Climate Data Foundations for Energy System Modeling and Resilience Planning

Presentation for NARUC-NASEO Resilience Cohort

Climate READi

Laura Fischer
Principal Team Lead, Climate Resilience Analysis
Manager, Program 262: Climate Risk and Resilience

April 10, 2026

www.epri.com

Today's Agenda

Motivations

- Regulators and state energy offices are being asked to evaluate analyses and investment justifications built on complex climate data.
- Climate READi resources can help decision-makers understand what climate data are available, how they should (and should not) be used for power system planning, and where important gaps remain.
- Participants will gain practical insight into:
  - Interpreting climate data and modeling in utility filings
  - Setting realistic expectations around uncertainty and extremes
  - Identifying priority areas for future data and research investments that support resilient, reliable energy systems

Relevance of Climate READi for state energy officials

Introduction to Climate READi Framework

Key insights from Climate READi climate data resources

Discussion and Q&A

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Objectives of today's training

1. Equip participants with the tools you need to evaluate the climate data choices that are being made in physical risk assessments
2. Orient attendees to Climate READi resources that companies may reference in physical climate risk assessments
3. Not intended to make you an expert in climate science or convert you into a climate modeler

Climate READi can be a resource for state energy officials too!

How is Climate READi relevant to regulators and state energy officials?

01 Climate READi provides a consistent and replicable process for conducting physical climate risk assessment and identifying investment options.

02 Climate READi explains what physical climate risk assessments can reasonably deliver based on current science and analysis capabilities.

03 The Climate READi Framework was built with power system application in mind. Resources are tailored to industry-specific needs.

Why would regulators state energy officials need guidance on climate data?

04 Officials in some jurisdictions are setting guidance on what climate data, models, and/or emissions scenarios should be used in these assessments.

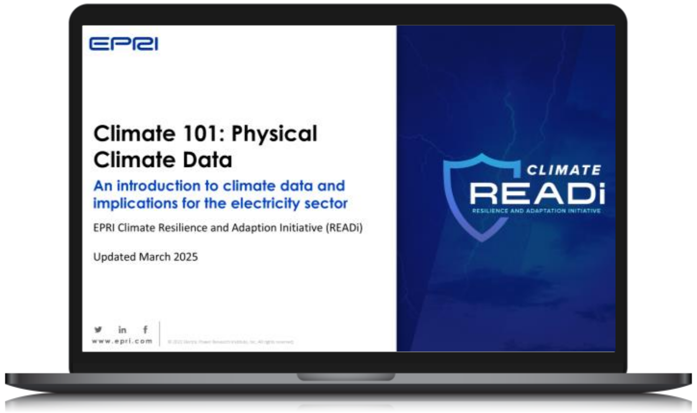
05 Companies may use different climate data inputs in their risk assessments and resilience planning, making comparisons across outcomes difficult.

03 The market for climate data production is very active with multiple providers offering data solutions.

Climate 101 Course Offerings

Nearly 1000 people have taken a Climate 101 training!

Access self-guided training here. To schedule a training, contact ClimateREADi@epri.com



EPRI

Climate 101: Physical Climate Data

An introduction to climate data and implications for the electricity sector

EPRI Climate Resilience and Adaption Initiative (READi)

Updated March 2025

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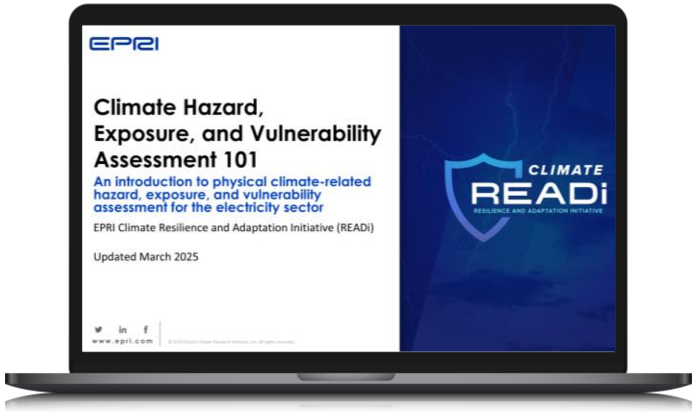
CLIMATE READi

RESILIENCE AND ADAPTATION INITIATIVE



EPRI

Climate Hazard, Exposure, and Vulnerability Assessment 101

An introduction to physical climate-related hazard, exposure, and vulnerability assessment for the electricity sector

EPRI Climate Resilience and Adaptation Initiative (READi)

Updated March 2025

www.epri.com

CLIMATE READi

RESILIENCE AND ADAPTATION INITIATIVE

EPRI

Climate Resilient Investment Prioritization 101

An introduction for the electricity sector

CLIMATE READi

EPRI Climate Resilience and Adaptation Initiative (READi)

January 2025

www.epri.com

Physical Climate Data 101

1. Climate Data Overview
2. Climate Models, Emissions Scenarios & Projection Data
3. Trends &Understanding of Extreme Events

Hazard, Exposure, and Vulnerability Assessment 101

4. Hazard Assessment
5. Exposure Assessment
6. Vulnerability Assessment & Case Study

Climate Resilient Investment Prioritization 101

7. Assessment Scoping
8. Impact & Consequence Assessment
9. Resilience Decision-Making

Today’s Agenda

CLIMATE READi
RESILIENCE AND ADAPTATION INITIATIVE

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How can we better evaluate risk and make decisions regarding extreme weather and climatological impacts to the power system?

CLIMATE
READi
RESILIENCE AND ADAPTATION INITIATIVE

Access all results, story maps, and the framework at:

climatereadi.epri.com

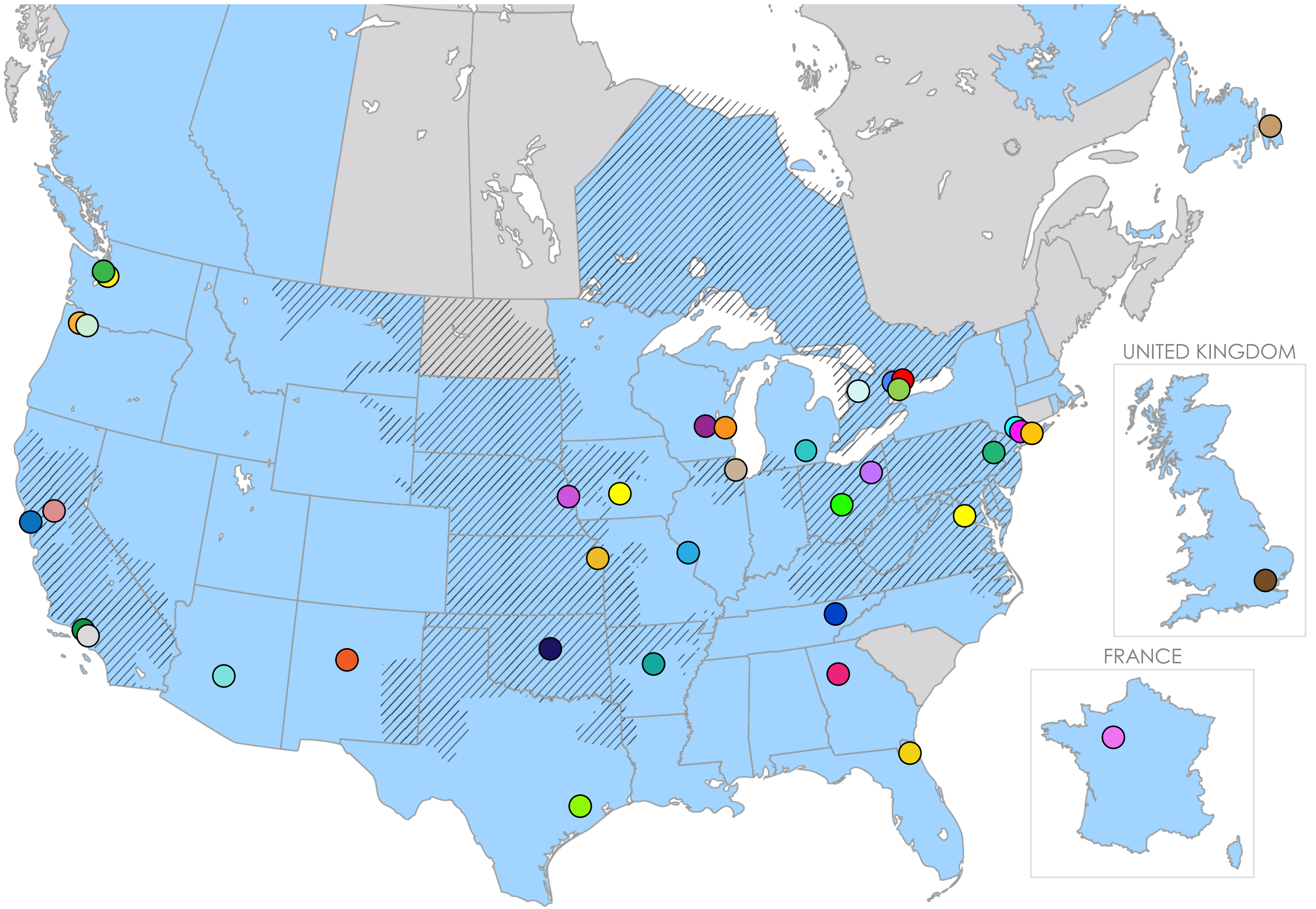
EPRI Climate Resilience and Adaptation Initiative (READi)

- **COMPREHENSIVE:** Develop a *Common Framework* addressing the entirety of the power system, planning through operations
- **CONSISTENT:** Provide an informed approach to climate risk assessment and strategic resilience planning that can be replicated
- **COLLABORATIVE:** Drive stakeholder alignment on adaptation strategies for efficient and effective investment

Final Product: A Common Framework

- Climate data assessment and application guidance
- Vulnerability assessment
- Risk mitigation investment
- Hardening technologies
- Adaptation strategies
- Research priorities

Climate READi Members



○ Member Headquarters ▢ Member Operating States/Provinces ▨ ISO Service Territories *(only HQ location shown for IPPs)*

aes Indiana
aes Ohio
Alliant Energy
Ameren
American Electric Power
Boundless Energy
Berkshire Hathaway Energy
Bonneville Power Administration
BrucePower
California ISO
Consumers Energy
evergy
conEdison
exelon
FirstEnergy
CenterPoint Energy
hydro one
ieso
Connecting Today. Powering Tomorrow.
FORTIS INC.
LA DWP Los Angeles Department of Water & Power
JEA
New York State of Opportunity. NY Power Authority
LIPA Long Island Power Authority
nationalgrid
your energy partner
OPPD Omaha Public Power District
OG&E
Ontario Power Generation
PNM
PGE
PG&E
Rte
ppl
PSE Puget Sound Energy
Seattle City Light
SRP
Southern California Edison
TVA Tennessee Valley Authority
Southern Company
SPP Southwest Power Pool
WEC Energy Group
VISTRA

Climate READi Affinity Group (CRAG)

The Climate READi Affinity Group (CRAG) brings together experts from over 110 organizations—including academia, consulting, finance, insurance, NGOs, national labs, government, and regulatory bodies—to address the critical challenge of resilience and adaptation in the energy sector. We're continuing to grow, so if your organization is interested in joining, please contact us at ClimateREADi@epri.com.

