March 18, 2026
NARUC Transmission State Working Group

Load Forecasting for Transmission Planning: Extreme Weather

W. Neal Mann, PhD
Principal Energy Systems Engineer

Jiali Wang, PhD
Principal Atmospheric & Earth Scientist

Tom Wall, PhD
Department Manager, Infrastructure Security & Resilience

David Sehloff, PhD
Principal Energy Systems Engineer

OUTLINE

- **Introduction** (Neal Mann)
- **Extreme weather: past, present, and future** (Jiali Wang)
- **Using historic and synthetic weather scenarios for infrastructure planning** (Tom Wall)
- **Extreme weather impacts to transmission systems** (David Sehloff)
- **Incorporating extreme weather into load projection workflows** (Neal Mann)
- **Recommendations** (Neal Mann)

INTRODUCTION

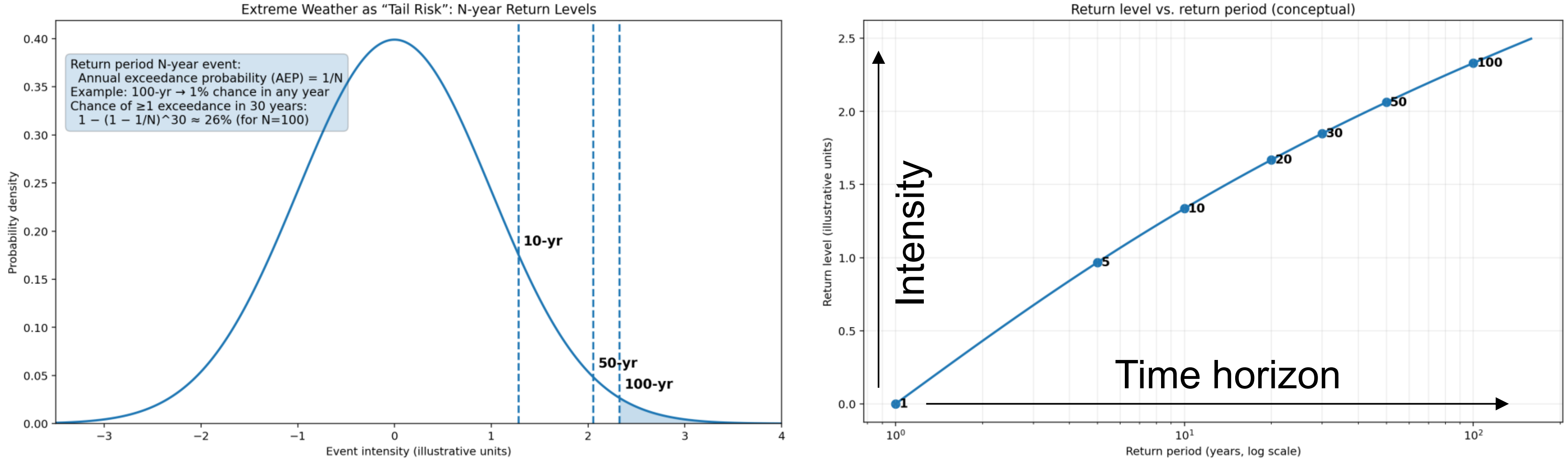
Key Directives Related to Extreme Weather from FERC Order 1920

- "…perform **sensitivity analyses of uncertain operational outcomes** during multiple concurrent and sustained generation and/or transmission outages due to an extreme weather event across a wide area…"
- "…use "**best available data**" in developing Long-Term Scenarios.
  - The Commission proposed to define "best available data inputs" as data inputs that are timely and developed using diverse and expert perspectives, adopted via a process that satisfies the Order Nos. 890 and 1000 transparency transmission planning principles described above, and reflect the list of factors that transmission providers must incorporate into Long-Term Scenarios.
  - The Commission stated that another example of data inputs that could meet this requirement are the most recent data on renewable energy potential and distributed energy resources developed by national labs."

EXTREME WEATHER: PAST, PRESENT, AND FUTURE (JIALI WANG)

WHAT DO WE MEAN BY “EXTREME WEATHER”?

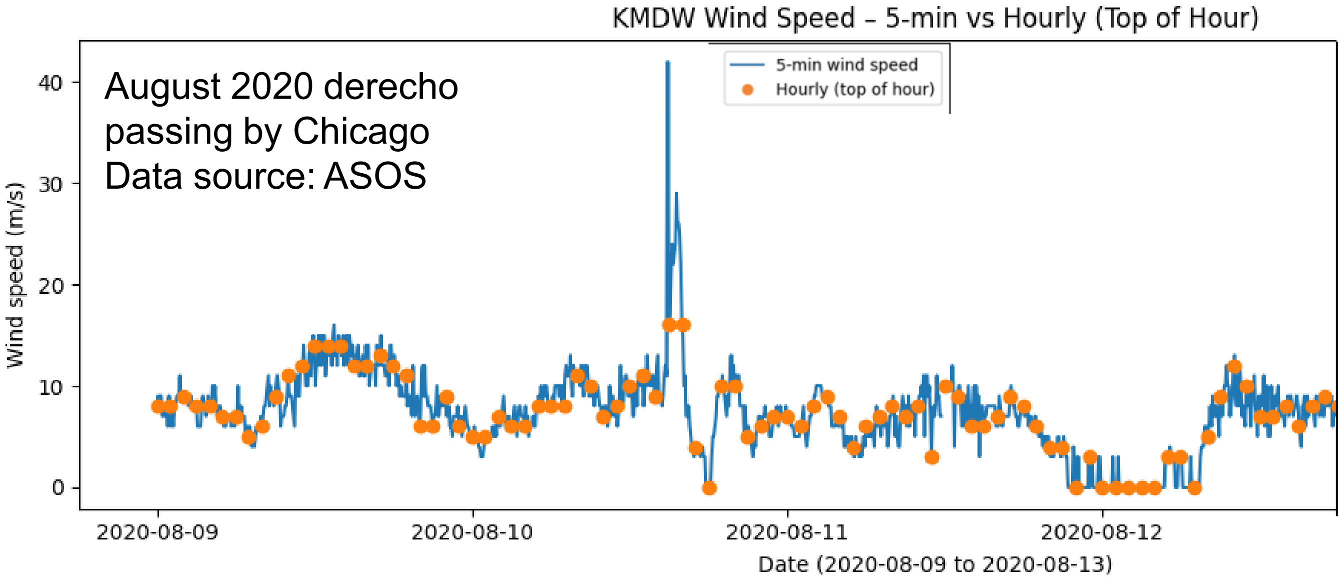
- Events in the tail of the distribution: rare, high-impact
- N-year event: annual exceedance probability =1/N
  - 100-year event →1% chance in ANY year
  - 100-year event over 30 years => 26%



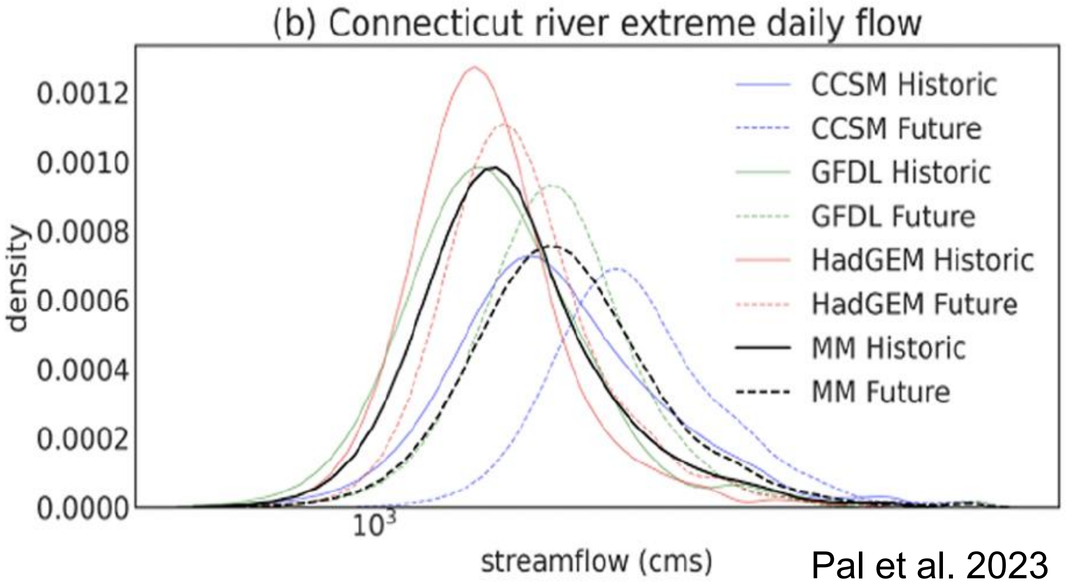
Conceptual figures created by ChatGPT v5.2

WHAT DATA DO WE NEED TO QUANTIFY EXTREME WEATHER RISK?

- Long records/large ensembles
  - Generalized Extreme Value Theory (GEV): Short records can mis-estimate rare-event risk
- High spatial and temporal resolutions (a few km; hourly or sub-hourly)
- Nonstationarity: trends and evolving variability



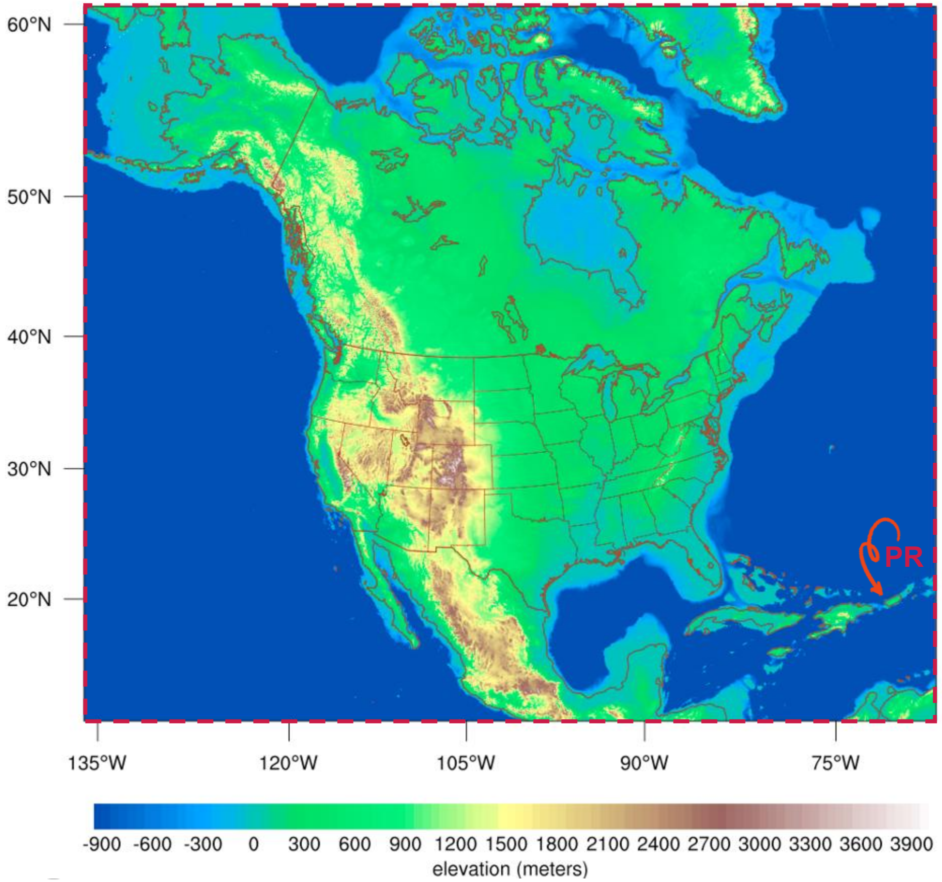
August 2020 derecho passing by Chicago
Data source: ASOS



