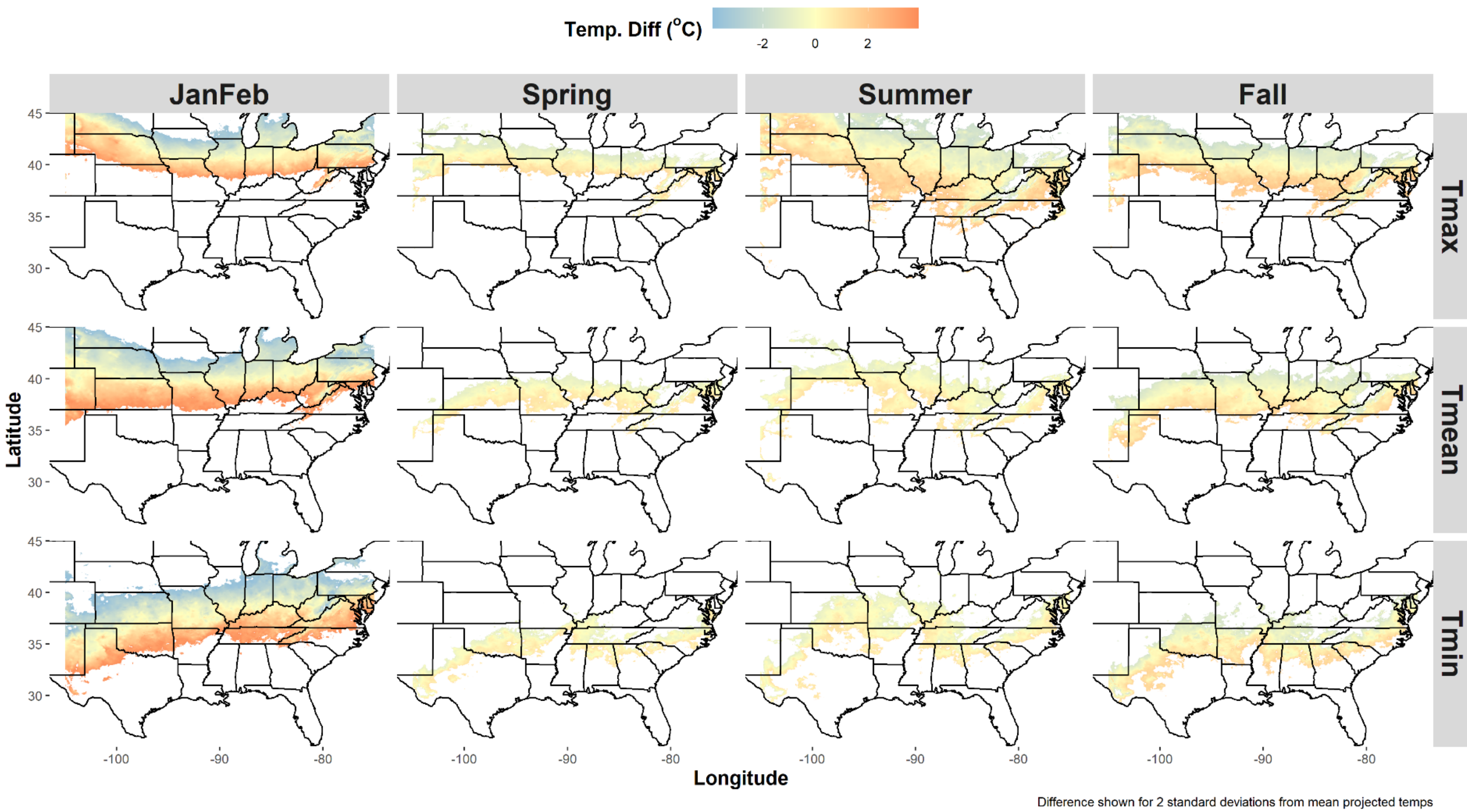


FIGURE 17 Modern seasonal analog regions for northern Illinois' mid-century climate. Maps depict analog regions based on projected average seasonal minimum (Tmin), mean (Tmean), and maximum (Tmax) temperatures. Each map illustrates the difference between the respective mid-century temperature value and modern (2012-2021) observed temperatures.

10 HEAT INDEX

Heat index is an important weather variable since the combination of temperature and relative humidity – rather than temperature alone – is a major driver in space cooling demand. When overheated, the human body's physiological response is to cool itself via perspiration, as the evaporation of sweat helps to transfer heat away from the body. However, as relative humidity increases, and the surrounding air becomes more saturated with water, the rate of evaporation slows considerably, reducing the body's ability to cool itself. Because of this, higher heat indices often drive greater demand for space cooling. Moreover, higher humidity levels also affect air conditioners themselves, as units must expend more energy on dehumidification. Taken together, the combined impact of heat and relative humidity is an important determinant in service demand.

Using daily average, maximum, and minimum temperature and relative humidity readings, Argonne computes the daily average, maximum, and minimum heat index for each grid cell within ComEd's study area.[1] These daily readings are then grouped by season and averaged to produce a seasonal average of the maximum, minimum, and average heat index; the same process is also conducted for an annual average. Of note, the National Weather Service only calculates the heat index for temperatures above 80°F. Accordingly, Argonne's analysis of the seasonal average heat index does not include any values for the winter season, since there are no historical or projected days in which the winter temperature exceeds 80°F. Therefore, given that heat index measurements are most relevant to the summer months (within ComEd's service territory), analysts present the change in summer seasonal average, maximum, and minimum heat index values from the baseline period to mid-century (Figure 18). While the impacts are less severe, the Argonne team also presents the change in annual average, maximum, and minimum heat index values.

Heat-Related Workplace Hazards

The Occupational Safety and Health Administration recognizes extreme heat and humidity as a serious climate resilience issue, with increasing health and safety risks resulting from more extreme weather. Hotter environments not only present direct risks in the form of heat exhaustion or heat stroke, they also amplify preexisting maladies and lead to higher rates of workplace accidents and injuries. Outdoor workforces are directly exposed to the impacts of intense heat, whereas a lack of adequate resources for indoor cooling and ventilation, or a workplace that involves the presence of additional heat sources (e.g., kitchens, furnaces), can create equally serious risks to indoor workers. Heat-related hazards are an important issue for ComEd, as many of its employees regularly conduct outdoor maintenance and construction work, including on days when extreme weather affects grid operations. ComEd is committed to ensuring that businesses and communities across northern Illinois are equipped with the resources needed to mitigate heat-related risks, and it recognizes its important role as a key community partner. Evaluating heat index projections under climate change is an important indicator to help in planning for health risks to the workforce, and a key priority for safety-focused organizations like ComEd.