Consultants

Finance and Insurance

ESG and Disclosure

Environ. NGOs

Academia/ Research Orgs

Industry Groups

National Laboratories

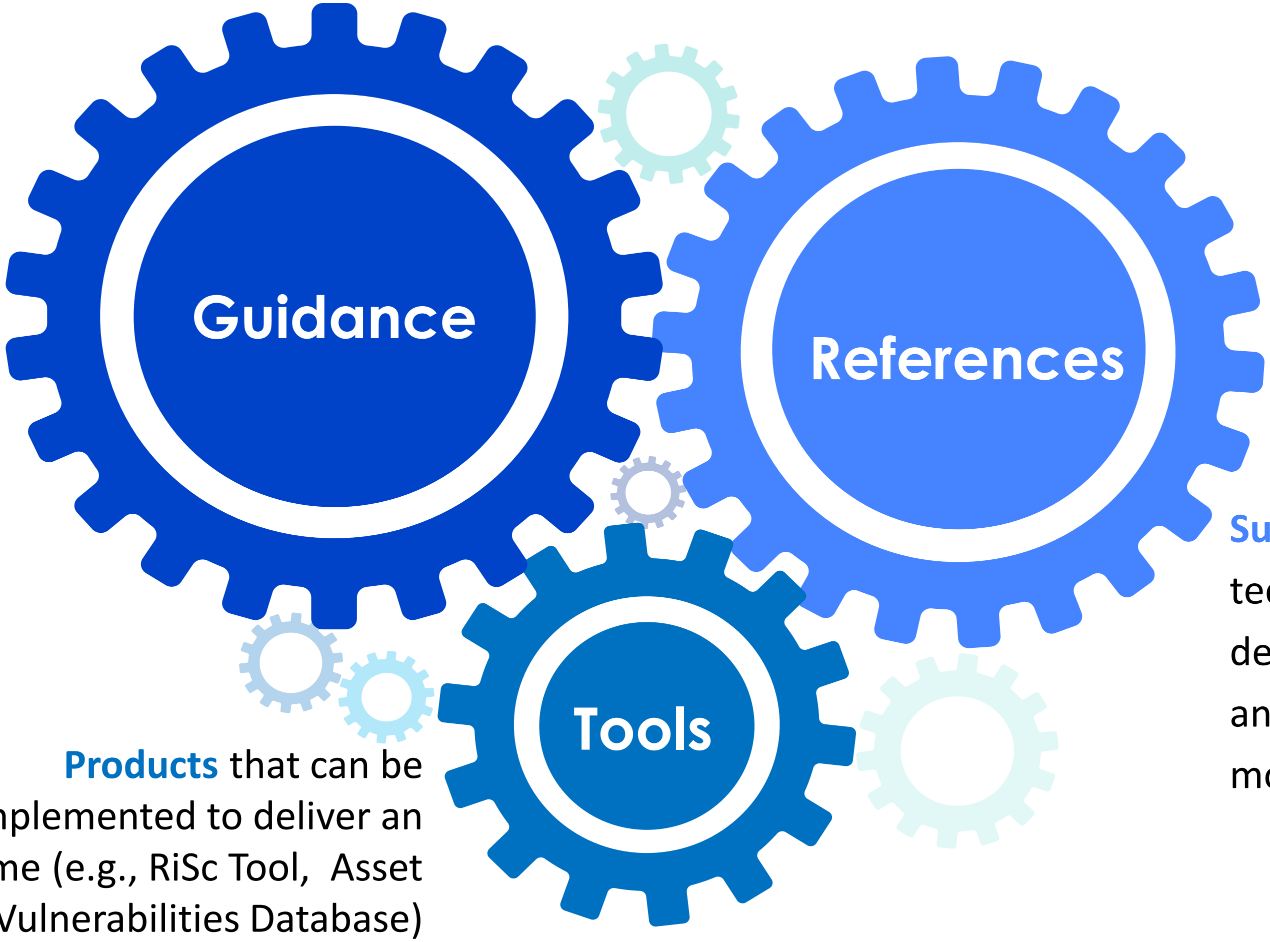
Regulators and Policy Makers

Codes and Standards Bodies

- 319Climate
- Accenture
- ADEX
- AECOM
- AEGIS
- Alison Silverstein (Consultant)
- Andrew Dessler (Texas A&M)
- Applied Weather Associates
- Argonne National Laboratory
- Baringa
- Battelle
- Black & Veatch
- Brookhaven National Laboratory
- CAMPUT
- Canadian Climate Institute
- CANDU Owners Group
- CarbonPlan
- CDP North America
- Center for Climate & Energy Solutions
- Central Research Institute of Electric Power Industry
- Charles River Associates
- Chemonics
- Clark Miller (Consultant)
- Clean Air Task Force
- Climate Equity Foundation
- Climate Risk Institute
- Columbia University
- Copperleaf Technologies
- Cornell University
- Courtney Cole (Consultant)
- CSA Group
- Desert Research Institute
- Disaster Tech
- Eagle Rock Analytics
- Earthmover
- Eaton
- Ecohealth Strategies
- Electricity Canada
- Energy and Environmental Economics, Inc.
- Energy Networks Association
- Energy Systems Integration Group
- Enline Transmission
- Exponent
- EY Canada
- Grid Lab
- Guidehouse
- Houston Advanced Research Center
- ICF
- IEEE
- Imperial College London
- Institute of Nuclear Power Operations
- Integral Consulting
- International Hydropower Association
- Jacobs Engineering
- James Doss-Gollin (Rice University)
- Jupiter Intelligence
- Khalifa University
- King Abdullah University of Science and Technology
- King's College London
- Korea Atomic Energy Research Institute
- Lawrence Berkeley National Laboratory
- Lawrence Livermore National Laboratory
- McCormick Taylor
- Michigan Technological University
- Midwest Climate Collaborative
- Model World Consulting
- Natl. Association of Regulatory Utility Commissioners
- Natl. Association of State Energy Officials
- Natl. Center for Atmospheric Research
- Natl. Oceanic and Atmospheric Administration
- Natl. Renewable Energy Laboratory
- Newbridge Energy Consulting
- North American Electric Reliability Corporation
- North American Transmission Forum
- Nuclear Energy Institute
- Nuclear Electric Insurance Limited
- Nuclear Innovation Institute
- Oak Ridge National Laboratory
- Oregon State University
- Pacific Northwest National Laboratory
- Pacific Northwest Utilities Conference Committee
- Pike Engineering
- Power Systems Engineering Research Center
- Quanta Services
- RAND Corporation
- Resources for the Future
- RS Poles
- RUNWITHIT Synthetics
- Sharply Focused
- Sinapsis Energia
- SLR Consulting
- Stonybrook University
- Storm Impact
- Sunairio
- TECNALIA Research & Innovation
- TRC Companies
- Union of Concerned Scientists
- Universidad Pontificia
- University of Albany
- University of Arizona
- University of Illinois
- University of Michigan
- University of Nottingham
- University of Oklahoma
- University of Reading
- University of Saskatchewan
- University of South Alabama
- University of Toronto
- Verdantas
- Viridi

THE *Climate READi: Power Framework*

While there are many deliverables from Climate READi: Power, key **Framework** products are categorized and mapped as guidance, references, and tools.



How-to documents for executing a climate resilience assessment for a system or question of interest

Support resources providing technical rationale and deeper understanding of guidance and/or tools (e.g., training modules, methodologies)

Products that can be implemented to deliver an outcome (e.g., RiSc Tool, Asset Vulnerabilities Database)

THE Climate READi: Power Framework

	READi	Climate Data	Asset Vulnerability	System Risk
Guidance	Climate READi Compass: Navigating Physical Climate Risk Assessments for the Power System	Climate Data Users Guide Climate Hazard and Exposure Assessment Guidance for Power System Applications	Asset Vulnerability and Response Assessment Guidance Climate Vulnerability Assessment Guidance for Nuclear Power Plant Fragility Curves for Quantifying Physical Climate Risk in the Electric Power Sector	Planning for Climate Resilience in the Power System: A Guide for Model Implementation Investing for Climate Resilience in the Power System: A Guide for Adaptation Prioritization and Decision-Making
References	Climate 101 Modules Case Studies and Story Maps	Approaches to Future Hourly Time Series for Climate-Resilient Power System Planning An Approach to Defining Temperature Extreme Events: A Threshold-based Probabilistic Approach to Defining Extreme Temperature Events Compound Hazards and the Power Sector in a Changing Climate Climate Data Gaps Assessment	Asset Vulnerability Literature Review Series	Developing a Climate Informed Modeling Framework for Power System Planning – A Synthetic Texas Case Study Practices for Representing Climate Impacts in Bulk Electric System Models Metrics to Evaluate Effectiveness of Resilience Strategy Deployment
Tools	Disclosing Physical Climate Risk: Inventory of Climate READi Resources to Support Reporting and Disclosure Activities	Climate Data Inventory Wildfire Tool Inventory and Evaluation	Climate-Related Vulnerabilities and Adaptations for Electric Power System Assets	Climate Risk Screening (RiSc) Tool

Story Maps and Case Studies

Interactive deliverables illustrating implementation of Climate READi guidance and methods with new releases planned through 2026

Access all story maps here.

How can extreme heat impact asset performance?

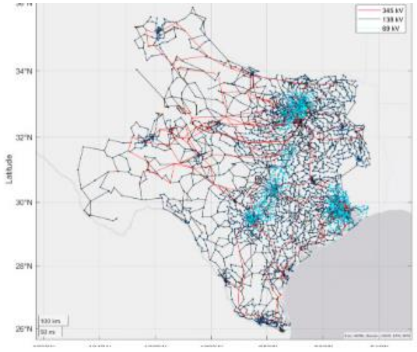
This study develops fragility curves to relate the impact of high ambient air temperatures on the performance of inverters, distribution transformers, and battery energy storage systems.

Will hurricanes cause more outages in the future?

Developed with EPRI and PNNL, this story map combines synthetic storm tracks and outage predictions to show how hurricane-related outages may change across Gulf and Atlantic coast counties under future climate conditions.

Does co-locating wind and solar installations improve resilience?

This story map analyzes decades of wind and solar data at 1,723 U.S. sites to reveal seasonal and interannual variability, resource complementarity, and implications for net-load and storage needs.



See an example of climate-informed system planning.