Pal et al. 2023

DATA EXAMPLES

- Argonne Downscaling Data Archive (ADDA): a **coherent system** that simulates all weather types
  - Spatial/Temporal resolution: 4 km and 1-hr (Akinsanola et al. 2024; Peco et al. 2026)
  - AI-based downscaling for small-scale high-impact variables: 250m for winds (Ma et al. 2025)



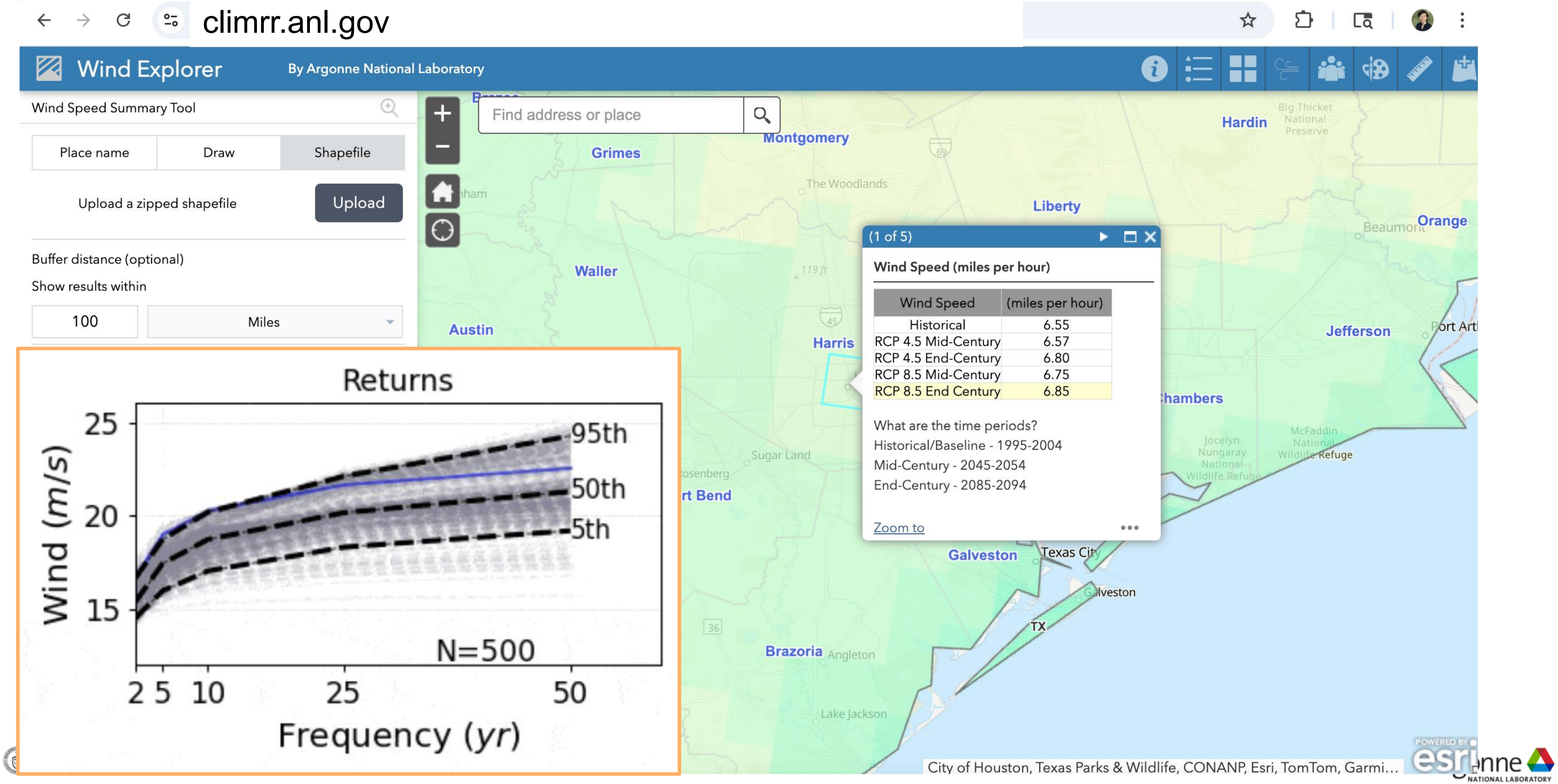
Initial and lateral boundary conditions	Historical	Forward looking Periods	Forward looking Scenarios
ERA5 (reanalysis)	2001-2020	NA	NA
CESM2	1995-2014	2041-2060	Mitigation
		2041-2060	Business as usual
HadGEM-GC31-LL	1995-2014	2041-2060	Mitigation
		2041-2060	Business as usual
MPI-ESM1-2-HR	1995-2014	2041-2060	Mitigation
		2041-2060	Business as usual

200 years of weather data provides robust climatology for risk assessment with uncertainty quantified.

DATA EXAMPLES

- **Dynamically downscaled datasets (high computational demand):**
  - CONUS404 created by NSF NCAR (Rasmussen et al. 2023)
    - 4km & 1hour. Covers CONUS.
    - Forward-looking: PGW approach.
  - Northern Illinois University (Gensini et al. 2023)
    - 3.75km & 15min for near-surface variables. Covers CONUS.
    - Forward-looking: bias-corrected CESM driven.
  - Puerto Rico regional dataset (Bowden et al. 2022)
    - 2 km & 1hour
  - *There are many more!*
- **Statistically downscaled datasets (low computational demand):**
  - EPRI: quantile delta mapping for hourly weather data (Smith et al. 2025)

NATIONAL MAP EXPLORERS FOR EXTREME EVENTS



Wind Speed (miles per hour)

Wind Speed	(miles per hour)
Historical	6.55
RCP 4.5 Mid-Century	6.57
RCP 4.5 End-Century	6.80
RCP 8.5 Mid-Century	6.75
RCP 8.5 End Century	6.85

What are the time periods?
Historical/Baseline - 1995-2004
Mid-Century - 2045-2054
End-Century - 2085-2094

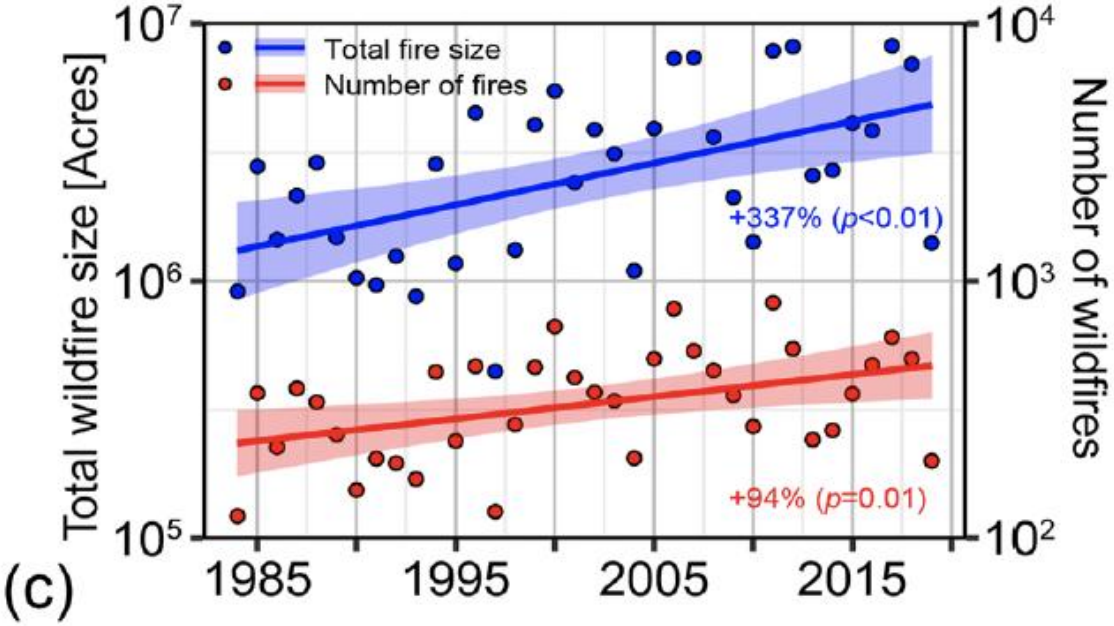
FINDINGS OF EXTREME WEATHER EVENTS

Studies based on ADDA

- Wildfires (Yu et al. 2023)
- Flooding over Northeastern US (Pal et al. 2023)
- Tropical cyclones (Jung et al. in prep)
- Drought (Gamelin et al. 2022)
- Nor’easters (Pringle et al. 2021)

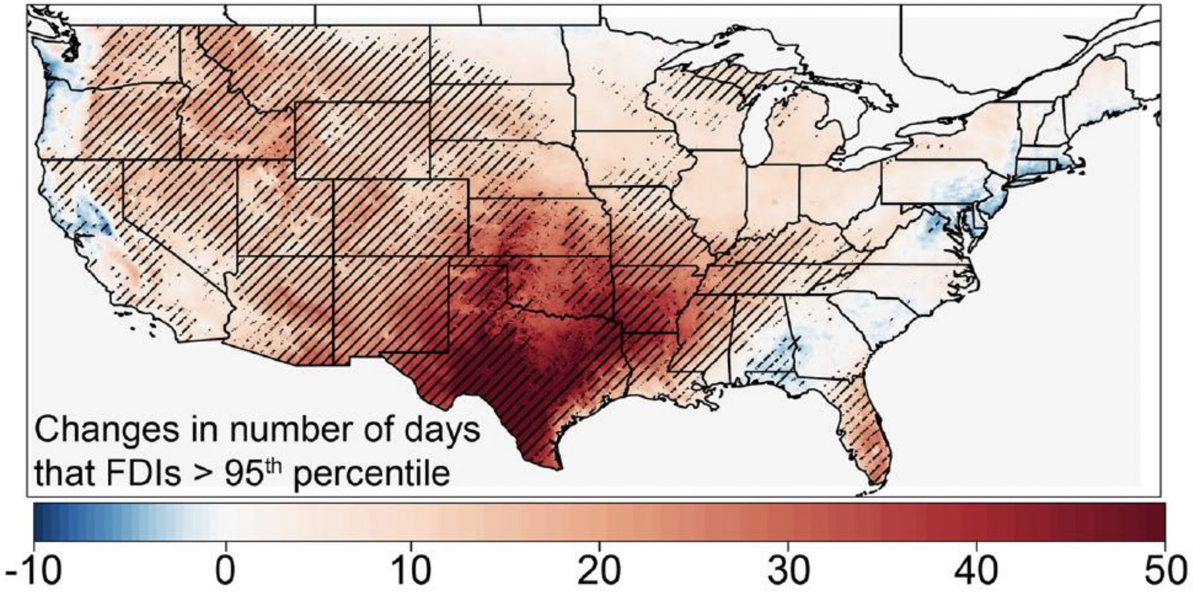
WILDFIRES

MTBS observed fires



Both size and frequency are increasing significantly.