[1] Heat index formulas available at https://www.wpc.ncep.noaa.gov/html/heatindex_equation.shtml

Over the summer, the average maximum heat index shows a marked increase by mid-century, particularly for the southern portions of ComEd's service area. This increase in maximum heat index projections points to a future with markedly higher peak heat. Importantly, these impacts are expected to occur during those months in which heat, and therefore demand for space cooling, has historically been the highest. In other words, mid-century heat index projections point to more frequent and more intense levels of demand during the times in which historical loads have already placed the greatest stress on the electric system.

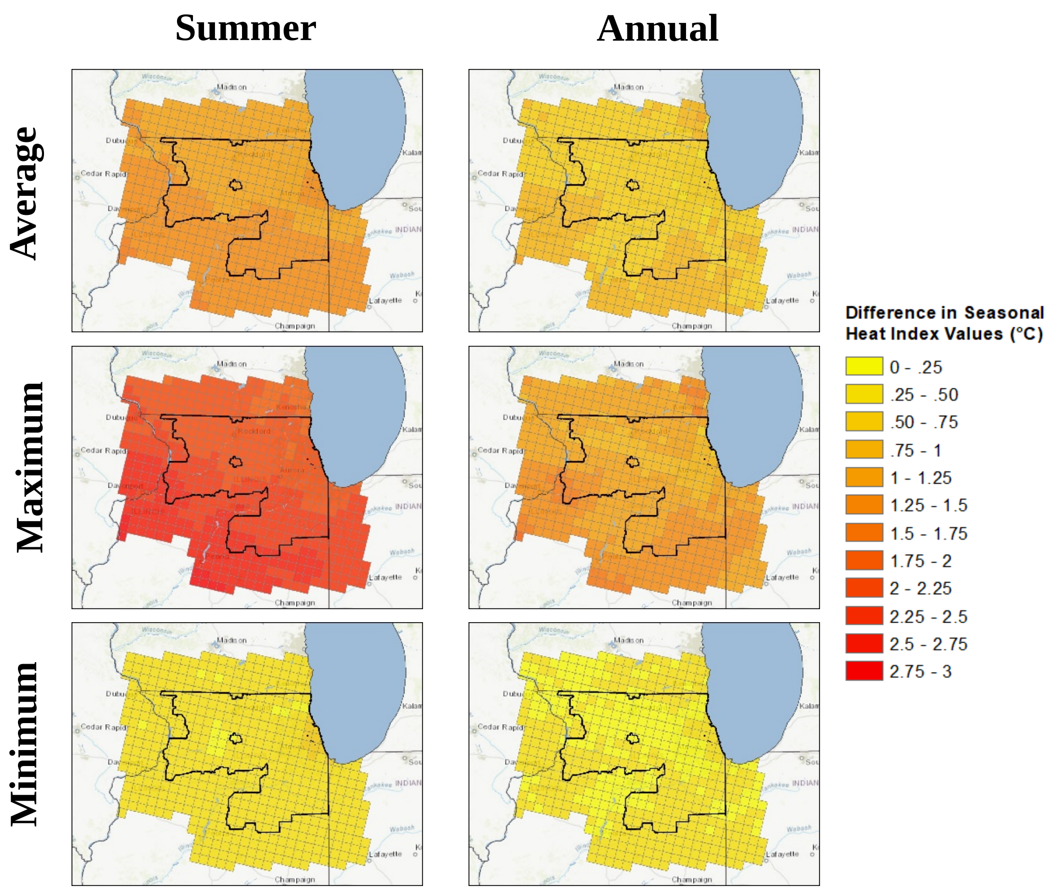


FIGURE 18 Change in the summer and annual average, maximum, and minimum heat index from the baseline to mid-century periods.

11 AVERAGE WIND

Argonne's downscaled regional climate model provides information about two primary components of wind, measured in 3-hour intervals and at various elevations above ground level. These components are *u*, which represents the zonal (west to east) vector, and *v*, which represents the meridional (south to north) vector. Each of these components contains values for wind speed and direction. The *u* component is positive if the wind comes from the west (i.e., blows towards the east) and negative if the wind comes from the east (i.e., blows towards the west), whereas the *v* component is positive if the wind comes from the south and negative if the wind comes from the north. Together, the *u* and *v* components can be used to calculate the combined wind vector, providing both the speed and meteorological direction (e.g., northwest or southwest) at a given time.

This analysis considers only the daily maximum wind vector for each grid cell, given that maximum wind speeds are an important consideration when designing infrastructure. Wind vectors were also only evaluated at an elevation of 10 meters above ground level, although future analyses could consider higher elevations (e.g., up to 100 meters) to investigate changes in wind profiles that could affect taller assets (e.g., transmission towers, wind turbines). For this study, analysts extract the *u* (speed and west-east direction) and *v* (speed and south-north direction) components associated with the daily measurement with the greatest wind speed, and then use trigonometric functions to produce the average maximum wind vectors by season for both the baseline (1995-2004) and mid-century (2045-2054) periods. Likewise, daily maximum wind vectors are also used to calculate annual average wind speed and direction. Analysts were careful to note that the wind speeds calculated here do not fully account for convection (i.e., rising currents of warm air), which can produce extreme rain and wind events. As a result, the true maximum wind speeds experienced at a given point in time, which pose the greatest risk to electrical distribution infrastructure, are underrepresented in the data.

Relative to observed changes in projected temperatures, the Argonne team's analysis of wind characteristics reveals comparatively limited changes in wind patterns; many parts of ComEd's service area project to have small *reductions in* maximum wind speeds. Across ComEd's entire service territory, wind speeds are projected to decrease in the winter (-1.51%), summer (-1.90%), and fall (-2.96%) seasons. Only the spring season, which has historically been a season of relatively limited wind in ComEd's service area, projects to have a noticeable increase in wind speeds at mid-century (3.95%). Averaged over the course of a year, these seasonal variations produce a small, negative change in annual wind speeds (-0.52%), which is a magnitude similar to normal year-to-year variability in average annual wind speeds. However, although most of the service territory exhibits a reduction in annual average wind speeds by mid-century, those areas located in Chicago exhibit small (>1%) gains in annual wind speeds.