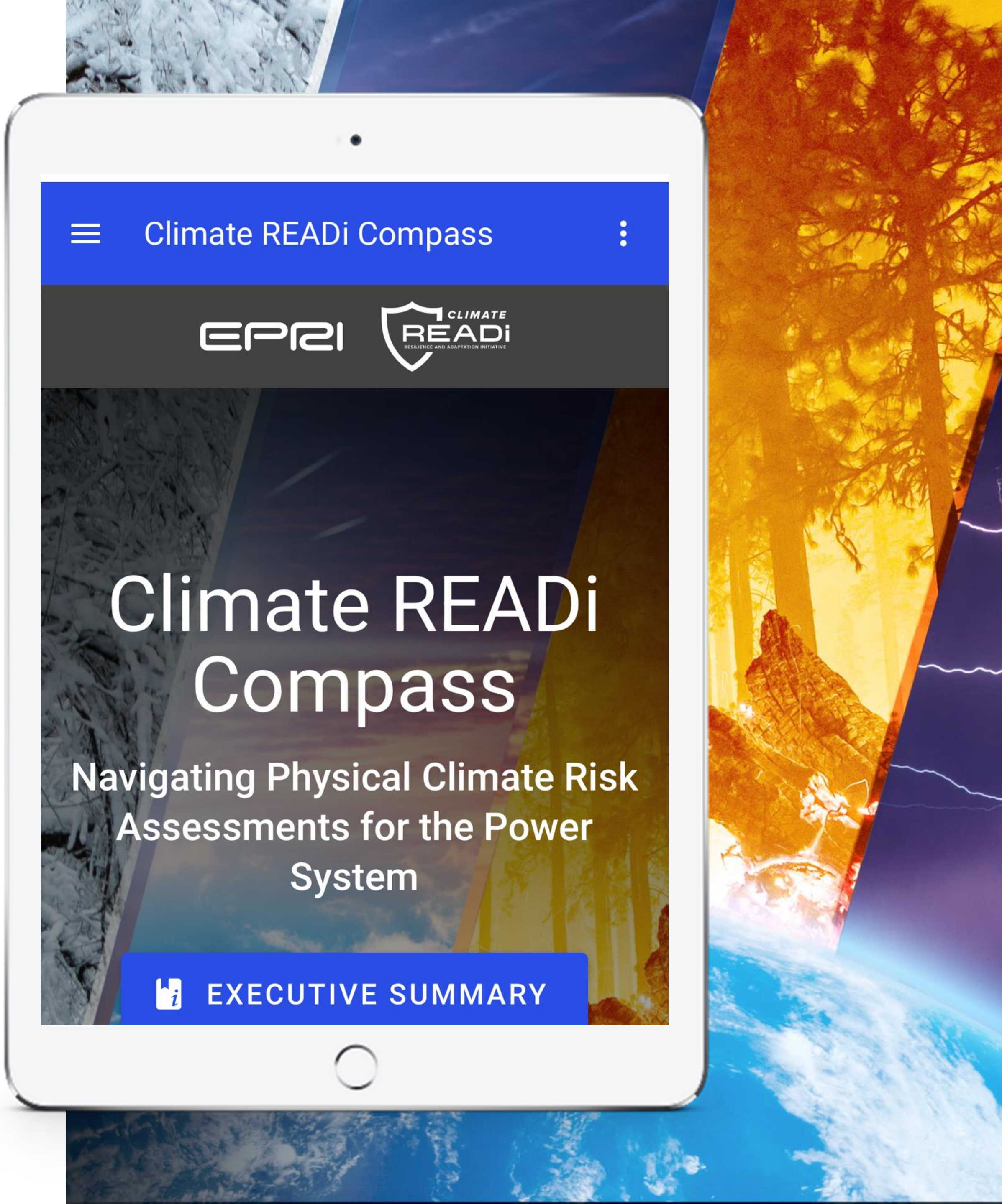
This story map presents key results from testing a climate-informed power system modeling framework using a synthetic Texas grid to support resilience planning.

Climate READi Compass:

Navigating Physical Climate Risk Assessments for the Electric Power Sector

Compass provides practitioners with a single resource for navigating the Climate READi Framework and identifying the elements of the Framework best suited to their current implementation needs.

Access Compass here!



Climate READi Compass

Navigating Physical Climate Risk Assessments for the Power System

www.epri.com

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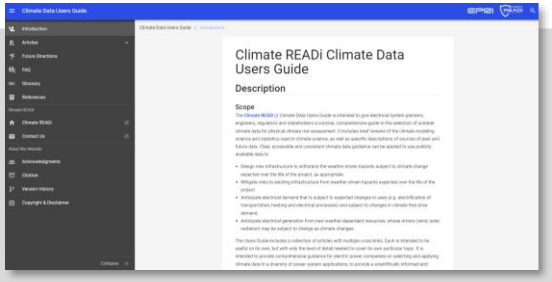
- **Key insights from Climate READi climate data resources**
- Discussion and Q&A

Physical Climate Data and Focus Area enables more informed and confident application of climate data in power system analysis.

Guidance



Climate READi Climate Data Users Guide

Description

Scope

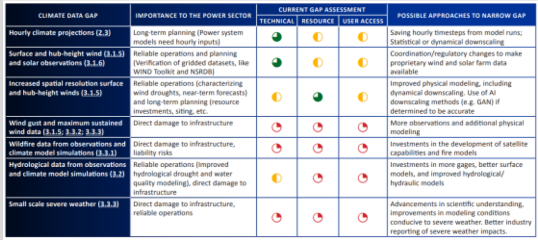
[Climate Data User Guide](#)
Value of Climate Data User's Guide for Climate READi members

Climate Hazard and Exposure Assessment Guidance for Power System Applications

Guidance to conduct practical climate hazard and exposure assessments in support of physical climate risk assessments.

[Climate Hazard and Exposure Assessment Guidance](#)
Step-by-step guide for completing hazard and exposure assessment

References



CLIMATE DATA GAP	IMPORTANCE TO THE POWER SECTOR	CURRENT GAP ASSESSMENT			POSSIBLE APPROACHES TO NARROW GAP
		TECHNICAL	RESOURCE	USER ACCESS	
Hourly climate projections (2.3)	Long-term planning (Power system models need hourly inputs)	◕	◐	◐	Saving hourly timesteps from model runs; Statistical or dynamical downscaling
Surface and hub-height wind (3.1.5) and solar observations (3.1.6)	Reliable operations and planning (Verification of gridded datasets, like WIND Toolkit and NSRDB)	◕	◐	◐	Coordination/regulatory changes to make proprietary wind and solar farm data available
Increased spatial resolution surface and hub-height winds (3.1.5)	Reliable operations (characterizing wind droughts, near-term forecasts) and long-term planning (resource investments, siting, etc.	◐	◕	◐	Improved physical modeling, including dynamical downscaling. Use of AI downscaling methods (e.g. GAN) if determined to be accurate
Wind gust and maximum sustained wind data (3.1.5; 3.3.2; 3.3.3)	Direct damage to infrastructure	◔	◔	◔	More observations and additional physical modeling
Wildfire data from observations and climate model simulations (3.3.1)	Direct damage to infrastructure, liability risks	◔	◔	◔	Investments in the development of satellite capabilities and fire models
Hydrological data from observations and climate model simulations (3.2)	Reliable operations (improved hydrological drought and water quality modeling), direct damage to infrastructure	◐	◔	◔	Investments in more gages, better surface models, and improved hydrological/ hydraulic models
Small scale severe weather (3.3.3)	Direct damage to infrastructure, reliable operations	◔	◔	◔	Advancements in scientific understanding, improvements in modeling conditions conducive to severe weather. Better industry reporting of severe weather impacts.

[Climate Data Gap Assessment](#)
Explain extent and limitations of current hazard assessment and climate data development capabilities

[Compound Hazards WP](#)

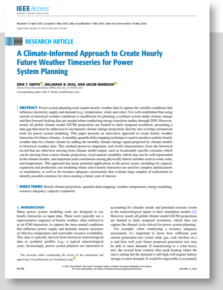
CLIMATE READi

EPRI

TECHNICAL REPORT

COMPOUND HAZARDS AND THE POWER SECTOR IN A CHANGING CLIMATE

June 2025



IEEE Access

Received 15 April 2025, accepted 2 May 2025, date of publication 7 May 2025, date of current version 16 May 2025.

RESEARCH ARTICLE

A Climate-Informed Approach to Create Hourly Future Weather Timeseries for Power System Planning

ERIK T. SMITH, DELAVANE B. DIAZ, AND JACOB MARDIAN

Electric Power Research Institute (EPRI), Palo Alto, CA 94304, USA

Corresponding author: Erik T. Smith (esmith@epri.com)

ABSTRACT Power system planning tools require hourly weather data to capture the variable conditions that influence electricity supply and demand (e.g., temperature, wind, and solar). It is well-established that using current or historical weather conditions is insufficient for planning a resilient system under climate change and that forward-looking data are needed when conducting energy transition studies through 2050. However, nearly all global climate model (GCM) projections are limited to daily temporal resolution, presenting a data gap that must be addressed to incorporate climate change projections directly into existing commercial tools for power system modeling. This paper presents an innovative approach to create hourly weather timeseries for future climates. A monthly quantile delta mapping technique is used to produce realistic hourly weather data for a future climate by adding the monthly climate change signal projected by climate models to historical weather data. This method preserves important, real-world characteristics from the historical record that are otherwise missing from climate model output, such as locationally specific extremes which can be missing from coarse climate projections, local natural variability which may not be well represented in the climate models, and important joint correlations among physically linked variables such as wind, solar, and temperature. This approach has many potential applications in the power sector, including for capacity expansion and production cost modeling where select hourly timeseries are used for complex optimizations or simulations, as well as for resource adequacy assessments that evaluate large samples of realizations to identify possible extremes for stress-testing a future year of interest.

INDEX TERMS Hourly climate projections, quantile delta mapping, weather, temperature, energy modeling, resource adequacy, capacity expansion.

I. INTRODUCTION

Many power system modeling tools are designed to use hourly timeseries as input data. These tools typically use a representative sequence of hourly weather, often referred to as an 8760 timeseries, to capture the intra-annual conditions that influence power supply and demand, namely measures of effective temperature and renewable resource availability. This data is typically derived from historical meteorological data or synthetic profiles (e.g., a typical meteorological year). Increasingly, power system planners are interested in accounting for climatic trends and potential extreme events in the meteorological inputs to their simulation models [1]. However, nearly all global climate model (GCM) projections are limited to daily temporal resolution, which does not capture the diurnal cycle critical for power system planning.

For example, when conducting a resource adequacy assessment, it's important to know how sufficient your current generation mix (wind, solar, gas, coal, nuclear, etc.) is and how well your future proposed generation mix may be able to meet demand. If transitioning to a solar heavy mix, the several hour window after peak heating where the sun is setting but the demand is still high will require battery storage to meet demand. It would be impossible to accurately

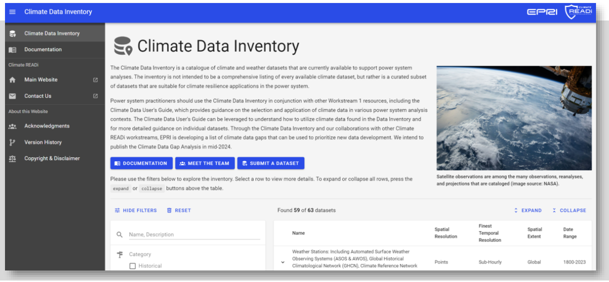
The associate editor coordinating the review of this manuscript and approving it for publication was Xiaodong Liang.