ADDA-projection

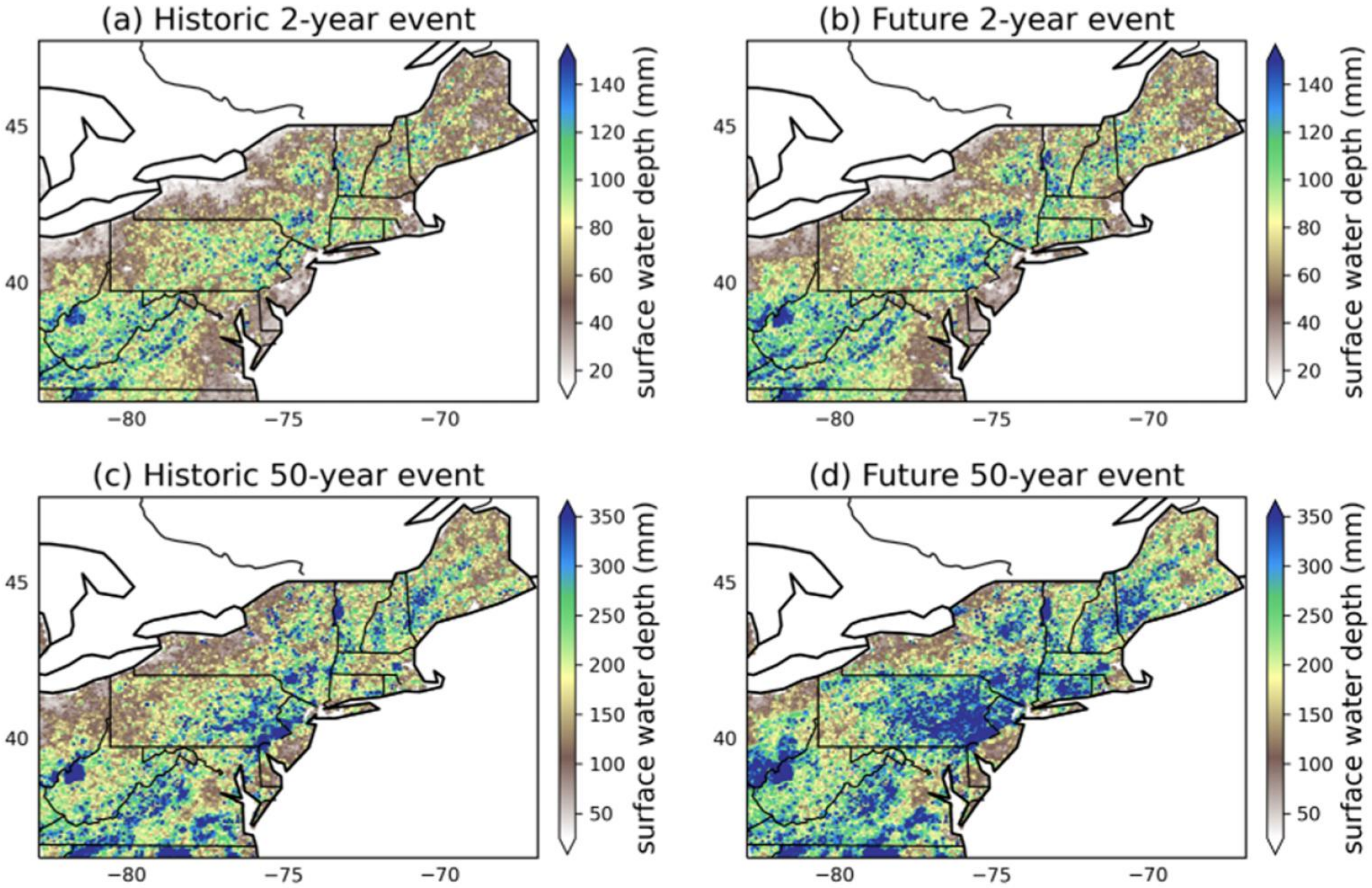


Changes in number of days that FDIs > 95th percentile

Yu et al. 2023

INLAND FLOODING DUE TO RAINFALL

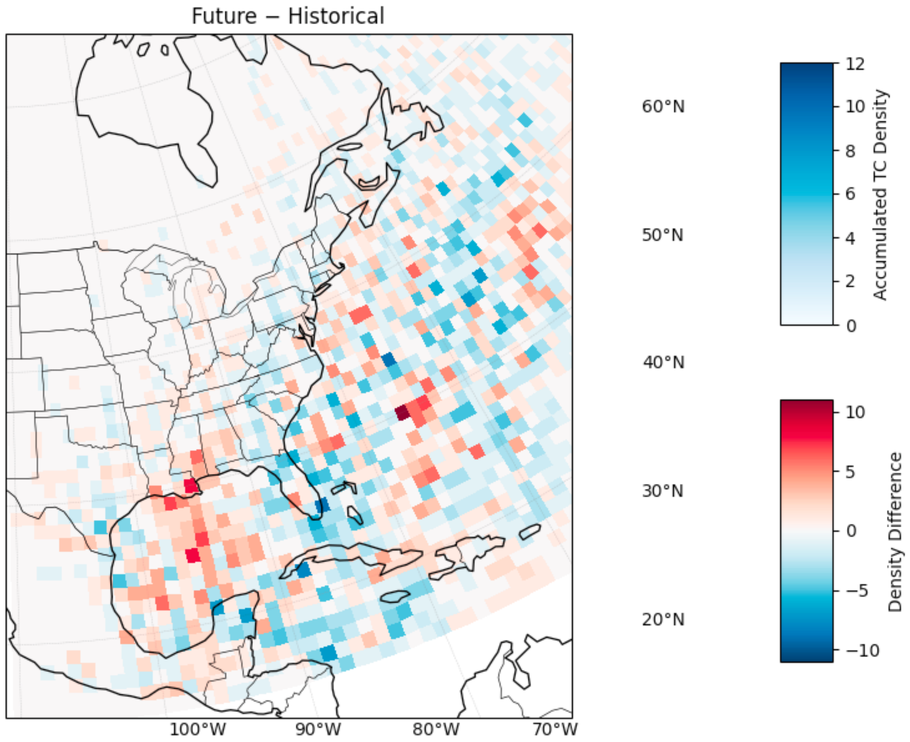
Current scenario **Forward-looking scenario**



Pal et al. 2023

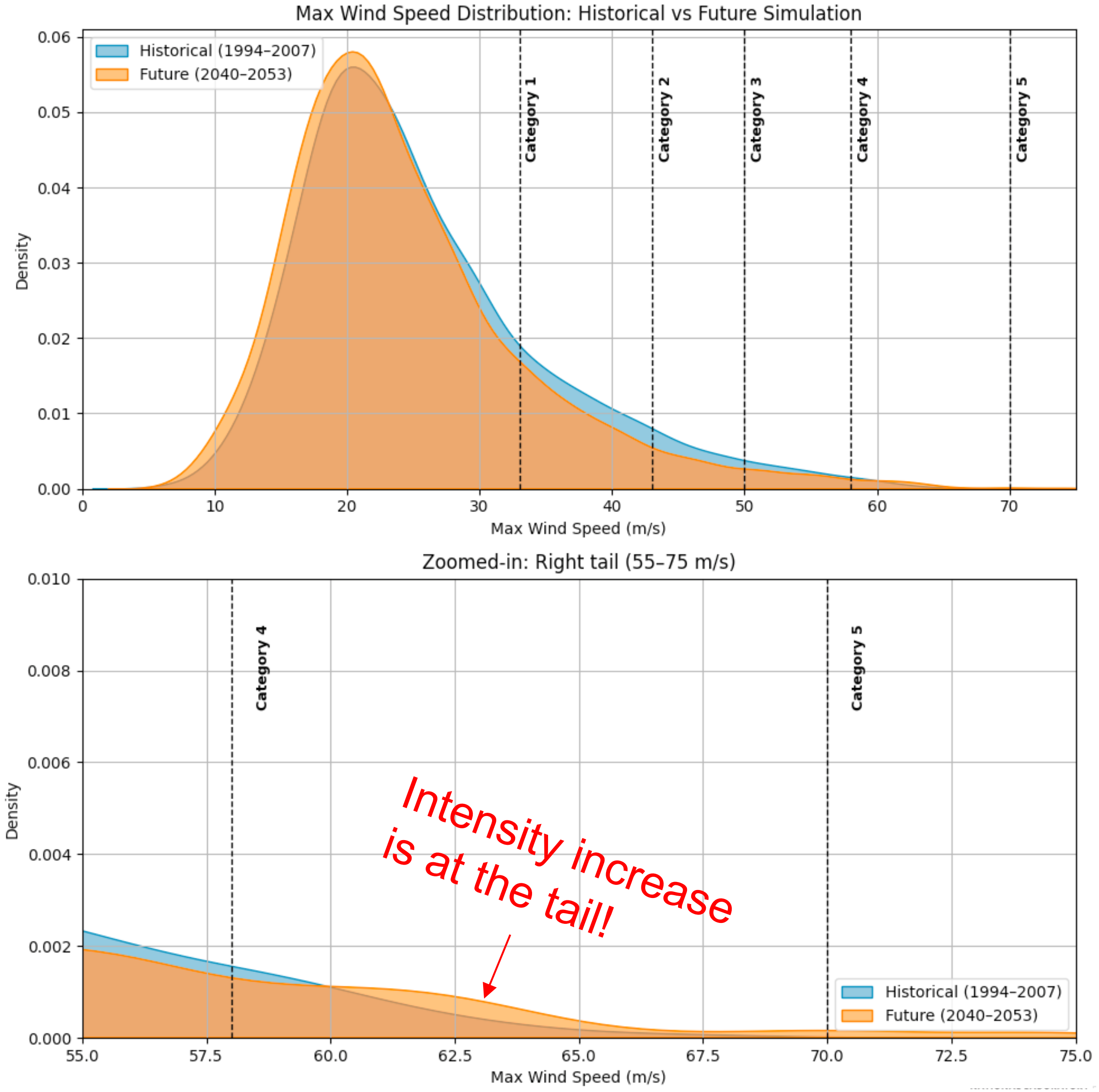
TROPICAL CYCLONE TRACK DENSITY AND INTENSITY

Difference in track density



Preliminary based on one forward-looking scenario: There seems to be more TCs affecting Gulf coast

PDF for Maximum wind speeds



Intensity increase is at the tail!