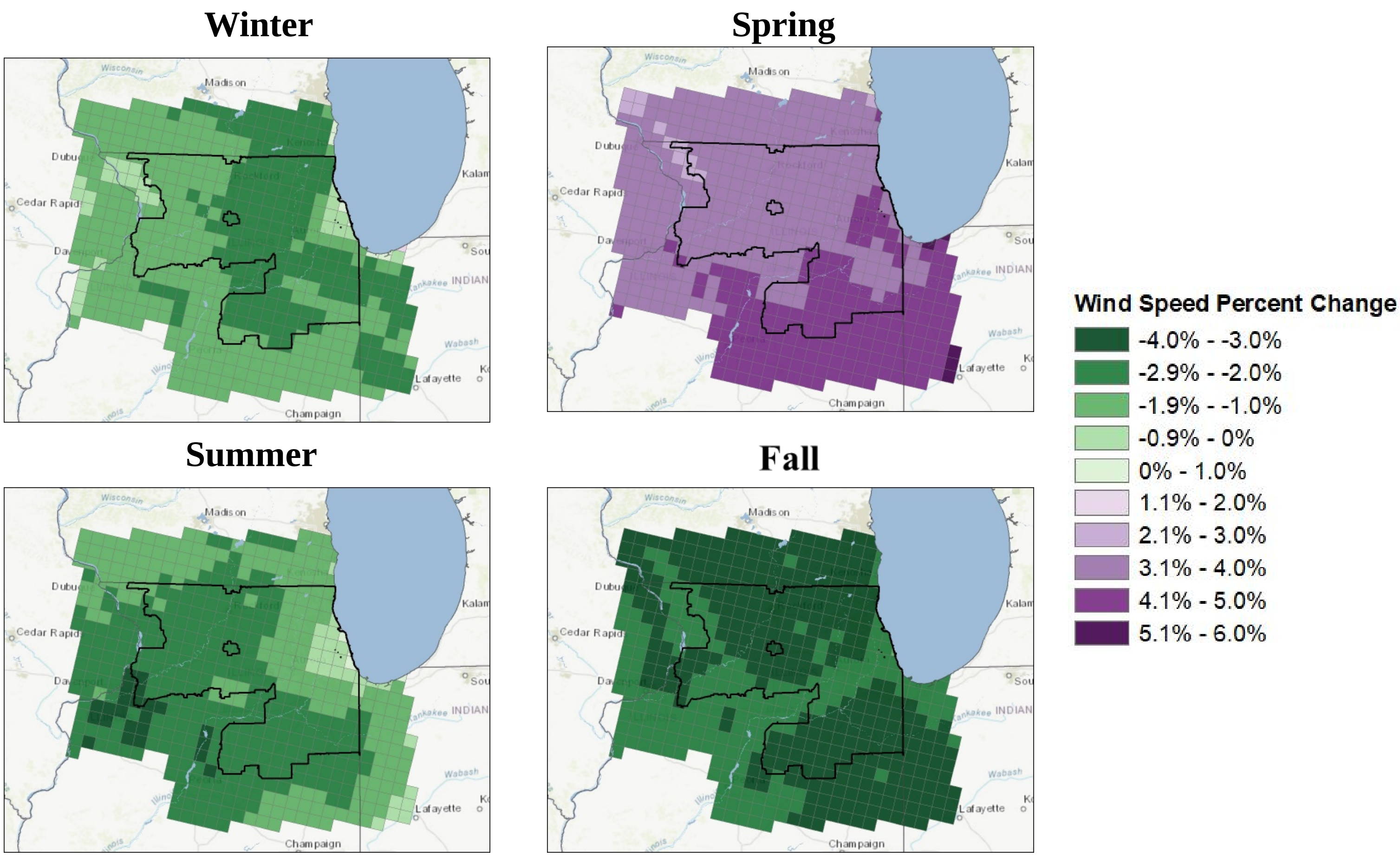


FIGURE 19 Percentage change in the seasonal averages of the daily maximum wind speeds, from baseline to mid-century.

Base Period **Mid-Century**

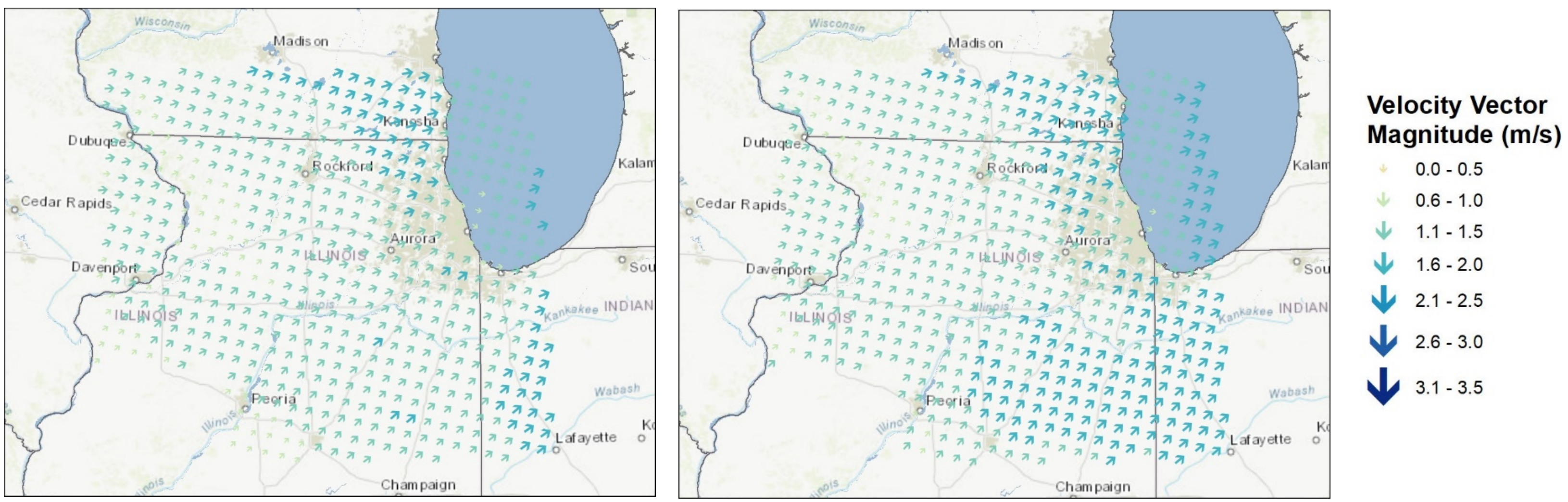


FIGURE 20 Annual averages of the daily maximum wind speed and direction for the baseline and mid-century periods.