82796

VOLUME 13, 2025

[Climate-Informed Approach to Hourly Future Weather Timeseries](#)
Create climate-adjusted, physically consistent hourly weather data for power system applications

Tools



Climate Data Inventory

The Climate Data Inventory is a catalogue of climate and weather datasets that are currently available to support power system analyses. The inventory is not intended to be a comprehensive listing of every available climate dataset, but rather is a curated subset of datasets that are suitable for climate resilience applications in the power system.

Power system practitioners should use the Climate Data Inventory in conjunction with other Workstream 1 resources, including the Climate Data User's Guide, which provides guidance on the selection and application of climate data in various power system analysis contexts. The Climate Data User's Guide can be leveraged to understand how to utilize climate data found in the Data Inventory and for more detailed guidance on individual datasets. Through the Climate Data Inventory and our collaborations with other Climate READi workstreams, EPRI is developing a list of climate data gaps that can be used to prioritize new data development. We intend to publish the Climate Data Gap Analysis in mid-2024.

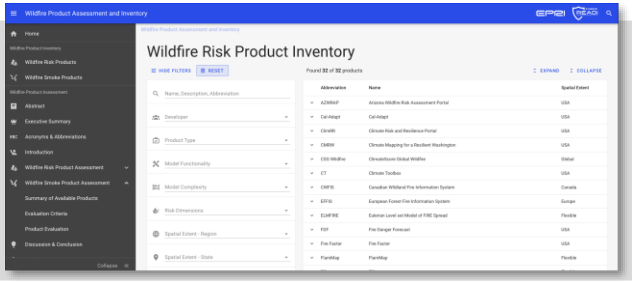
Please use the filters below to explore the inventory. Select a row to view more details. To expand or collapse all rows, press the `expand` or `collapse` buttons above the table.

Satellite observations are among the many observations, reanalyses, and projections that are cataloged (image source: NASA).

Found 59 of 63 datasets

Name	Spatial Resolution	Finest Temporal Resolution	Spatial Extent	Date Range
Weather Stations: Including Automated Surface Weather Observing Systems (ASOS & AWOS), Global Historical Climatological Network (GHCN), Climate Reference Network	Points	Sub-Hourly	Global	1800-2023

[Climate Data Inventory](#)
Identify relevant data from curated list of historical and projection datasets



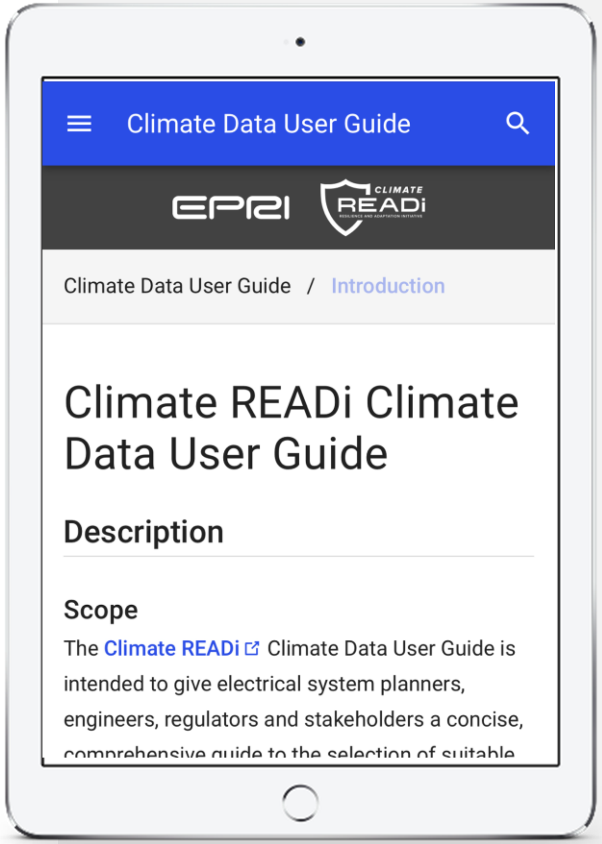
Wildfire Risk Product Inventory

Found 32 of 32 products

Abbreviation	Name	Spatial Extent
AZWRAP	Arizona Wildfire Risk Assessment Portal	USA
Cal-Adapt	Cal-Adapt	USA
ClimRR	Climate Risk and Resilience Portal	USA
CMRW	Climate Mapping for a Resilient Washington	USA
CSG Wildfire	ClimateScore Global Wildfire	Global
CT	Climate Toolbox	USA
CWFIS	Canadian Wildland Fire Information System	Canada
EFFIS	European Forest Fire Information System	Europe
ELMFIRE	Eulerian Level set Model of FIRE Spread	Flexible
FDF	Fire Danger Forecast	USA
Fire Factor	Fire Factor	USA
FlamMap	FlamMap	Flexible

[Wildfire Tool Inventory](#)
Identify wildfire risk products for specific applications

How to apply Physical Climate Data and Guidance resources



Climate Data User Guide / Introduction

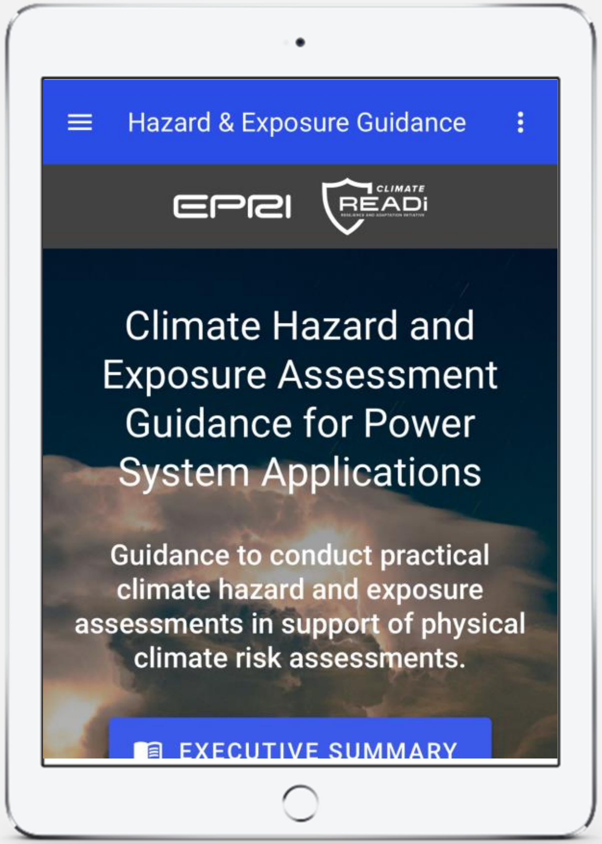
Climate READi Climate Data User Guide

Description

Scope

The Climate READi Climate Data User Guide is intended to give electrical system planners, engineers, regulators and stakeholders a concise, comprehensive guide to the selection of suitable

Access Climate Data User Guide >>



Climate Hazard and Exposure Assessment Guidance for Power System Applications

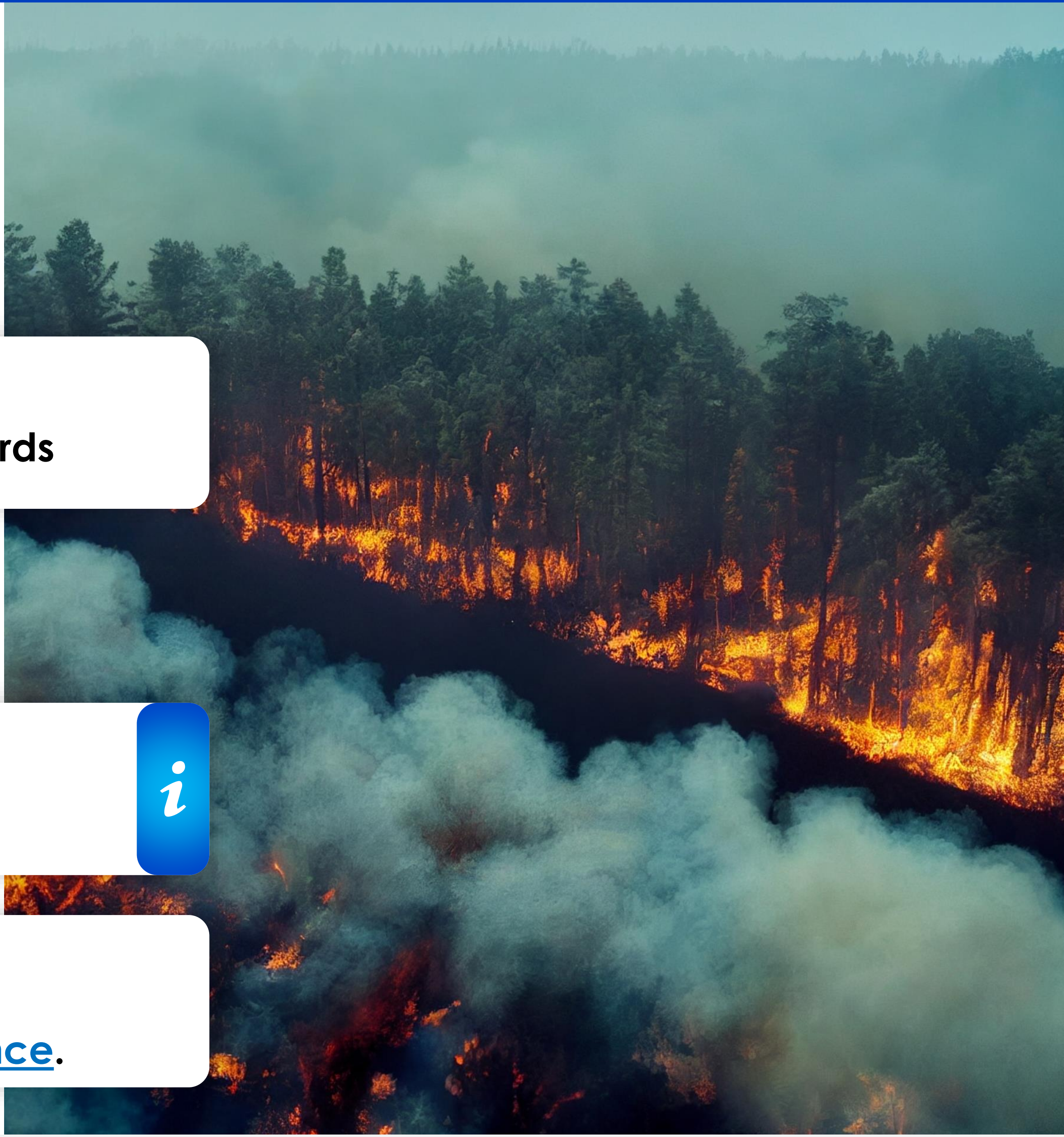
Guidance to conduct practical climate hazard and exposure assessments in support of physical climate risk assessments.