REFERENCES

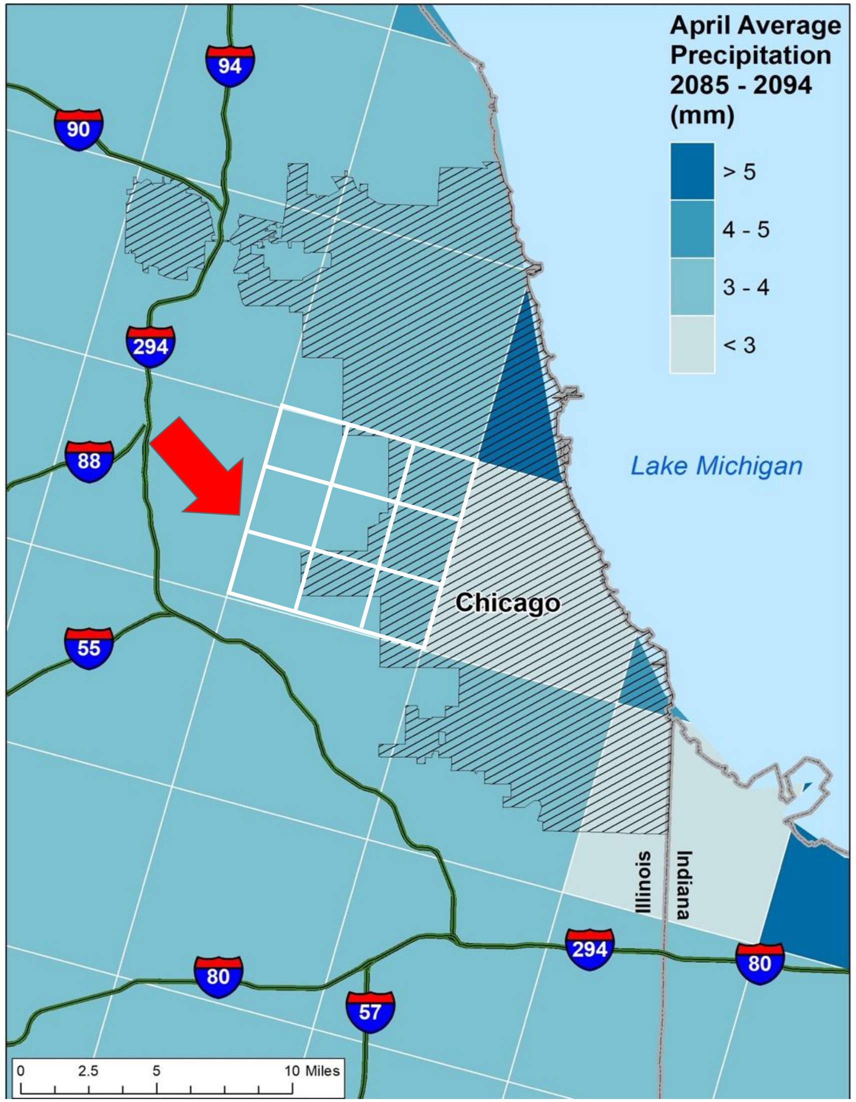
- Akinsanola et al. (2024). Evaluation of precipitation across the contiguous United States, Alaska, and Puerto Rico in multi-decadal convection-permitting simulations. Scientific Reports, 14(1), 1238.
- Peco et al. 2026, wind evaluation of ADDA: https://doi.org/10.5194/wes-2025-13
- Ma et al. 2025, AI-based downscaling: https://arxiv.org/abs/2510.03364
- Pal et al. 2023, Flooding risks in Northeastern US: https://doi.org/10.1016/j.ejrh.2023.101371
- Gensini et al. 2023, NIU's dynamical downscaling: https://doi.org/10.1007/s00382- 022-06306-0
- Rasmussen et al. 2023, CONUS-404: https://doi.org/10.1175/BAMS-D-21-0326.1
- Smith et al. 2025, EPRI's statistical downscaling: 10.1109/ACCESS.2025.3567864
- Yu et al. 2023, Fire danger indices: 10.1029/2023EF003823
- Gamelin et al. 2022. Projected U.S. Drought Extremes Through the 21st Century with Vapor Pressure Deficit. Scientific Reports **12**, Article number: 8615.
- Pringle et al. 2021. Projected Changes to Cool-Season Storm Tides in the 21st Century Along the Northeastern United States Coast. Earth's Future, 9(7), e2020EF001940.

USING HISTORIC AND SYNTHETIC WEATHER SCENARIOS FOR INFRASTRUCTURE PLANNING (TOM WALL)

TRANSLATING HIGH-RESOLUTION REGIONAL MODELING INTO ACTIONABLE INFORMATION

ARGONNE'S DOWNSCALED DATA ARCHIVE (ADDA)

- Weather Research and Forecasting (WRF) model
- Dynamically-downscaled data: 12km and 4km resolution
- >300 years of simulation data
- Relevance to energy sector and broader infrastructure community:
  - WRF/ADDA produces 60+ unique variables
  - Maintains spatiotemporal correlations across meteorological variables
  - Physics-based, addresses non-stationarity
- Historical, mid-century, and end-of-century



FEDERAL SPONSORS AND INDUSTRY COLLABORATORS

U.S. DEPARTMENT OF ENERGY | Office of Science

U.S. DEPARTMENT OF ENERGY | OFFICE OF Cybersecurity, Energy Security, and Emergency Response

U.S. DEPARTMENT OF ENERGY | OFFICE OF ELECTRICITY

GDO GRID DEPLOYMENT OFFICE

FEMA

exelon℠

comed℠ AN EXELON COMPANY

BERKSHIRE HATHAWAY ENERGY

NVEnergy

MIDAMERICAN ENERGY COMPANY®

ALTALINK A BERKSHIRE HATHAWAY ENERGY COMPANY

PACIFICORP

SDGE™

PG&E

Ameren

NEW YORK STATE OF OPPORTUNITY. | NY Power Authority

AT&T

AMERICAN PUBLIC POWER ASSOCIATION

EAGLE ROCK ANALYTICS

Baringa

EPRI | ELECTRIC POWER RESEARCH INSTITUTE

IBM®

asean

DIGITAL TOOLS & NATIONAL DATASETS

ClimRR Portal: Informing Local-Scale Utility Decision-Making

Online geospatial and data portal with translated, actionable weather-model-based data

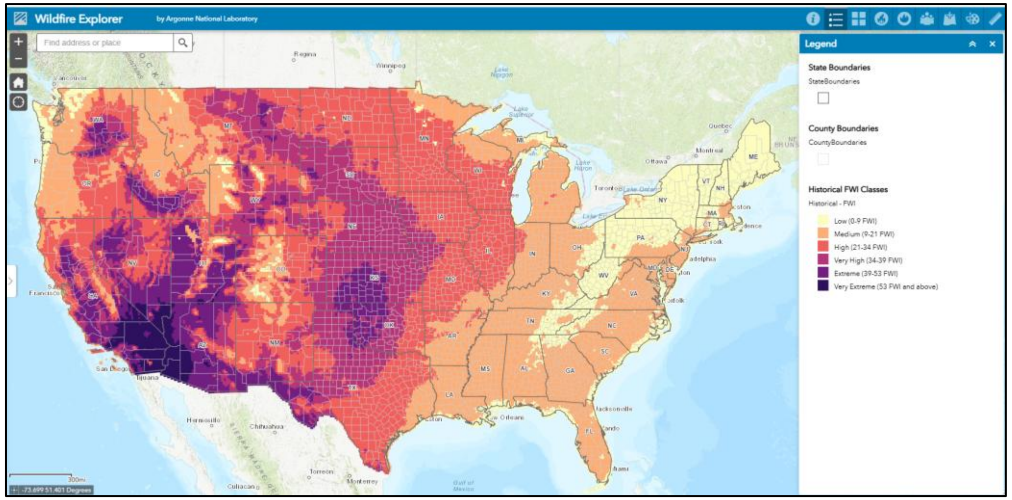
- Focus on readily accessible and useful data for energy and emergency management decisionmakers
- Collaboration among Argonne, DOE-GDO, AT&T
- Dataset-agnostic, currently populated with ADDA 12km

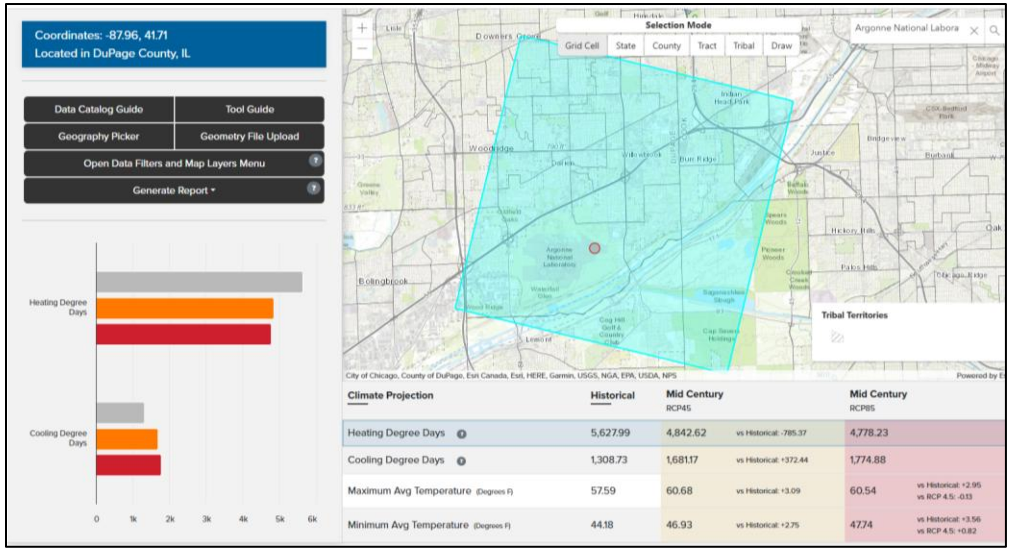
Key Features

- National Map Explorer
- Local Projections Tool
- Data Catalog / Download
- Data Lab