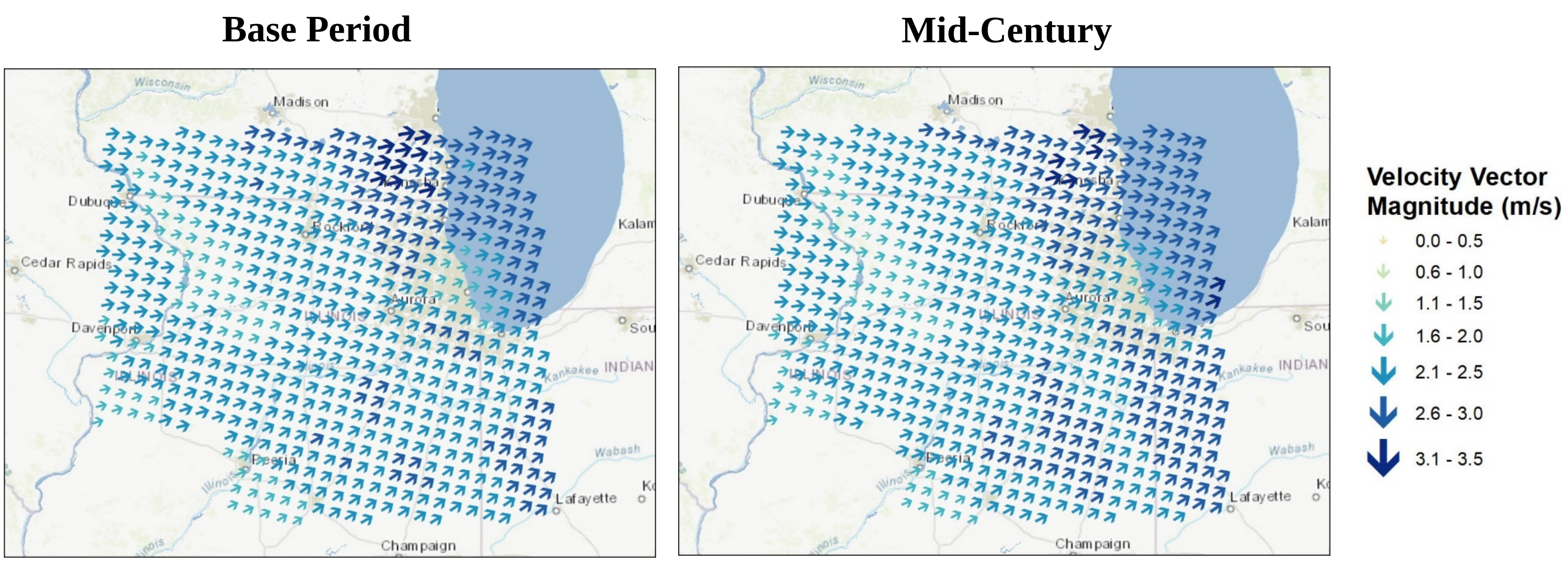


FIGURE 21 Winter averages of the daily maximum wind speed and direction for the baseline and mid-century periods.

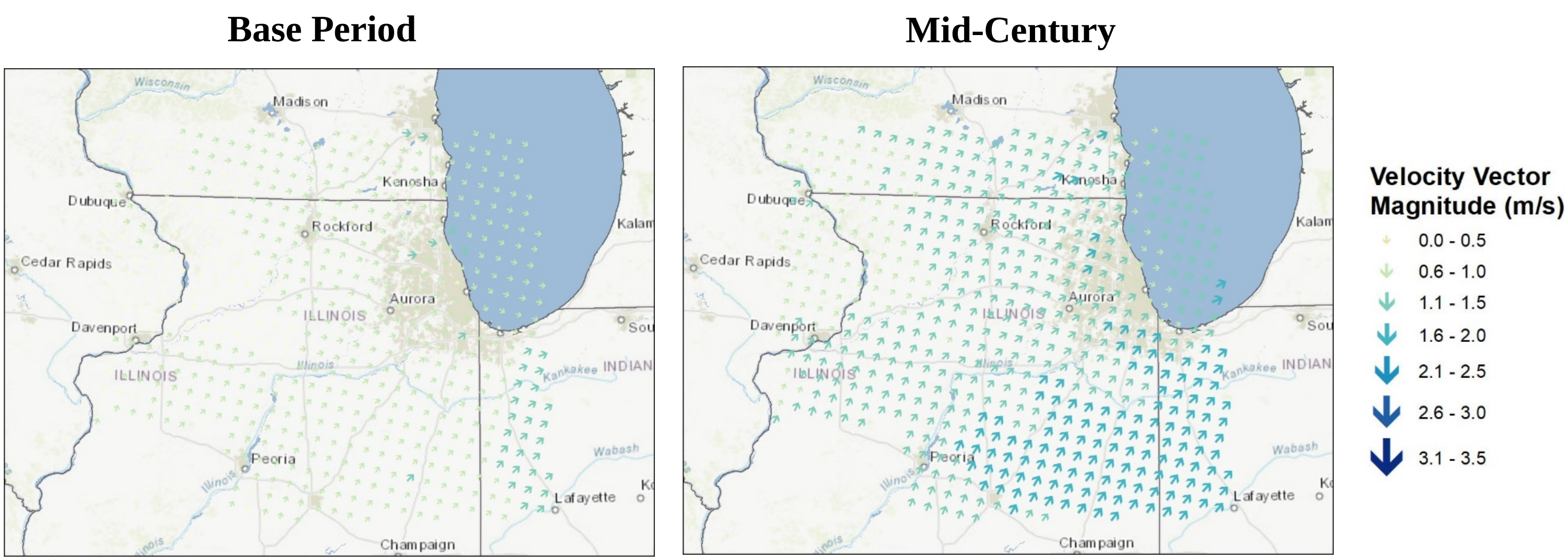


FIGURE 22 Spring averages of the daily maximum wind speed and direction for the baseline and mid-century periods.