Access Hazard and Exposure Assessment Guidance>>

1. **Discover changes in relevant climate hazards**
2. **Identify suitable climate data. Justify data choices.**
3. **Generate climate data for other Framework activities**

Consult the Climate Data User Guide and Hazard Assessment Guidance to understand and estimate trends in hazards that impact power system operations and planning.

Where can companies source hazard information?



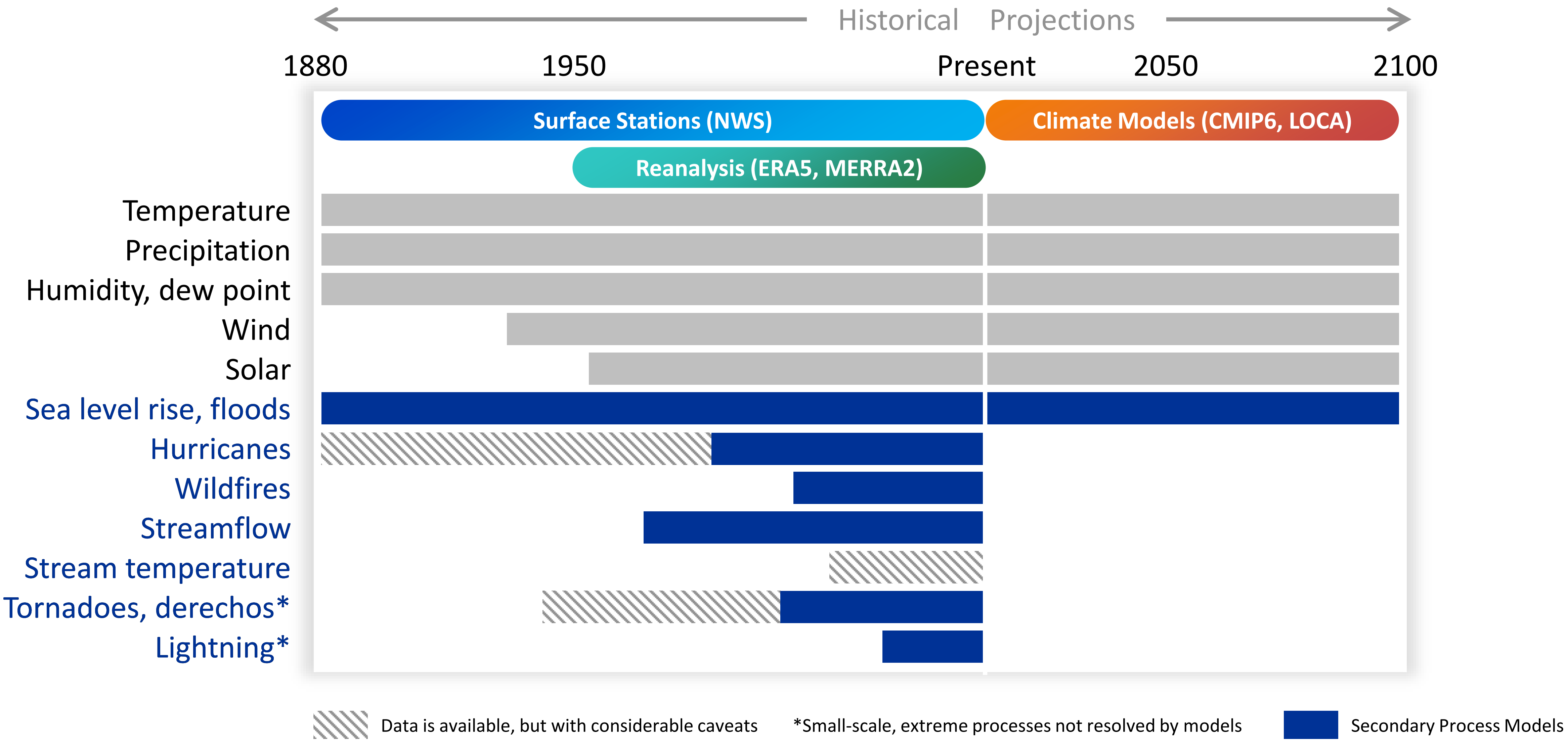
Analysis of climate data: observed and projected trends in relevant climate hazards

- Change is important
- Compound hazards

***Physical Climate Data 101* (Climate 101, Part I)**

EPRI's Climate Data Inventory, Climate Data User's Guide, and Hazard and Exposure Assessment Guidance.

Timescales of climate variables



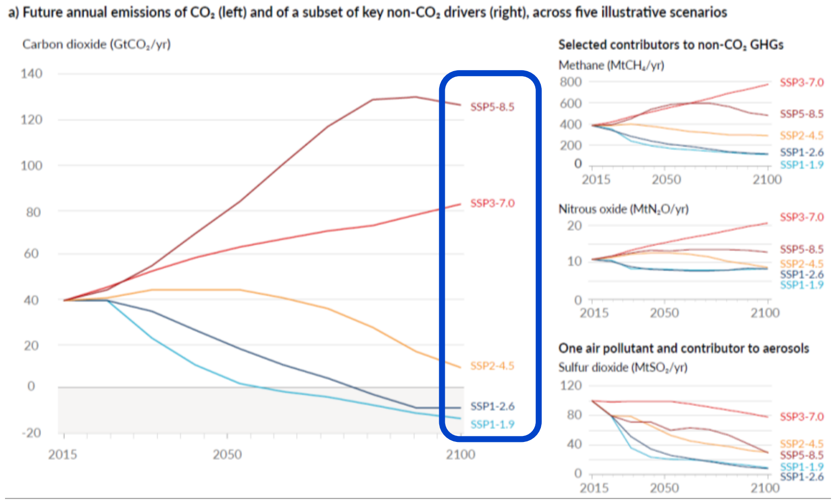
Climate projection data generated via sequential models

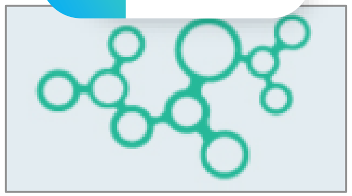
1 Standardized Climate Emissions Scenarios

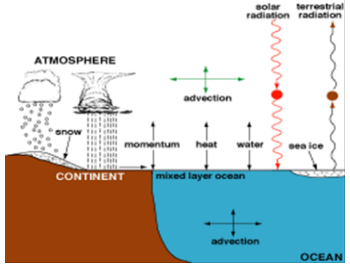
2 Global Climate Model (GCM)

3 Downscaling

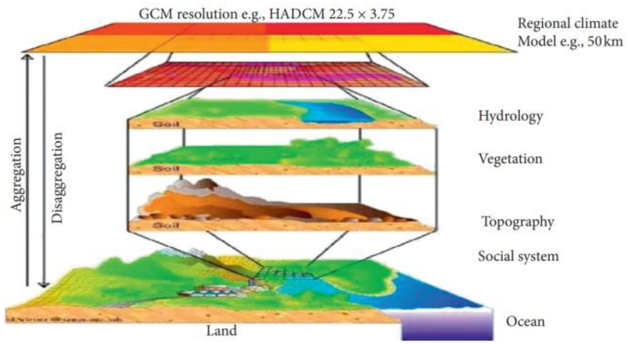
4 Secondary impact model


a) Future annual emissions of CO₂ (left) and of a subset of key non-CO₂ drivers (right), across five illustrative scenarios