Upcoming Enhancements

- LLM toolset, integrated chatbot
- AI/ML downscaled wind dataset
- Update to ADDA 4km dataset
- IDF curves—heat, cold, precip.
- Typical meteorological year for utility systems analysis
- Regional climate analogs tool
- Open source GIS plug-ins





Coordinates: -87.96, 41.71
Located in DuPage County, IL

Climate Projection	Historical	Mid Century RCP45		Mid Century RCP85	
Heating Degree Days	5,627.99	4,842.62	vs Historical: -785.37	4,778.23	
Cooling Degree Days	1,308.73	1,681.17	vs Historical: +372.44	1,774.88	
Maximum Avg Temperature (Degrees F)	57.59	60.68	vs Historical: +3.09	60.54	vs Historical: +2.95 vs RCP 4.5: -0.13
Minimum Avg Temperature (Degrees F)	44.18	46.93	vs Historical: +2.75	47.74	vs Historical: +3.56 vs RCP 4.5: +0.82

https://climrr.anl.gov

EXAMPLE OF NATIONAL DATASETS FOR UTILITIES

Co-Developing TMY / XMY Datasets

ELECTRIC POWER
RESEARCH INSTITUTE

- Collaborative project with EPRI to produce utility planning-relevant datasets for load forecasting and other applications
- Producing historical and future Typical Meteorological Year (TMY) and Extreme Meteorological Year (XMY) datasets for contiguous US
- Engaging with 6 utilities to solicit feedback and ensure dataset meets industry needs

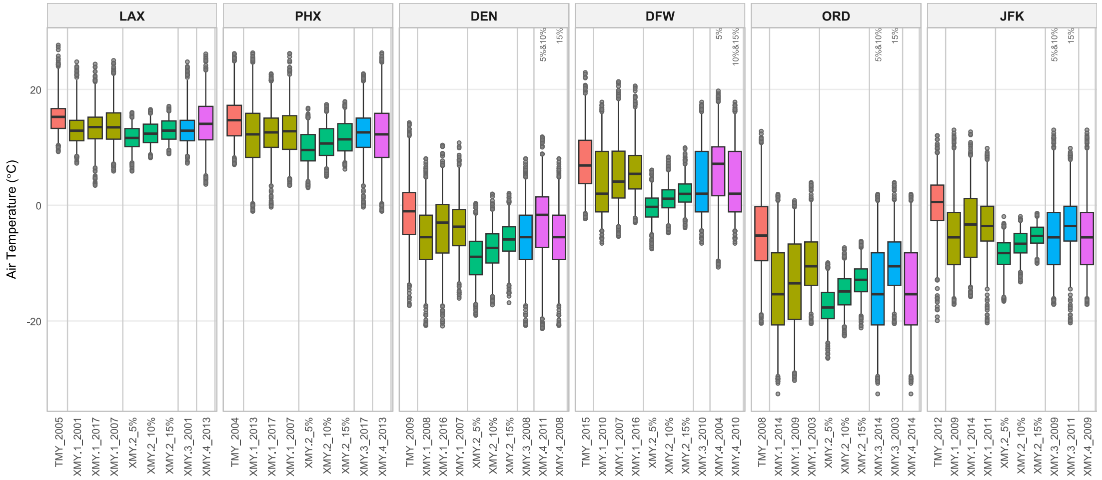
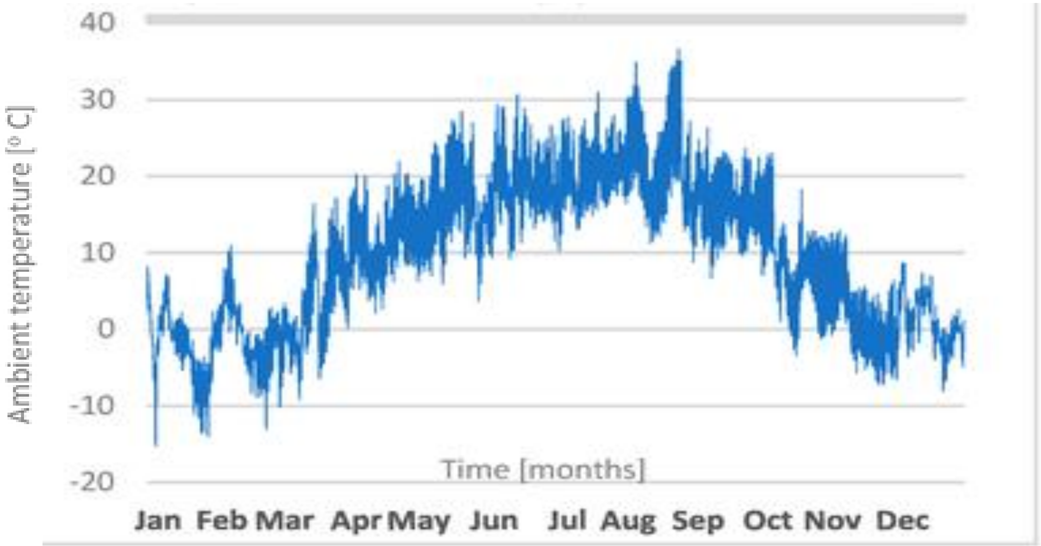


Image: EPRI (2026)

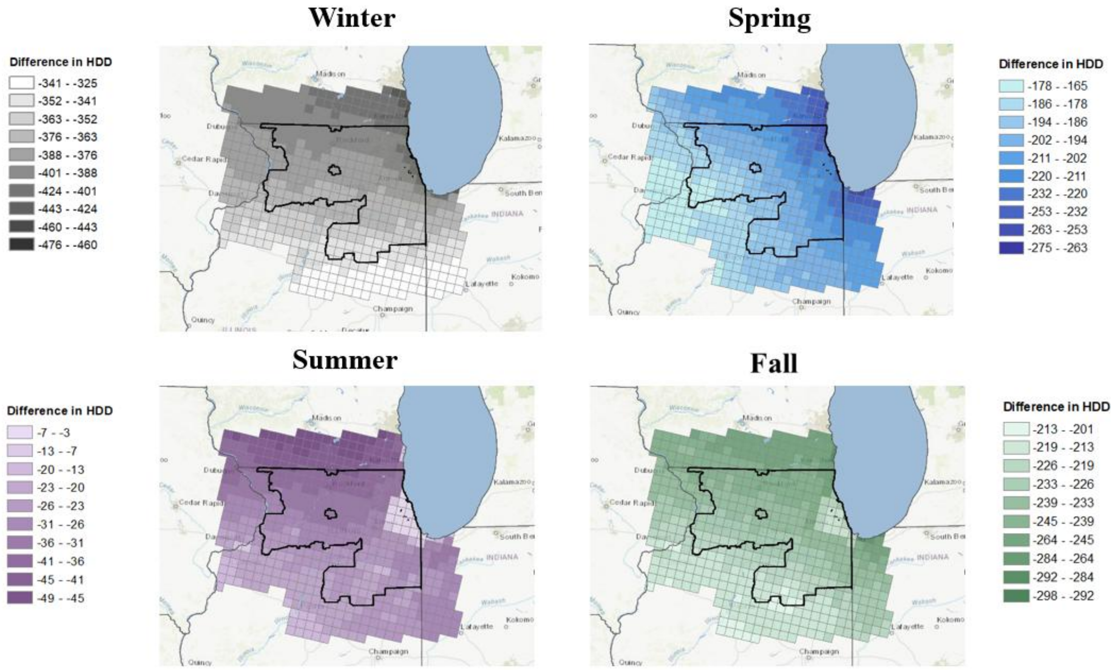


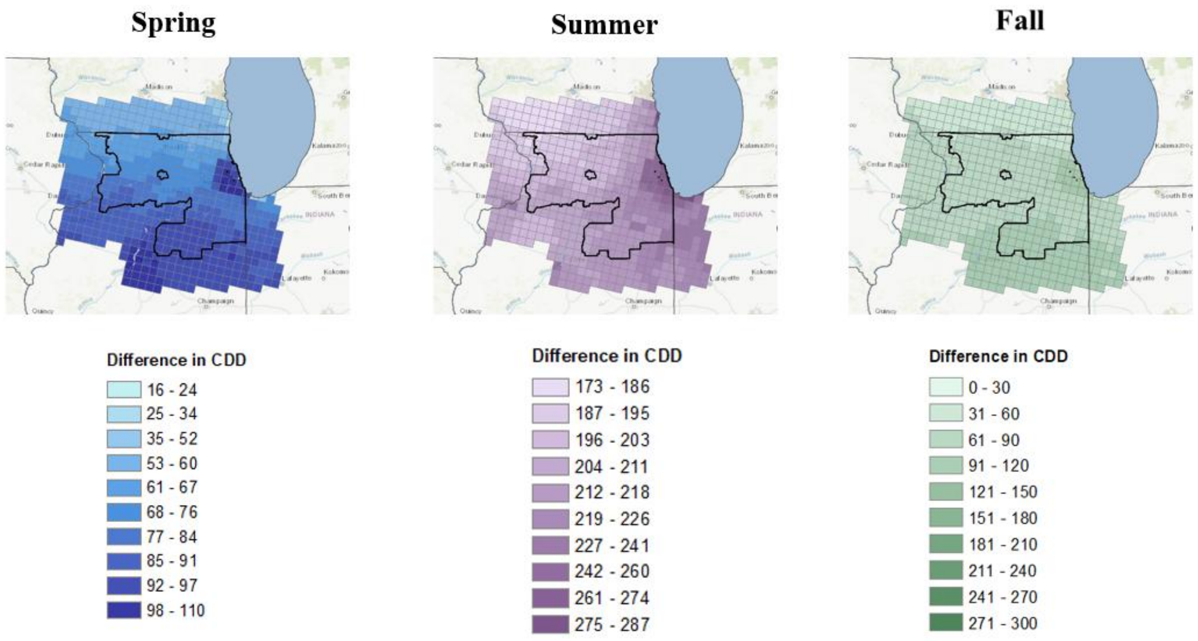
Cristea, Ciprian & Cristea, Maria & Micu, Dan & Ceclan, Andrei & Tirnovan, R. & Serban, Florica. (2022). Tridimensional Sustainability and Feasibility Assessment of Grid-Connected Solar Photovoltaic Systems Applied for the Technical University of Cluj-Napoca. Sustainability. 14. 10892. 10.3390/su141710892.