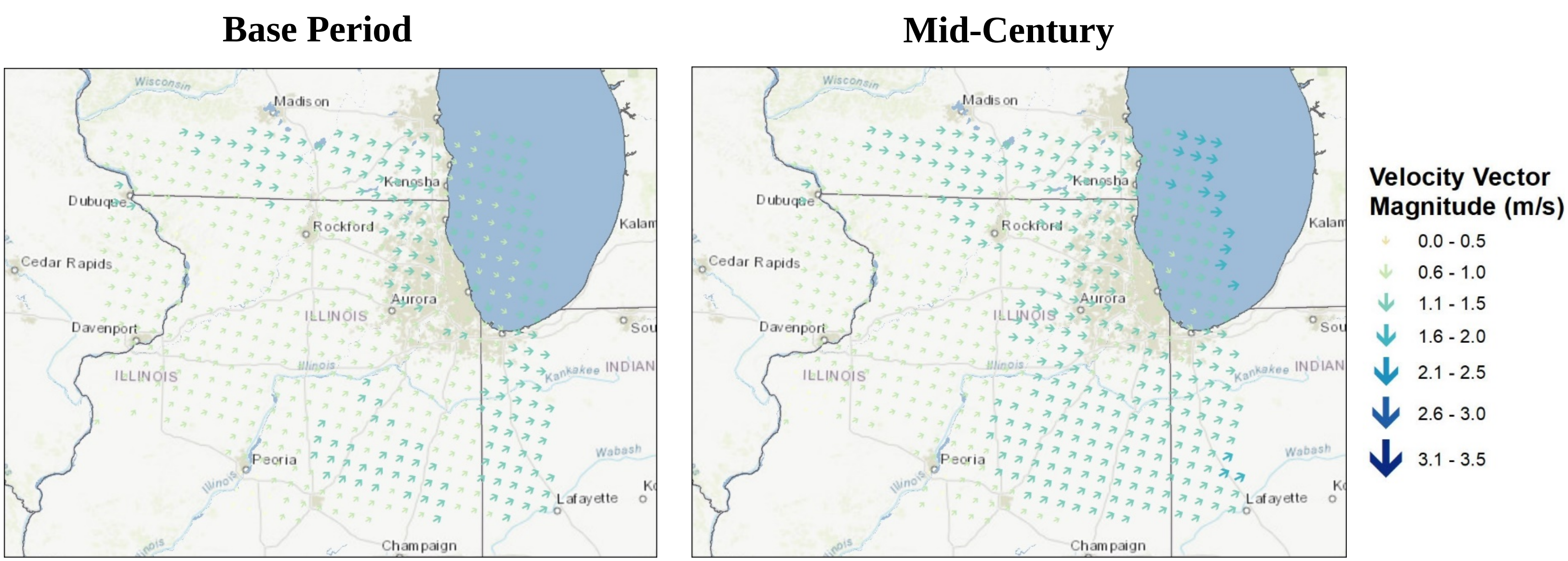


FIGURE 23 Summer averages of the daily maximum wind speed and direction for the baseline and mid-century periods.

Base Period

Mid-Century

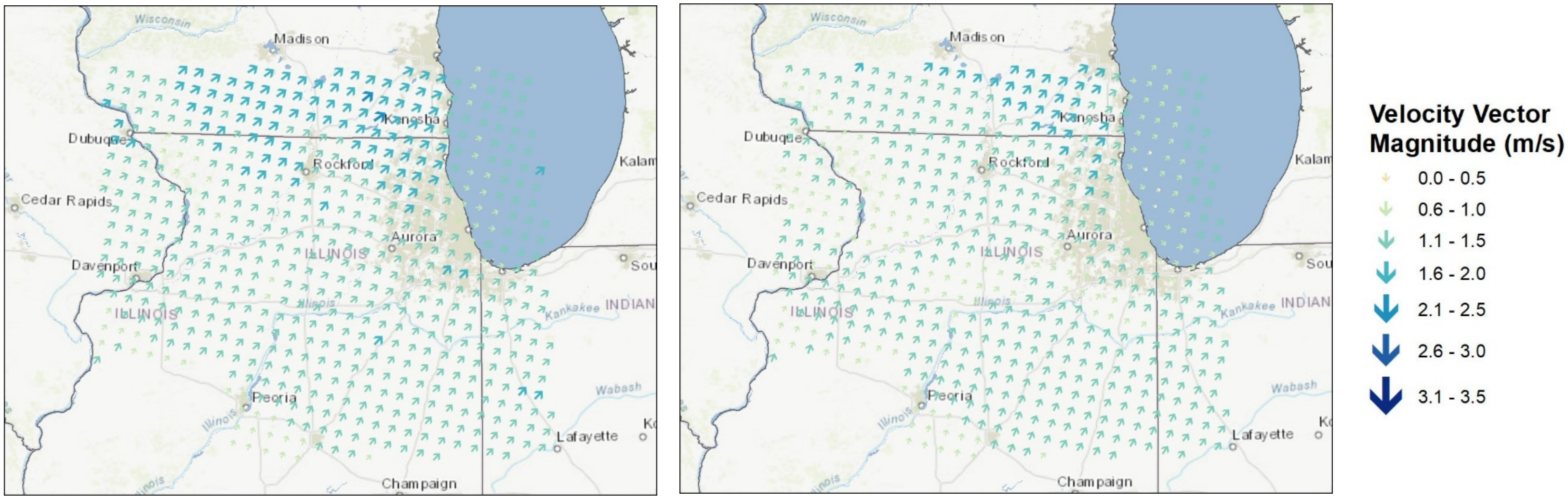


FIGURE 24 Autumn averages of the daily maximum wind speed and direction for the baseline and mid-century periods.

12 THE CLIMATE SENSITIVITY OF THE GRID

Argonne performed a literature review to identify and categorize climate sensitivities of the electric grid. Although this report is primarily concerned with climate impacts on distribution systems, the literature review includes climate vulnerabilities on generation and transmission operations to provide perspective across the electric delivery supply chain. The table below outlines how many different weather hazards impact electrical equipment by asset type, but additional research and consideration is needed to accurately characterize how each identified hazard may impact ComEd's distribution system. To complement this literature review, Argonne documented the hazards and asset types analyzed by two other utility-driven climate vulnerability studies: Southern California Edison's (SCE) Climate Adaption Vulnerability Assessment (CAVA) and Con Edison's Climate Change Vulnerability Study (CCVS). These studies provide valuable insight into how climate-related hazards will likely impact ComEd's operations and serve as a useful benchmark for its own risk analyses.