Statistical models

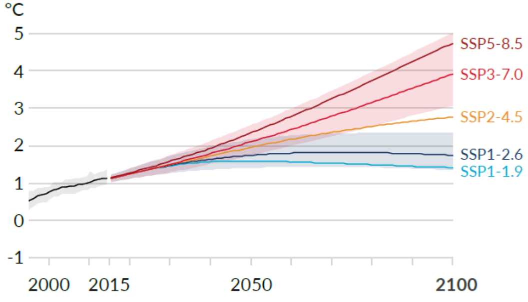


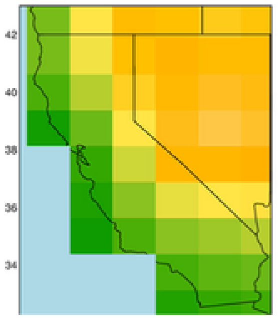
Dynamical models

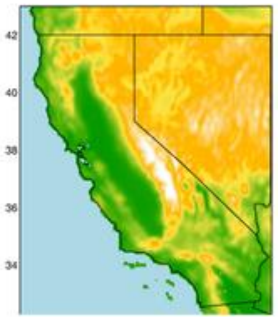


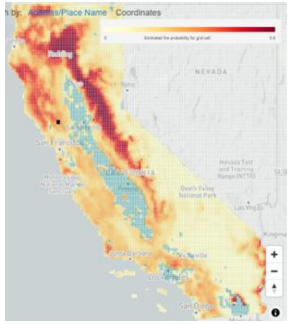
Output example

All levels of projection data can be applied in planning


Global surface temperature change relative to 1850-1900

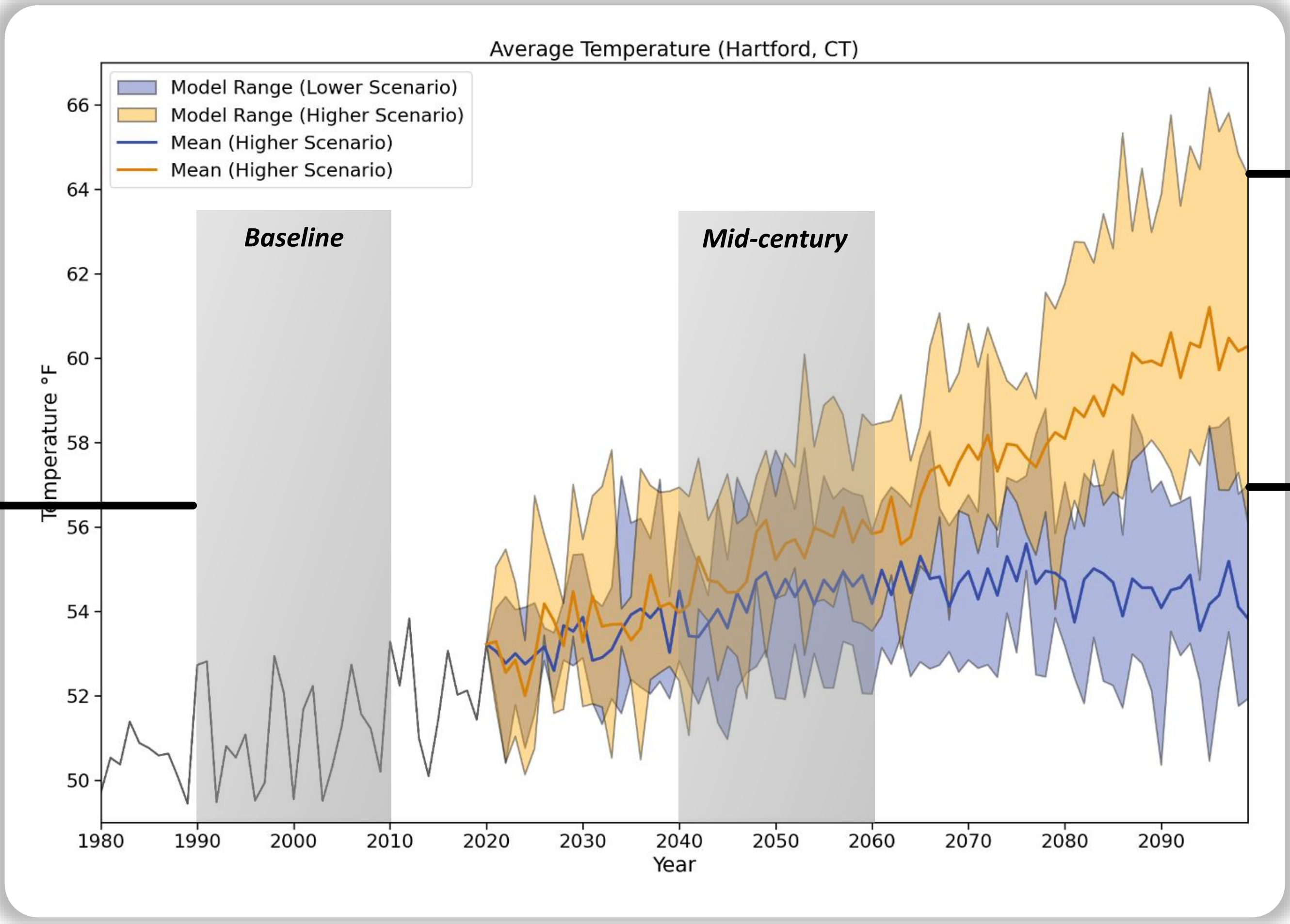






Source: IPCC AR6, NOAA, Al-Ghadi et al. (2020), USGS

Basics of understanding climate projections



Future trends can be compared to historical, or baseline, periods.

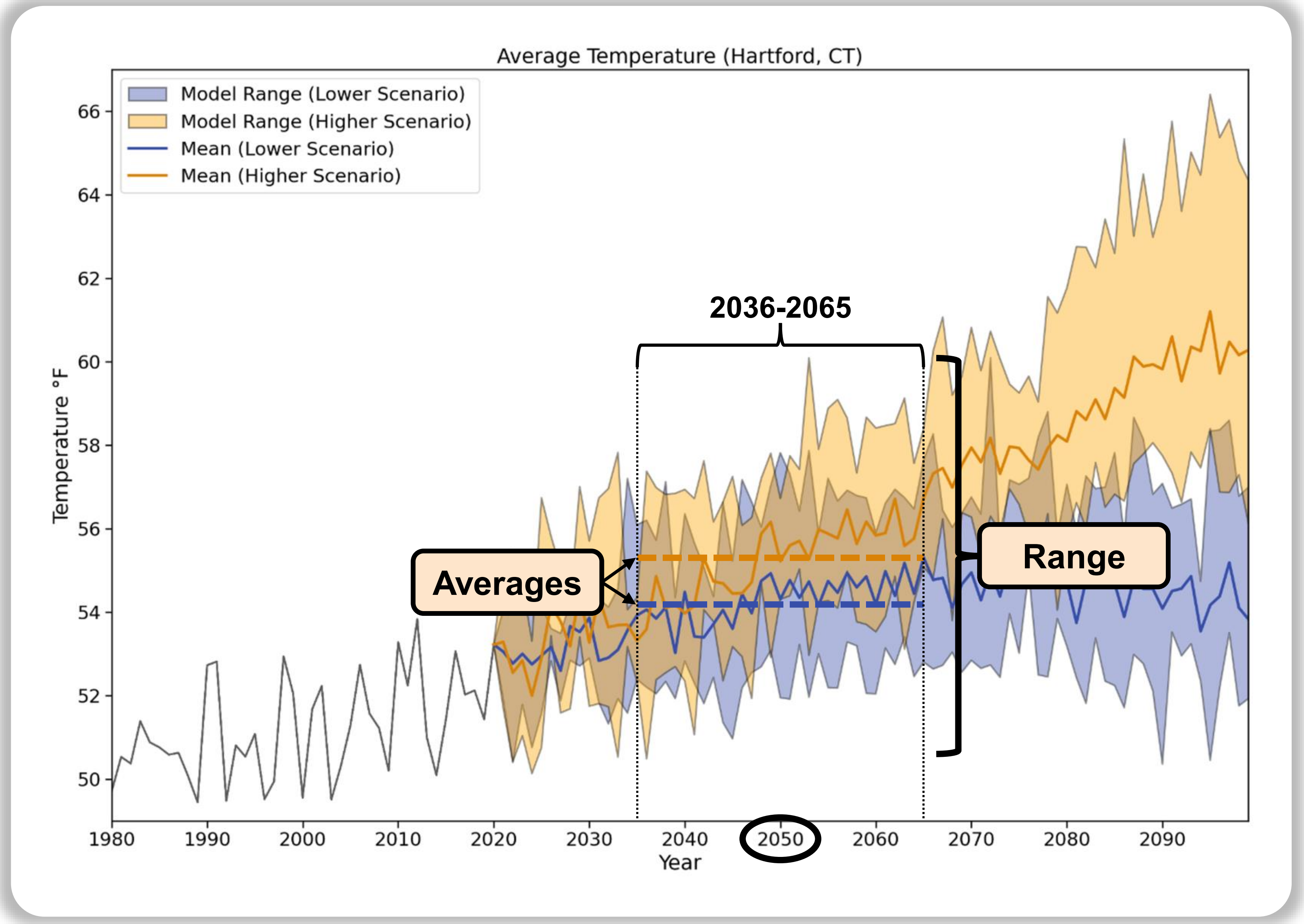
The range of projections across models (ensemble) is shown in the shaded period. The solid line represents the multi-model mean. Different methods are used to sample the ensemble to account for uncertainty.

Projections are relatively convergent between climate scenarios through 2050 but start to diverge significantly closer to the end of the century.

Projections shown for a single continuous variable (average temperature). Projections can be quantified in different ways depending on the application.

Source: EPRI analysis, adapted from Southern California Edison

A single year vs. 30-year average



Source: EPRI analysis, adapted from Southern California Edison

The goal of projections is to understand changes in the overall climate & climatology, not to predict individual events or years

A 30-year average more accurately captures the range of possibilities and avoids issues with outliers

Cold extremes: What does the science say?

Historical – High understanding

Extreme cold has **decreased** in frequency, intensity, and duration in most places

- Interannual variability reflects internal climate variability

Projections – High capability, evolving methods

Extreme cold is expected to continue to **decrease** in frequency and intensity for **most** places

- Event definition of absolute vs relative cold matters
- Extreme cold defined by absolute thresholds projected to decrease, but periods of extreme cold will still be possible

Geophysical Factors

Arctic Amplification: Arctic is warming faster than rest of the world

Weakens **Polar Vortex and *may* lead to extreme cold in mid-latitudes**
Where extreme cold lands depends on changes in circulations in the North Atlantic and Pacific

But **reduces amount of cold available**
Future extreme cold likely less intense or cover a smaller area **on average**

But **decreases temperature gradient between pole and equator**
Can push polar jet stream further north and have less impact on southern latitudes

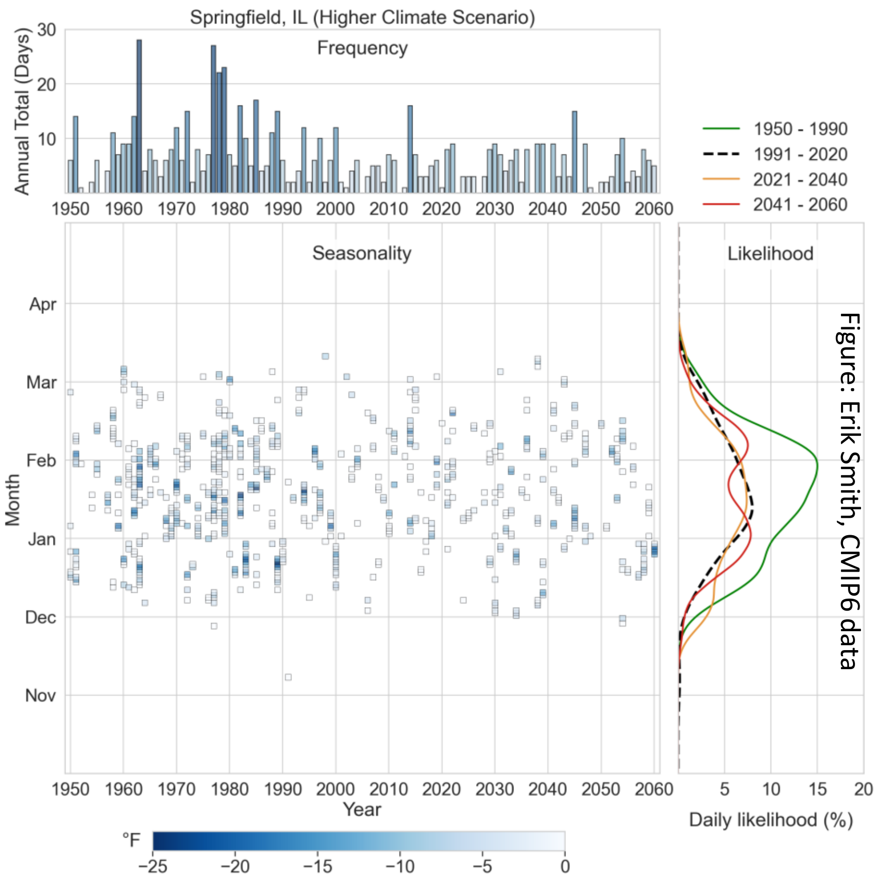


Figure: Erik Smith, CMIP6 data

Frequency of cold days with mean temperature below 32°F in Springfield, IL from 1951 – 2060.

High confidence in reduced risk of cold extremes most places

Source: EPRI analysis

Heat extremes: What does the science say?