EXAMPLE OF UTILITY DIRECT SUPPORT

Argonne, ComEd assess future weather impacts in Northern Illinois for load forecasting and grid investment

- **Heating Degree Days:** Annual decrease between 761 to 1060 territory-wide (Winter average decrease ~408)
- **Cooling Degree Days:** Annual increase between 258 to 399 territory-wide (Summer average increase ~230)

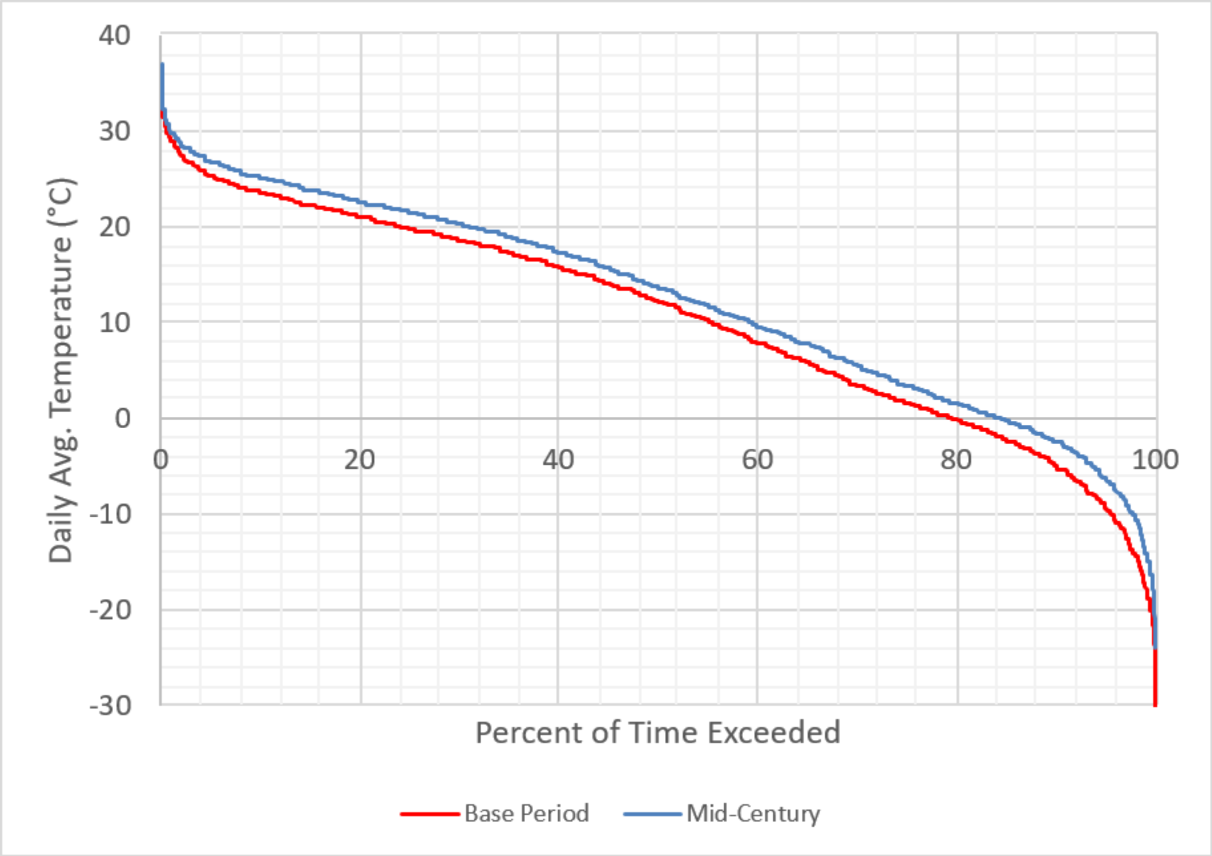




EXAMPLE OF UTILITY DIRECT SUPPORT

Argonne, ComEd assess future weather impacts in Northern Illinois

- Temperature extremes are critical for
  - Reliable operations of existing assets
  - Design and investment in future assets
  - Load forecasting
- Different **daily average** temperature thresholds are needed for different applications
- In northern Illinois:
  - Baseline: 35°C (95°F) exceeded ~1 days/decade
  - Mid-century: 35°C (95°F) exceeded ~4 days/decade

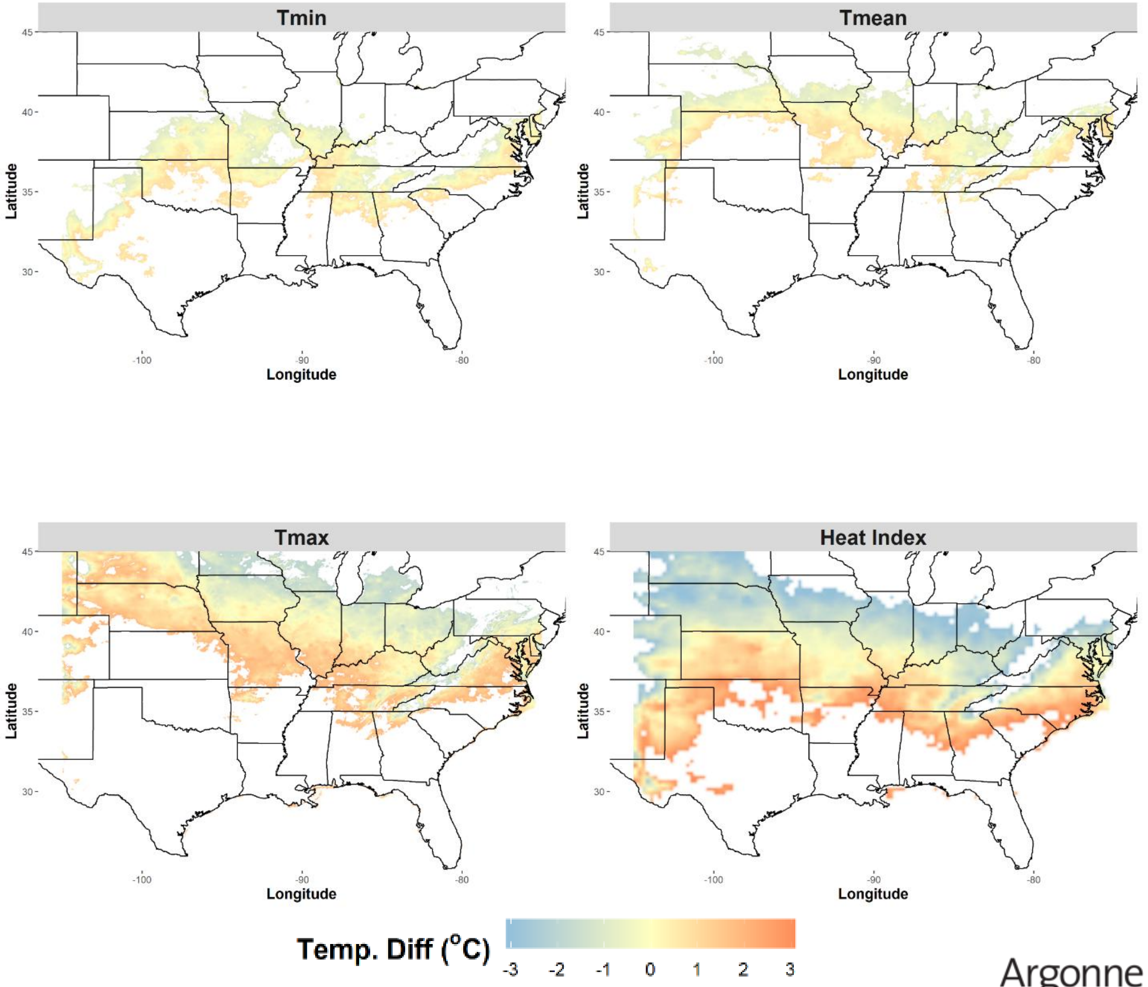


Percentage of time (days/year) that daily average temperatures exceed a given threshold for the baseline and mid-century periods

EXAMPLE OF UTILITY DIRECT SUPPORT

Argonne, ComEd assess future weather impacts in Northern Illinois

- Enables ComEd to better assess how future weather will affect regional communities, grid assets, future loads, and decarbonization efforts.
- High-resolution model outcomes tailored to ComEd's planning and analysis needs, and community and industry engagement activities.