TABLE 2 Climate sensitivities of the electric grid, including a benchmark of those climate hazards and asset types assessed in two industry-representative, utility-driven climate resilience studies.

Asset Type	Hazards	Effect	References[2]	Considered in SCE's CAVA?[3]	Considered in ConEd's CCVS?[4]
Gas Lines	Cold	Supply pressure collapse	[1]		✓
	Ice	Supply pressure collapse, fuel leak	[1]		
	Flooding	Destruction	[2]	✓	✓
	Fire	Destruction, ignition	[3]		
	Stream Flow	Earth destabilization (on banks), destruction at crossing	[4]		
Generation	Cold	Water supply icing, equipment freeze	[24], [1]	✓	✓
	Heat	Cooling water shortage, cooling water inefficacy, ambient cooling impacts	[5]	✓	✓
	Ice	Structural damage, water supply icing	[24]		
	Wind	Structural damage, hydroelectric overflow	[24], [6]		
	Stream Flow	Water supply overflow	[24]		
	Flooding	structural damage, maintenance route closure	[25]	✓	

2 See the Climate Sensitivities References list at the end of the document for full citation.

3 Southern California Edison's (SCE) Climate Adaption Vulnerability Assessment (CAVA), 2022: https://www.sce.com/about-us/environment/climate-adaptation

4 Consolidated Edison's (Con Edison)'s Climate Change Vulnerability Study (CCVS), 2019: https://www.coned.com/en/our-energy-future/our-energy-vision/storm-hardening-enhancement-plan

Asset Type	Hazards	Effect	References[5]	Considered in SCE's CAVA?[6]	Considered in ConEd's CCVS?[7]
Transmission Lines	Heat	Sagging, ampacity derating	[7], [8]	✓	✓
	Humidity	Insulation derating, flashover	[2], [3]		
	Wind	Cross-whipping, snapping, grounding contact	[7]		✓
	Ice	Snapping, flashover faults	[9], [10]		✓
	Flooding	Buried asset damage	[11]	✓	✓
	Overgrowth	Debris fall, arcing contact	[12]	✓	
Transmission Structures	Wind	Toppling	[2]		✓
	Flooding	Maintenance route closure	[13]		
	Ice	Toppling	[25], [10]		
	Stream Flow	Earth destabilization (on embankments)	[4]		
Transformers	Heat	Derating, loss of asset life, overloading	[14], [15]	✓	✓
	Humidity	Insulation derating, loss of asset life, heating, ventilation, and air-conditioning (HVAC) demand	[16], [15], [17], [18]		
	Flooding	Destruction, faulting	[19]	✓	✓
	Cold	Overloading, HVAC demand	[15]		
Switchgear	Cold	Freezing, gas pressure loss	[20]		
	Ice	Freezing	[20]		
Other Substation Assets	Humidity	Grounding impedance, HVAC demand	[2], [15], [17], [18]		
	Heat	Overloading	[15]		
	Flooding	Destruction, maintenance route closure	[2], [19]	✓	
Distribution Lines	Wind	Cross-whipping, snapping, grounding contact	[7]		✓
	Heat	Sagging, ampacity derating, overloading	[6]	✓	
	Ice	Snapping, debris fall	[10]		✓
	Overgrowth	Debris fall, arcing contact	[12]	✓	
	Flooding	Buried asset damage, maintenance route closure	[11]		✓
	Humidity	Insulator derating, HVAC demand	[2], [15], [17], [18]		

5 See the Climate Sensitivities References list at the end of the document for full citation.

6 Southern California Edison's (SCE) Climate Adaption Vulnerability Assessment (CAVA), 2022: https://www.sce.com/about-us/environment/climate-adaptation

7 Consolidated Edison's (Con Edison)'s Climate Change Vulnerability Study (CCVS), 2019: https://www.coned.com/en/our-energy-future/our-energy-vision/storm-hardening-enhancement-plan

Asset Type	Hazards	Effect	References[8]	Considered in SCE's CAVA?[9]	Considered in ConEd's CCVS?[10]
Distribution Poles	Cold	Freeze expansion (concrete)	[21]		
	Wind	Toppling, debris fall	[2]	✓	✓
	Flooding	Toppling, maintenance route closure	[2]		
	Stream Flow	Earth destabilization, toppling	[4]		
	Ice	Toppling, debris fall, freeze expansion	[21]		✓
	Overgrowth	Debris fall, maintenance interference	[22]	✓	
DERs (SOLAR), Community Microgrid	Heat	Self-islanding, overloading, battery derating	[23]	✓	
	Cold	Self-islanding, overloading, photovoltaic (PV) icing	[23]		
	Wind	Debris fall, unseating/destruction	[23]		
	Flooding	Destruction, grounding	[23]		
	Humidity	HVAC demand (depletion)	[15], [17], [18]		
	Ice	PV and battery icing, maintenance prevention	[23]		

ComEd Examples:

- **ComEd Restores Power to More Than 90 Percent of Customers Following Damaging Derecho and Tornados (2020) - https://www.comed.com/News/Pages/NewsReleases/2020-08-13.aspx**
- **ComEd prepared to Support Customers as Extreme Heat Hits its Communities (2019) - https://www.comed.com/News/Pages/NewsReleases/2019-07-19.aspx**
- **About 2,000 ComEd Customers Without Power Amid Brutal Cold (2019) - https://www.cbsnews.com/chicago/news/comed-power-outages-extreme-cold-weather-deep-freeze/**

8 See the Climate Sensitivities References list at the end of the document for full citation.

9 Southern California Edison's (SCE) Climate Adaption Vulnerability Assessment (CAVA), 2022: https://www.sce.com/about-us/environment/climate-adaptation

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13 CLIMATE RISK-INFORMED PLANNING FOR COMED'S DISTRIBUTION GRID

Throughout this study, ComEd consulted with internal subject-matter experts from across the organization.[11] Their feedback and interaction enabled the Argonne team to better customize the data outputs and tailor them to ComEd's infrastructure and grid planning needs. This interaction also enabled ComEd's experts to conduct an initial internal assessment of the ways in which the future mid-century climate conditions projected across their service territory could affect their system, and explore opportunities to adapt ComEd's systems, facilities, and assets to meet the needs of electricity delivery under future climate conditions.