Historical – High understanding

Extreme heat has become **more common**

- Climate change has more than doubled the probability of heat waves in some locations
- Daily minimum temperatures (overnight lows) warming faster than daily maximums (daytime highs)

Projections – High capability

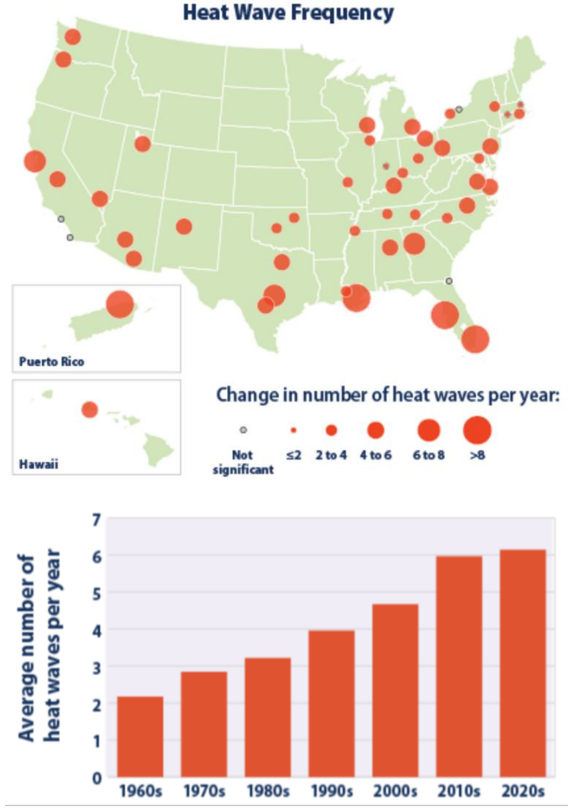
Extreme heat is expected to continue to **increase in frequency**

- Daily minimum temperatures are expected to keep warming faster than daily maximums

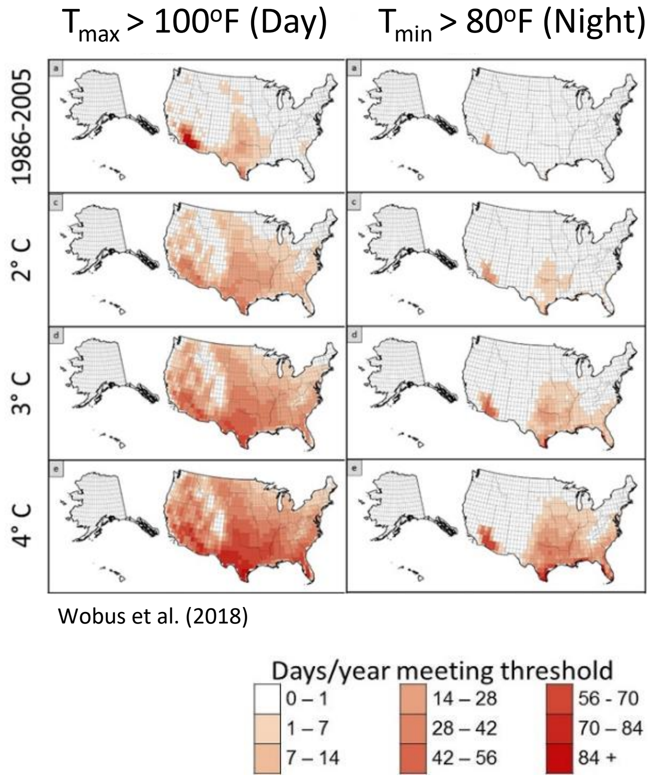
Geophysical Factors

- Patterns of warming will be non-uniform, spatially and seasonally
- Internal climate variability can amplify or offset extreme heat in any given year
- Drought and extreme heat interact with a positive feedback effect

Historical



Projected



Wobus et al. (2018)

High confidence in increasing risk of heat extremes

Sources: US EPA (left), Wobus et al. (2018; right)

Precipitation, Droughts : What does the science say?

Historical – Medium understanding

Precipitation is increasing in intensity

- A higher % of precipitation falls as heavy precipitation
- Warmer atmosphere holds more liquid

Projections – Medium capability

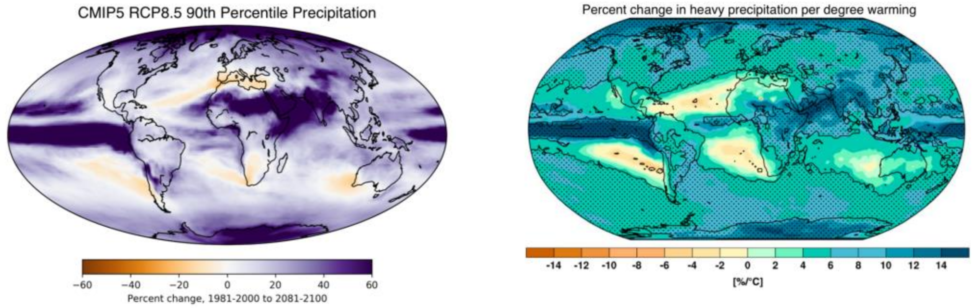
The historical trends are expected to continue

- Wetter places are expected to keep getting wetter
- Precipitation may be more variable in future (Pendergrass et al., 2017)
- Increased variability in rainfall + warmer temperatures will lead to more extreme droughts

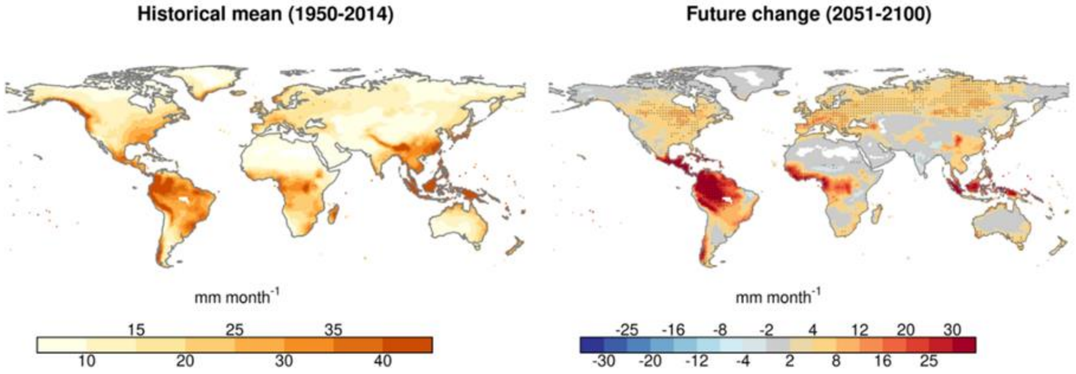
Uncertainties

- Drought frequency is less certain in U.S.
- Interannual variability
- If precipitation doesn't increase as temperatures warm, there will be a deficit. Soil moisture difficult to represent and project.
- Climate models do not include convection, a source of heavy precipitation events, and are generally poor at resolving clouds
- Climate models poorly simulate historical droughts and are generally thought to underestimate future droughts (Ault et al., 2014)

Heavy Precipitation Frequency



Drought Frequency



Medium understanding/confidence of precipitation changes

Sources: Carbon Brief (top); CMIP6, Ukkola et al. (2020, bottom)

Wildfires: What does the science say?

Historical – Medium understanding

Warming temperatures and changes in precipitation are linked to the increase in wildfire frequency

- Fire season has increased in length
- Fires are burning more area

Projections – Low capability

The increase in wildfire probability is expected to continue as temperatures continue to warm

- 75% of annual variability in burned area can be explained by a single climate variable – fuel aridity
- Fuel aridity depends largely on temperature and precipitation (Abatzoglou & Williams, 2016)

Temperature - High

- High temps will dry out fuels due to higher evapotranspiration
- Need 15% increase in moisture to compensate for 1°F increase in temperature (Flannigan et al., 2016)

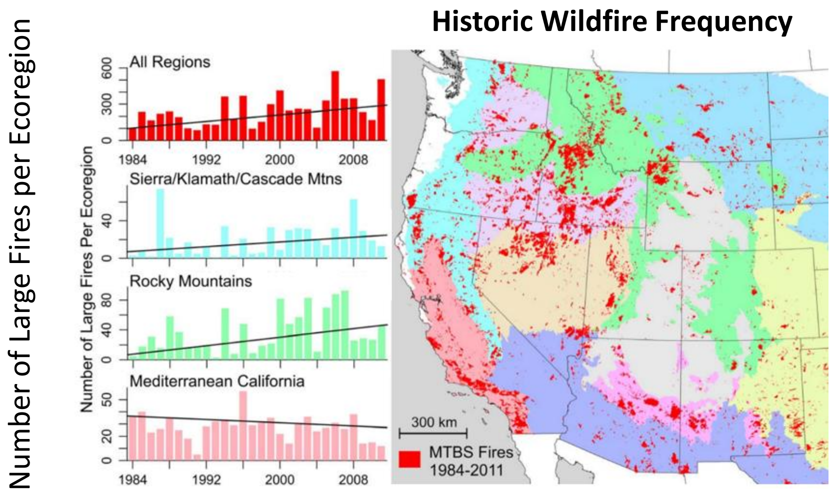
Precipitation - Low to Medium (depending on spatial scale)

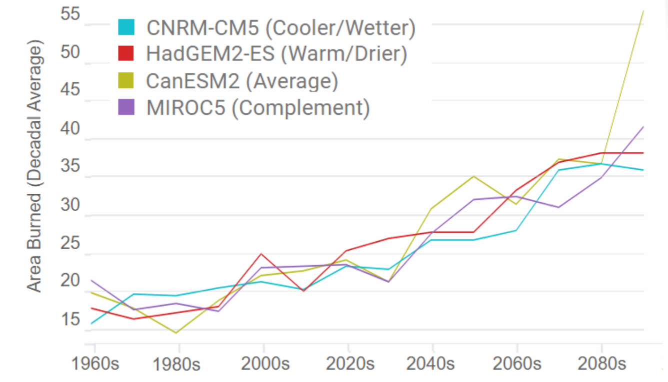
- Lack of precipitation can lead to drought

Uncertainties

- Interannual and spatial variability in precipitation/drought
- **Humans –** humans start most forest fires; Forest management

Historic Wildfire Frequency





Mixed understanding/confidence of wildfire changes

Sources: Dennison et al. (2014, top); 4th CA Climate Assessment for Napa, RCP8.5, central population scenario (bottom)

Coastal flooding: What does the science say?

Historical – High understanding

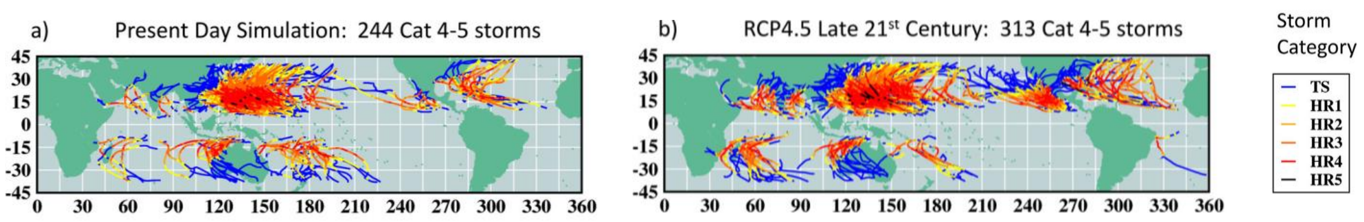
- Well-established trend of global SLR, with increasing days of sunny-day “nuisance” flooding

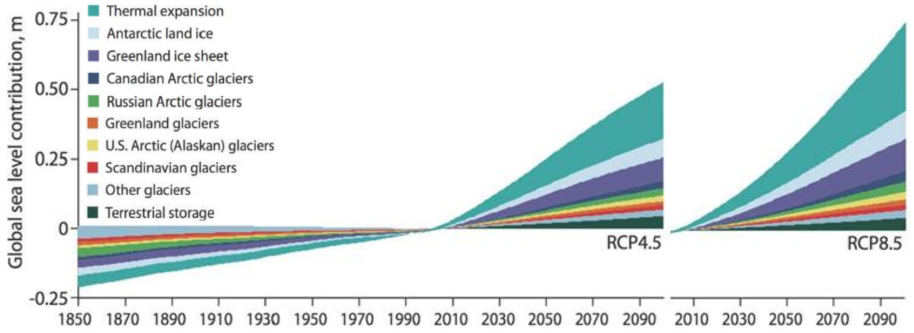
Projections – High capabilities

- Near-term global **sea level rise** already committed + local patterns of RSLR (land subsidence, uplift, ocean circulation, tides)
- Effect of SLR on storm surge levels is at least additive
- **Tropical cyclones** projected to become more intense (+1 to 10%) though may be fewer events projected globally
- Likely increase in **storm rainfall** rates (+10-15%) due to higher atmospheric moisture content