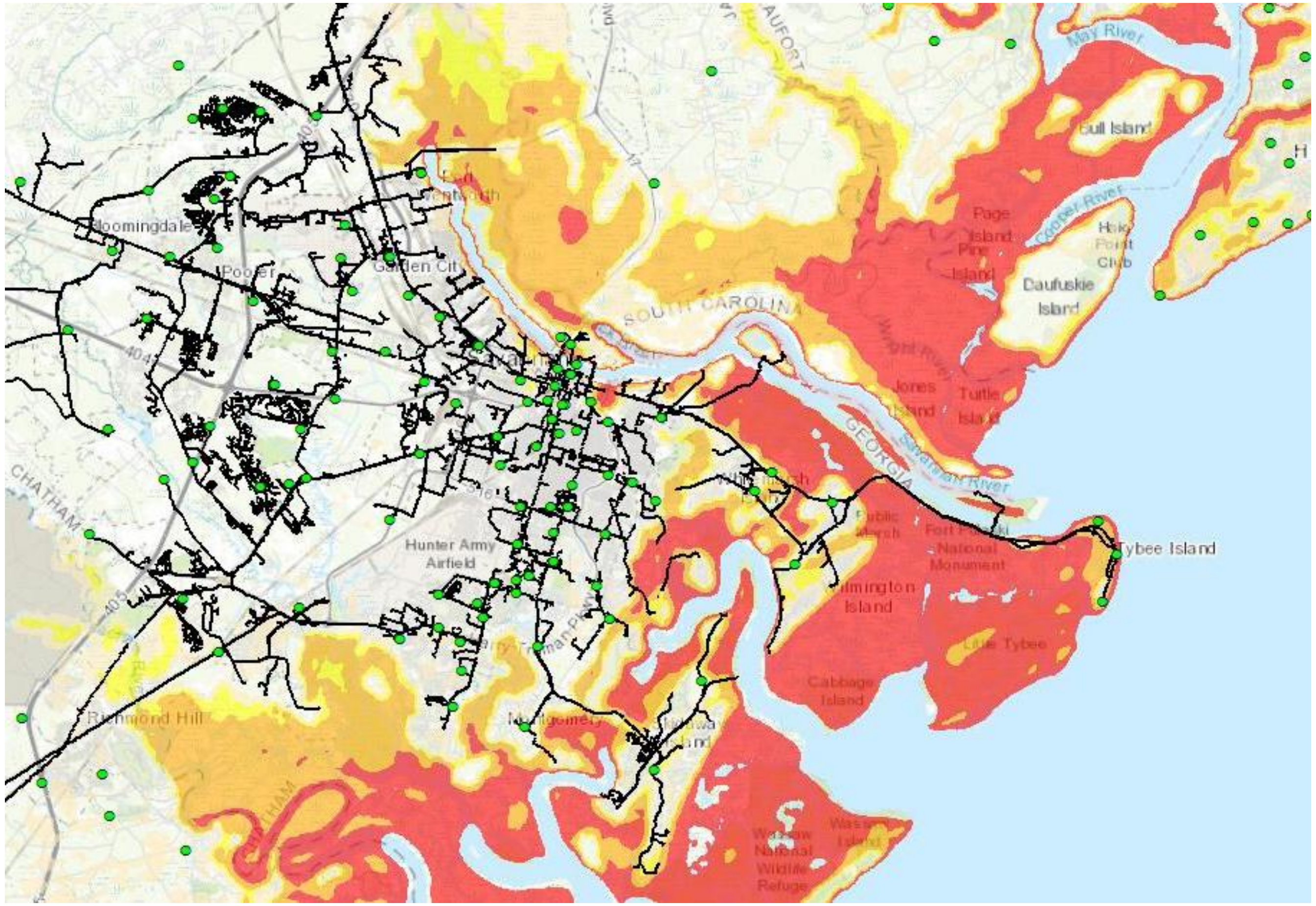


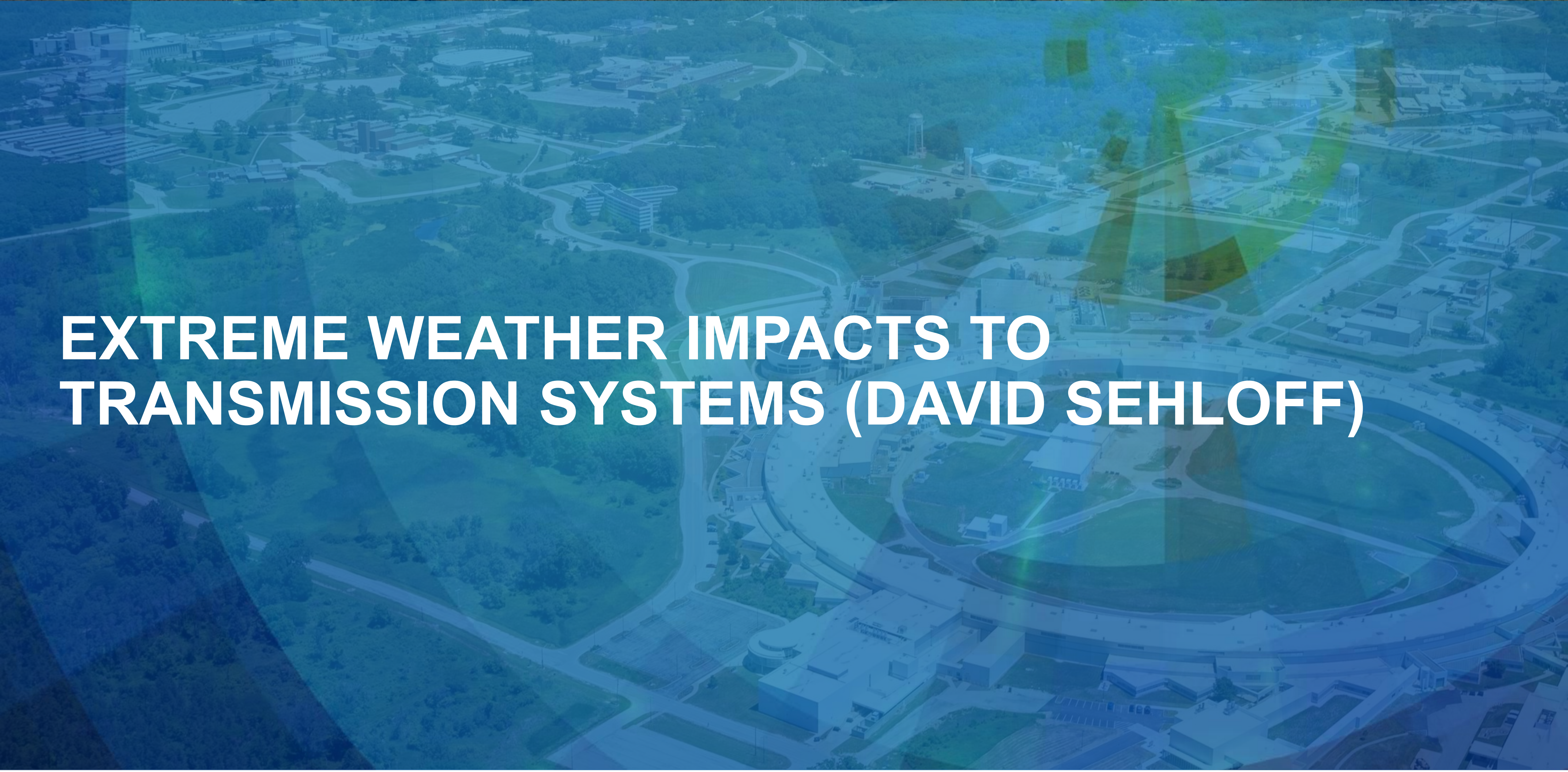
EXAMPLE OF UTILITY DIRECT SUPPORT

AT&T Partnership

PROJECTING COMBINED COASTAL AND INLAND FLOOD RISKS

- Future hurricane coastal flooding
  - Winds, wave and storm surge at 50m-90m resolution
- Future inland flooding projected at 200m resolution

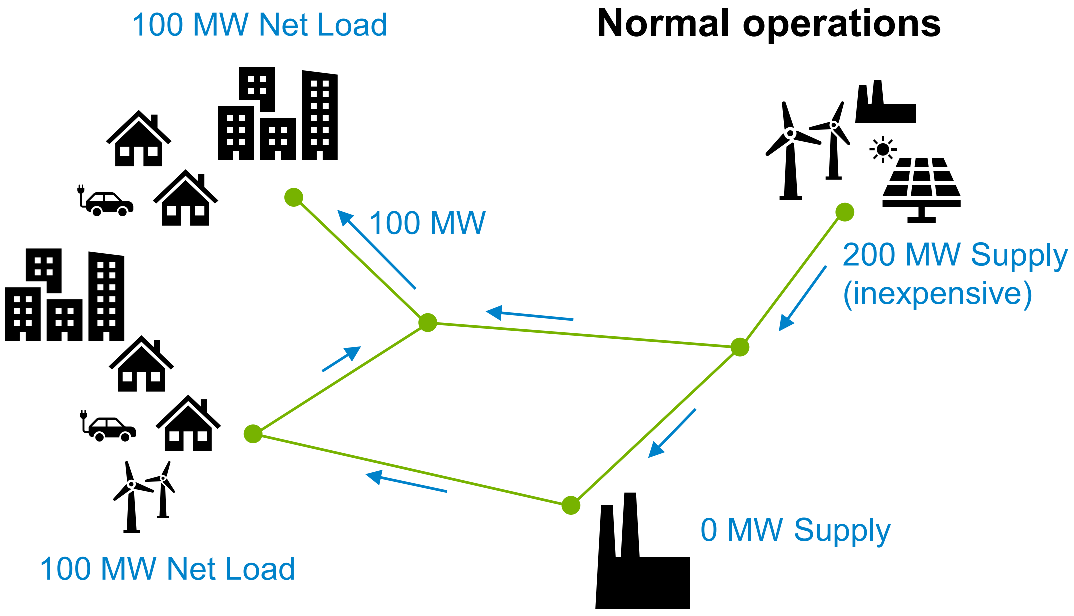


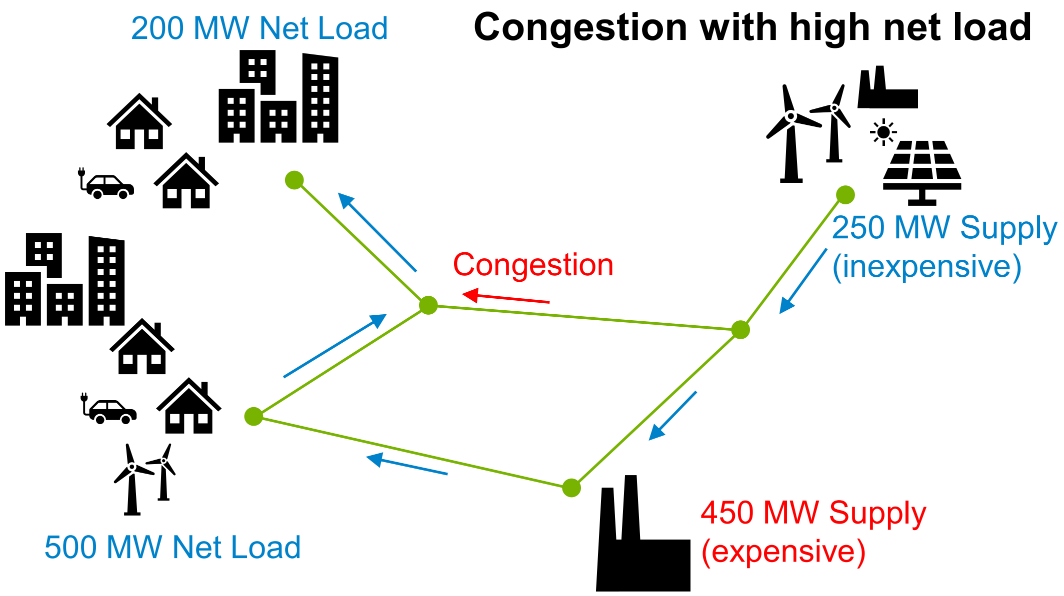


EXTREME WEATHER IMPACTS TO TRANSMISSION SYSTEMS (DAVID SEHLOFF)

IMPACTS OF AMBIENT CONDITIONS

- Weather impacts on generation and demand can change congestion patterns, which can lead to curtailment of inexpensive generation and an increase in cost.
- Ambient temperature and wind speed and direction also influence congestion through line capacity.
  - Static line capacity ratings are determined by conservative calculations which assume low (but nonzero) wind speed.
  - Ambient adjusted ratings include air temperature forecasts (required for transmission owners under FERC Order 881).
  - Dynamic line ratings are more detailed and require remote sensor networks.