In their assessment of potential climate impacts to their infrastructure and operations, ComEd experts considered industry standards from across their respective departments in light of the mid-century projections of temperature, wind, and humidity/heat-index presented in this report. As such, the potential impacts that they identified below represent a subset of the much broader range of climate impacts that will occur to ComEd's system and customers beyond just those studied here. (The report section *Future Research Agenda* identifies several additional climate impacts for consideration.) As noted, the climate projections presented in this report are based on the RCP8.5 scenario, and the impacts that the ComEd experts identified are in response to this worst-case projection of future climate. These effects, organized according to climate impact category, include the following.

Temperature

- Rising average temperatures and a reduction in freeze/frost days are expected to expand the growing season over time, which will increase vegetative density around ComEd infrastructure, thereby producing more opportunities for damaging equipment.
- Reduced insect die-off during the winter months may create more opportunities for pests, which can degrade the structural integrity of vegetation and increase the incidence of downed branches or trees disrupting grid assets.
- Shorter and warmer winters, and hotter and more humid summers may lead to faster decay of wooden utility poles caused by fungi and insects.
- Both distribution and transmission transformers would need to be derated by approximately 6% when planning for a change in 24-hour average ambient temperatures from 30°C to 35°C under present-day load profiles. Given this change in ambient average temperatures:
    - Substation transformers could age at a rate significantly faster than the historical average; under present-day load profiles, the transformer aging factor could be approximately 65% higher than normal;
    - Distribution transformers will have to derate by approximately 7.5% (i.e., 1.5% for every 1°C over a 24-hour average ambient temperature of 30°C), and transformer life would be reduced from 20.6 years to 12.4 years if not derated when temperatures rise to 35°C.

[11] Experts included vegetation management, capacity planning, distribution standards, reliability analysis, asset management, substation engineering, substation standards, transmission line engineering, relay and protection engineering, and ComEd's Renewable Energy, Advanced Control, and Telemetry Systems program.

    - Changing load patterns due to future temperature increases (i.e., greater air conditioning demand) could exacerbate these impacts, particularly at those locations where transformers will experience greater temperature increases.
- The cable ratings for underground 12kV and 34kV cables may need to be reduced to maintain the same life expectancy if changes in soil moisture and temperature reduce the rate at which underground conductors cool or dissipate heat.
- To address concerns with conductor capacity and line sag, high-performance conductors with new capabilities, or larger conductors may be needed.

Wind

- Increased wind speeds in spring may increase tree uprooting for certain species.
- Lower wind speeds can reduce the ability for ambient cooling of transmission and distribution lines.
- Reduced average wind speeds throughout the rest of the year will lower the production potential of wind-generation infrastructure, while amplifying warming impacts.

Humidity

- Condensation could increase the incidence of malfunctions among certain electrical components.
- Increased demands on HVAC may create additional load and stress on the energy system.

Given the expected climate impacts to various infrastructure and grid assets, Argonne has categorized adaptation options into three main areas of focus, including physical infrastructure, operations, and governance. Adaptation options within each focus area provide practical ways to begin considering how ComEd can use the hyper-local, mid-century climate conditions from this report to inform future grid-planning efforts.

13.1 Physical Infrastructure Considerations for Adaptation

- **Increase capacity:** Upgrade transformers to compensate for future load profiles, upgrade existing distribution lines to handle additional capacity, or construct additional lines to compensate for (a) derating caused by and future climate conditions and (b) additional loads caused by these same conditions.[xvii]

- **Revise design standards:** Build new equipment to appropriate, climate-informed design standards that can withstand future climate conditions. For example:
    - Design substation and distribution transformers for 35°C ambient temperatures
    - Waterproof critical equipment
    - Increase conductor sizes or shorten spans between poles to mitigate line sag
    - Increase sizing of HVAC equipment to prepare for longer cooling cycles and more intensive use

- **Revise construction standards:** Adjust construction standards to better protect electrical equipment from climate hazards.

13.2 Operational Considerations for Adaptation

- **Adjust derating guidelines:** Warmer temperatures for longer durations will induce more thermal stress on electrical equipment. ComEd should consider developing new derating strategies to reduce stress on critical electric equipment in high temperature risk regions within its service territory.

- **Adjust vegetation management practices:** Warmer temperatures will cause power lines to sag lower and change vegetation growth patterns, potentially causing more frequent contact between power lines and vegetation. ComEd should consider adjusting its vegetation management standards and practices to adapt to changing growing patterns.

- **Adjust inspection and maintenance practices:** Shorter, warmer winters and the potential for greater humidity could accelerate fungi- and insect-related decay in wooden utility poles. ComEd has already begun to inspect poles with greater frequency in response to observed changes to date, and may need to consider replacing them with non-wood alternatives in the future.

13.3 Governance Considerations for Adaptation

- **Increase energy efficiency programming:** To compensate for the possible need to derate existing power lines because of an increase in temperature and/or increase in demand caused by electrification efforts, additional energy efficiency programming may alleviate projected stress on the distribution system. ComEd would need to work with stakeholders to develop and seek approval for such strategies and programs based on climate adaptation needs.

- **Targeted rooftop solar incentives:** Targeted applications of distributed energy resources (DER) may help alleviate some stresses to the distribution system, such as increases in electricity demand, under certain conditions. However, the intermittency of solar generation is a challenge, meaning greater application of DER would need to be accompanied by other investments and not be relied upon as a stand-alone adaptation strategy. For these DER and other related investments, ComEd would similarly need to work with stakeholders to develop strategies, and seek approval for them, based on climate adaptation needs.

- **Develop additional emergency response capabilities:** Future climate conditions with more extreme temperature variations or storms affecting ComEd operations may exceed local response capabilities. ComEd should consider a plan to work with local, state, and federal emergency response organizations to ensure lifesaving supplies are readily deployable in the event of electric service disruptions.

- **Engage with peer groups:** Lead or participate in knowledge-sharing opportunities with peer groups and industries that are also working to prepare for climate risk. In particular, ComEd should seek to develop best practices that can be applied across sectors and be mutually beneficial.

13.4 Balancing an Uncertain Climate Future with Forecasted System Demand

By mid-century, distribution utilities like ComEd will need to manage the combined effects of climate-driven weather; changing grid uses through the electrification of transit, buildings, and industrial loads; and the wide adoption of intermittent renewable generation. To meet the challenge of these combined effects, utilities will need to ensure that they have sufficient system visibility, coordination, and control. Alongside this study of future climate impacts projected across ComEd's service territory, ComEd also commissioned the company Energy+Environmental Economics (E3) to conduct a study of decarbonization pathways that investigates the mid-century load and generation profiles required for ComEd to reach net-zero targets. With the outcomes of the E3 study, ComEd will need to track the changing policy environment driving electrification, as well as changing customer behavior and technological options, to ensure that the grid is ready to serve its changing role.

As a first step towards coordinated analysis of climate change mitigation and adaptation, Argonne and E3 have shared inputs and outputs from their two studies. A few examples of this coordinated analysis include the following:

- Argonne provided E3 with mid-century model outputs projecting seasonal weather changes so that E3 could adjust load projections accordingly. Hotter summers increase summer peak loads, but milder winters moderate peak loads that, as customers increasingly rely on electricity for heat, are projected to increase and potentially strain the electrical distribution system.
- Given the greater electrification of heating necessary to achieve net-zero goals, E3 found that ComEd will shift from seeing peak system loads in the summer (i.e., due to electricity demand for space cooling) to instead seeing peak system loads in the winter. Moreover, E3 found that the future winter peak load will significantly exceed the current summer system peak. Under these scenarios, some of the actions necessary to avoid derating under summer peaks may serve a second use by providing additional system capacity that can help to meet greater winter heating loads. These joint value propositions of addressing greater climate resilience in the summer and expanded capacity during the winter could apply across a range of distribution assets.
- E3 identified wind as a key generation source serving hydrogen production to meet peak demand with dispatchable generation. Argonne wind outputs are not incorporated into the E3 study, but seasonal changes in wind warrant further study.

Going forward, incorporating climate risk scenarios across the generation stack and into transmission studies will be important to ensure that resources are designed with sufficient climate resilience to avoid incurring the cost of subsequent unplanned adaptation investments.

14 FUTURE RESEARCH AGENDA: PHASE 2

This report provides an initial analysis of several climate variables of interest across ComEd's service by mid-century, but additional research will be necessary to more completely capture future climate conditions in northern Illinois and determine how they may specifically impact ComEd's operations. Therefore, Argonne proposes the following future research agenda for a Phase 2 project that build upon the studies conducted and summarized in this initial Phase 1 report.

14.1 Task 1: Research Additional Climate Variables

In addition to the climate variables outlined within this report, Argonne recommends continued research to outline mid-century climate conditions of the following climate variables as relevant to ComEd operations.

- **Flooding:** Flooding poses a dangerous risk to various electrical assets at ground level.[xviii]

- **Precipitation:** Precipitation patterns are expected to markedly change by end-of-century, with fewer events that produce greater amounts of rainfall. Beyond flood risks, heavy precipitation can damage electrical equipment.

- **Lightning/thunderstorms:** Lightning strikes can cause significant damage to electrical assets and a warming climate is projected to result in more destructive thunderstorms that could disrupt broad areas of the electric sector.

- **Ice storms:** Ice accumulation can topple or break power lines, utility poles, and trees, causing grid equipment damage.[xix]

- **Cloud coverage:** Cloud coverage greatly impacts the adequacy of utility-scale PV and DER systems under difference scenarios.[xx]

- **Vegetation growth:** Vegetation near power lines can interfere with or damage electrical equipment, potentially igniting electric fires and even wildfires.[xxi] These faults can also serve as the starting point for cascading outages.

- **Soil moisture levels:** Soil moisture levels affect the capacity of underground power cables and substation grounding grids.[xxii, xxiii]

- **Heat islands:** Areas with more urban land uses and less vegetative cover often experience localized warming, which can further stress infrastructure and influence service demand.

14.2 Task 2: Expand Research Metrics

Argonne suggests exploring how to better align the presentation of future climate conditions with ComEd's current risk management decision-making framework by developing innovative ways to articulate future climate conditions across ComEd's service territory. New presentation metrics may include statistical modeling to capture 50- or 10-year extremes, consecutive days (duration) of extremes, and/or more detailed seasonal comparisons of northern Illinois climate conditions (including an expanded set of climate impacts) to regions currently experiencing the conditions ComEd expects by mid-century.

14.3 Task 3: Develop a Grid Vulnerability Methodology

Argonne suggests developing a methodology to analyze what type of electric distribution equipment will become more vulnerable to climate-change impacts by comparing equipment design standards to climate related equipment failure thresholds. Because climate variables and electrical equipment vary in their complexities, separate methodologies may be necessary. To accomplish this, Argonne proposes a series of workshops with ComEd and industry experts to outline ComEd equipment design standards and failure thresholds caused by various weather conditions, along with considerations for how to incorporate storm-hardening measures into these standards.

In addition to ComEd operations, the methodology should include mechanisms to consider community vulnerabilities to changing climate conditions, particularly to critical customers with a heavy reliance on electricity, such as hospitals. Outlining where customers within ComEd's service territory lack transportation, are senior in age, or rely on electricity for life-sustaining medical devices will help ComEd and their stakeholders prioritize grid planning efforts to maximize community benefits.

14.4 Task 4: Construct an Interactive Grid Adaptation Tool

Building on the local future climate conditions from task one and the grid vulnerability methodology within task 3, Argonne suggests constructing an interactive geographic information system map overlaying hyper-local future climate conditions, grid equipment vulnerabilities by climate variable and equipment type, and ComEd's distribution infrastructure. This interactive grid adaptation map will allow ComEd to easily pinpoint where its existing infrastructure may become vulnerable to future climate conditions and more easily identify community vulnerabilities. Such a tool could also include the development and application of analytical models that assess relevant climate risks and evaluate the projected costs and benefits (e.g., reduced outage rates) of weather-hardening projects to mitigate these risks.

14.5 Task 5: Collaboratively Assess Climate Risks to Communities

Community engagement is an essential component in understanding climate-change impacts to ComEd customers. In the second phase of this study, Argonne will identify community vulnerabilities to climate change through both literature reviews and direct community engagement. Argonne's recently launched program Community Research on Climate and Urban Science, in coordination with ComEd-led community engagement activities, will be an essential resource in this work, allowing ComEd to draw from a community-level climate impact assessment. Argonne and ComEd will work together to target realistic, grid-centric resilience solutions that can help communities to address the risks they identify.

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