Normal operations

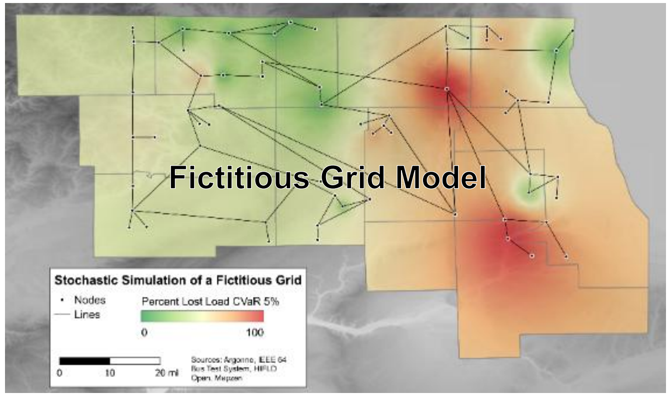

Congestion with high net load

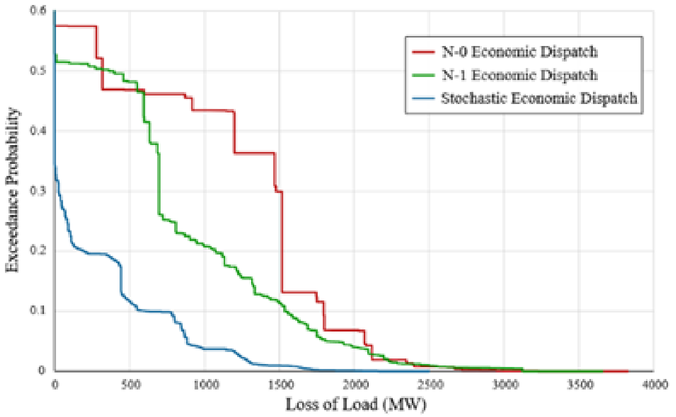
IMPACTS OF NATURAL HAZARDS

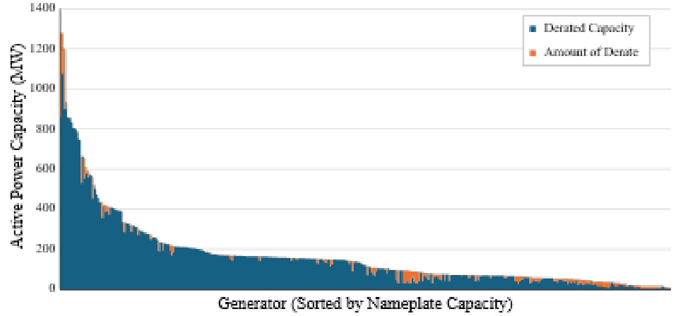
- Regional system operators and utilities consider hazards which can derate, damage, or destroy transmission lines, transformers, and other transmission equipment:
  - Coastal or Inland Flooding
  - Cyclone
  - Earthquake
  - Extreme Heat
  - Tsunami
  - Wildfire
  - Wind (Sustained and/or Gusts)
  - Winter Storm: Combination of Ice, Snow and Wind
- Transmission systems are planned and operated for N-1 security, but these conditions can create outages not captured by N-1 criteria.
- The sudden loss of more than one component due to these hazards may cause impacts which lead to other failures, initiating a cascading failure across the system.

ANALYSIS OF WEATHER IMPACTS

- Argonne builds and maintains analysis tools to characterize system resilience to weather conditions.
- The EPClimate tool’s stochastic framework represents uncertainty in extreme weather-driven impacts and propagates this to component derates, forced outages, and resulting systemwide impacts.
- The tool has been used to analyze the New York Power Authority (NYPA) system under high temperature and flooding conditions.
- Recent updates include more detailed thermal plant derates and a more accurate economic dispatch model.
- Weather variables are incorporated through derating and fragility curves in a preprocessing step.
- HEADOUT is a related Argonne tool which includes a suite of fragility curves, focused on hurricanes and expanding to other variables including conductor icing.







CONSIDERATIONS FOR STATES

Transmission planning questions for ISOs/RTOs, transmission owners, and utilities:

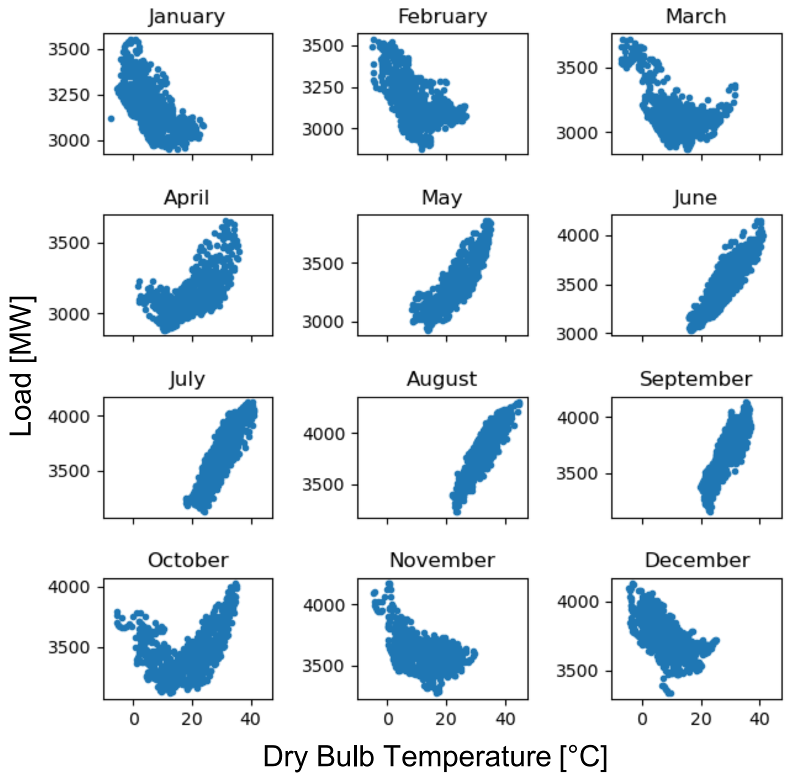
- How are weather sensitivities included in the scenarios used for transmission planning? Are these representative for the region?
- How are natural hazards considered in operations and planning?
- What type of line ratings are assumed, and what is the source of ambient values?
- What kind of contingency analysis does the power system analysis include? N-1, correlated outages, cascading impacts?

INCORPORATING EXTREME WEATHER INTO LOAD PROJECTION WORKFLOWS (NEAL MANN)

USING WEATHER DATA IN LONG-TERM LOAD MODELING

- Weather (especially dry bulb temperature) drives hour-to-hour, diurnal, and seasonal load patterns
  - Dividing the year into seasons, months, or weeks can create models with lower error
- Load models are trained using historical data, but the algorithms used can yield significantly different results during extreme weather periods
  - Traditional linear autoregressive methods might have higher errors than newer machine learning algorithms
  - Use a cross-validation approach to test load model performance under extreme weather conditions

ERCOT Far West Weather Zone, 2019

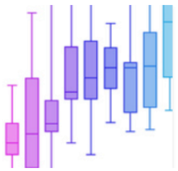


WORKFLOW TO APPLY WEATHER IMPACTS TO CAPACITY EXPANSION PROBLEMS

Weather Scenarios

High-Frequency & High-Spatial Resolution Synthetic Weather

Analyze and screen possible future weather patterns

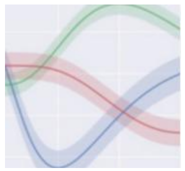


- Temperature
- Precipitation
- Wind speed/direction
- Solar irradiance
- Humidity

Weather to Grid Translation

Translation Models

Generate probabilistic grid event scenarios

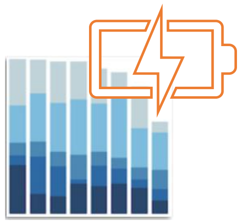


- Electricity demand
- Wind/solar profile
- Fuel supply constraints
- Grid asset de-rating
- Grid asset outage

Power System Planning

Argonne’s Power System Model A-LEAF

Power system capacity expansion planning and production cost simulations



- Generation/energy storage mix and dispatch
- Transmission expansion and flows
- Energy and reserves prices

EXAMPLES OF LONG-TERM LOAD FORECASTING ASSUMPTIONS

	CAISO	ERCOT	ISO-NE	MISO	NWPCC	NYISO	PJM	SPP
Peak annual exceedance probabilities (Px)	P50, P20, P10	P50, P10	P50, P10	P10	P10	P90, P10, P1	P50, P10	None
Weather variables	Dry bulb temp.	Dry bulb temp.	Dry bulb temp., dew point temp., wind speed	Dry bulb temp.	Dry bulb temp., streamflows, wind speed, solar irradiance	Dry bulb temp., humidity	Dry bulb temp., humidity, wind speed, cloud cover	Dry bulb temp., humidity, wind speed, solar irradiance
Historical weather years	Recent decades (unspecified)	17 (2008–2024)	27 (1998–2024)	20 (1997–2016)	80 (1929–2008)	69 (1950–2018)	31 (1993–2023)	15 (2006–2020)
Synthetic weather year trends	In Progress	None	73 (EPRI QDM)	None	None	Post-1992 linear trends	None	None
Weather data sources	Unknown	Schneider Electric/DTN	ERA5, ASOS, EPRI …	Purdue MRCC/NCEI	Unknown	Unknown (ASOS?)	Unknown	NOAA

RECOMMENDATIONS

RECOMMENDATIONS

Defining high-impact, low-frequency event scenarios

- **Define your risk tolerance**
  - Probability of exceedance P10 (10% per year) is typically used but is too high to capture tail risks
- **Sample from an appropriate number of weather years for your risk tolerance**
  - E.g., P10 needs 50 years for a 99.5% exceedance probability
- **Use power system models that incorporate probabilistic component deratings and outages**
- **Use a cross-validation approach to test load model performance under extreme weather conditions**

RECOMMENDATIONS

Best available data inputs

- **Use weather data that are fully cross-correlated in space and time**
  - Especially important for compound hazard modeling
- **Consider data sources that have been peer reviewed and extensively validated for your region**
  - Models produce spatially biased results to various degrees
- **Review long-term weather trends and analyze the implications for your region**
  - Data sources include trends in various ways (e.g., dynamical downscaling)
- **Higher spatial and temporal resolutions are needed to model local and short-term hazards**
  - E.g., wind gust damage to a transmission line

ACKNOWLEDGEMENTS

- **Funding:** Argonne National Laboratory's work was supported by the U.S. Department of Energy's Office of Electricity (formerly Grid Deployment Office), State Technical Assistance Program, under contract DE-AC02-06CH11357.

NOTICES

License

The submitted manuscript has been created by UChicago Argonne, LLC, Operator of Argonne National Laboratory (“Argonne”). Argonne, a U.S. Department of Energy Office of Science laboratory, is operated under Contract No. DE-AC02-06CH11357. The U.S. Government retains for itself, and others acting on its behalf, a paid-up nonexclusive, irrevocable worldwide license in said article to reproduce, prepare derivative works, distribute copies to the public, and perform publicly and display publicly, by or on behalf of the Government. The Department of Energy will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan. http://energy.gov/downloads/doe-public-access-plan

Disclaimer

This information was prepared as an account of work sponsored by an agency of the U.S. Government. Neither the U.S. Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness, of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. References herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. Government or any agency thereof.

QUESTIONS?

W. Neal Mann, PhD
Principal Energy Systems Engineer

wmann@anl.gov

Jiali Wang, PhD
Principal Atmospheric & Earth Scientist

Tom Wall, PhD
Department Manager, Infrastructure Security & Resilience

David Sehloff, PhD
Principal Energy Systems Engineer

Argonne
NATIONAL LABORATORY

U.S. DEPARTMENT
of ENERGY