Uncertainties

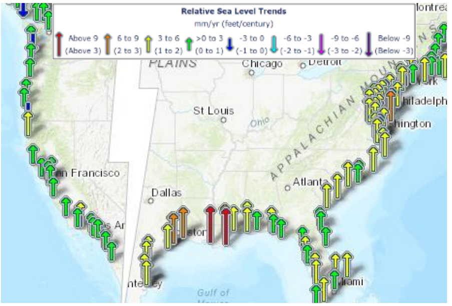
- Spatial pattern of tropical cyclones (by basin, storm path)

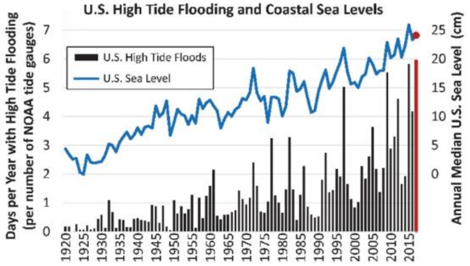




Flood Risk = Global SLR + VLM + local dynamics + storms

NCA4 Ch 2 Key Message 4:
Global SLR *very likely** to reach 0.3–0.6 feet (9–18 cm) by 2030, 0.5–1.2 feet (15–38 cm) by 2050
** 5-95th percentile* relative to 2000





High confidence in increased risk of coastal flooding

Sources: SWIPA Report, Arctic Monitoring Assessment Programme (top); Knutson et al. (2015, far left, © American Meteorological Society. Used with permission); NOAA RSL Laboratory for Satellite Altimetry (bottom middle); NOAA NCDC High Tide Flooding (bottom right)

Severe Storms: What does the science say?

Historical – Medium understanding

Temperature and extreme precipitation are increasing

- A higher % of precipitation falls as heavy precipitation
- Higher temperatures and greater humidity mean more convection
- Historical trends suggest increase in convective instability outweighs other confounding factors (e.g., reduced wind shear)

Projections – Low capabilities

Base processes of convection and cyclone formation are impacted by climate change…

- **Convective instability** increases with temperature and humidity
- Likely increase in **storm rainfall** rates (+10-15%) due to higher atmospheric moisture content

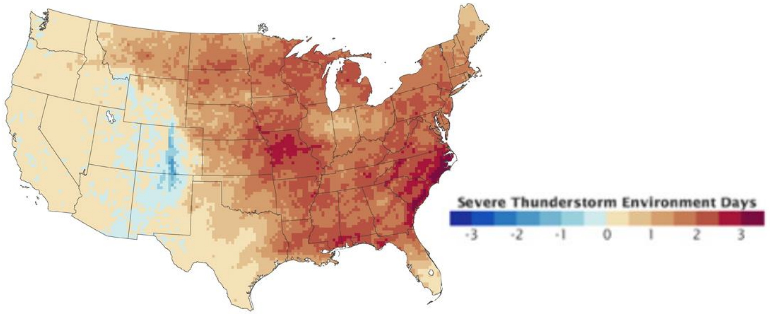
…but explicit modeling of convection remains a challenge

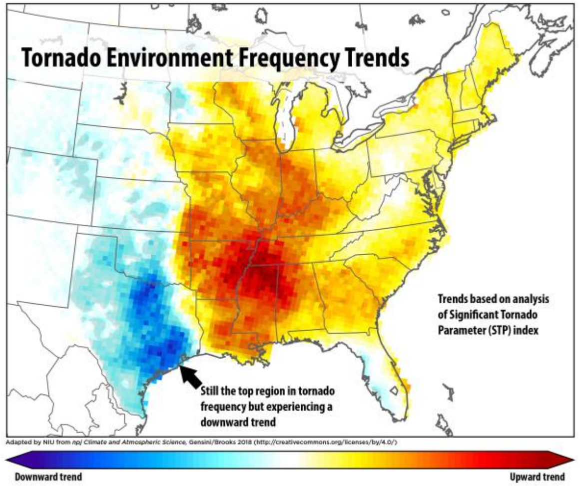
- GCM models rely on a high level of parameterization with much uncertainty
- Spatial resolution of models too coarse to represent many convection-related processes
- Simulation of convection-related processes like lightning or flash flooding not resolved in climate models

Uncertainties

- Parameterization of convection processes in GCMs
- Increase in reporting of extreme storms over the last century obscures trend detection
- Lightning also difficult to project due to coarse spatial scale of models

Projected change in summer severe thunderstorm environment days by late-century




Tornado Environment Frequency Trends

Trends based on analysis of Significant Tornado Parameter (STP) index

Still the top region in tornado frequency but experiencing a downward trend

Adapted by NIU from *npj Climate and Atmospheric Science*, Gensini/Brooks 2018 (http://creativecommons.org/licenses/by/4.0/)

Mixed understanding/confidence of severe storm changes

Sources: NASA Earth Observatory (top), Gensini & Brooks (2018, bottom)

Leveraging Machine Learning to Project Future Tornado Activity in the United States

EPRI

CLIMATE READi

Leveraging Machine Learning to Project Future Tornado Activity in the United States

READi Insights February 2025

KEY TAKEAWAYS

- Machine learning can effectively reproduce historical tornado patterns with limited inputs.
- The capability of machine learning to project future conditions is generally limited by the climate models representation of large-scale circulation patterns.
- Projections using machine learning suggest an increase in tornado activity in the Midwest and a shift in tornado timing toward early spring and winter.

INTRODUCTION

More than half of the power outages across the United States (U.S.) are estimated to have occurred from severe storms [1]. In fact, the United States records the highest number of annual tornado-related fatalities and property damage of any country in the world. Understanding current and future trends in tornado frequency, intensity, and geographic distribution is essential for quantifying risk and improving preparedness.

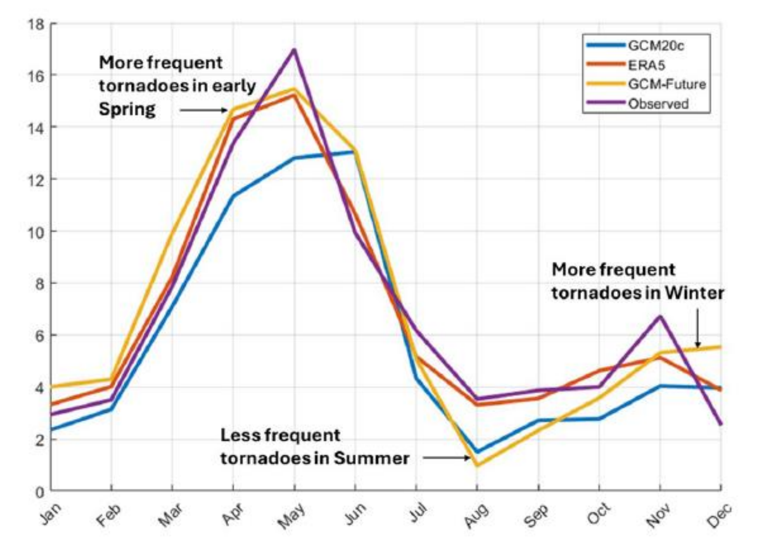
While the impact of climate change on temperature and precipitation are reasonably well understood, it's more difficult to project the effect of climate change on tornadoes. Tornadoes are far too small to be simulated directly by global climate models, and even the storms that produce them are not well-resolved by those models. But given their impact on power systems, it's worth exploring alternative methods that can be used to estimate potential changes to tornado patterns in a warmer world. One such approach is to leverage what climate models do well — simulate large scale circulation patterns — and link these patterns to small-scale phenomena, like tornadoes. This type of approach provides insight into the future likelihood of conditions favorable for tornado formation.

Climate READi's *Climate Data Gap Assessment* (3002030951) identified forward-looking information on tornadoes and other severe weather phenomena as a key climate data gap for the electric power sector. Through this research, EPRI and Kent State University collaborated to deploy a novel machine learning approach, synoptic typing, to understand how the large-scale atmospheric circulation patterns conducive for tornadoes may change in a warmer climate. Specifically, this approach classifies tornadic circulation patterns in the U.S. and predicts how the frequency of these patterns may change over time and across different regions.

Synoptic typically refers to large-scale weather patterns at a snapshot in time

HISTORICAL TORNADO TRENDS IN THE U.S

Since 1950, observational records show an increase in tornado frequency in the United States. But this increase is likely due to improved remote sensing technologies and the increase in infrastructure in previously remote places (Figure 1) [2]. In other words, tornado tracking has improved. Compared to weak



More frequent tornadoes in early Spring

Less frequent tornadoes in Summer

More frequent tornadoes in Winter

- Collaboration with Kent State University to apply a novel machine learning method to advance progress on a key climate data gap.
- Projections from this method suggest an increase in tornado activity in the Midwest, with a shift in tornado timing toward early spring and winter.

Contact Erik Smith (esmith@epri.com) for more information about the study.

Download here >>

Snow & Ice: What does the science say?

Historical – Medium understanding

Freezing rain frequency has increased in the Arctic and decreased in mid-latitudes in the Northern Hemisphere

- A warmer atmosphere generally shifts freezing rain poleward

Extreme snowfall trends are less clear

- Extreme snowfall more correlated with temperature than precipitation in the U.S.

Projections – Medium capability

Increase in warming reduces frequency of extreme cold events, but competing effects of temperature and precipitation make projection of ice events uncertain

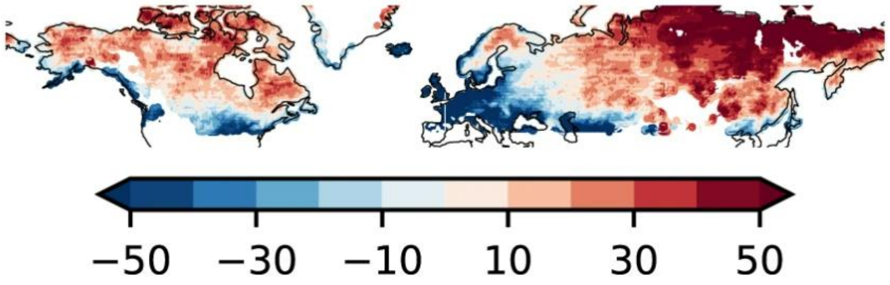
- Projections suggest the poleward shift of ice events will continue; e.g., more ice storms near the poles and fewer in the mid-latitudes
- Projections also suggest a potential increase in events during the winter and decrease in the spring and fall

Snowfall changes also uncertain

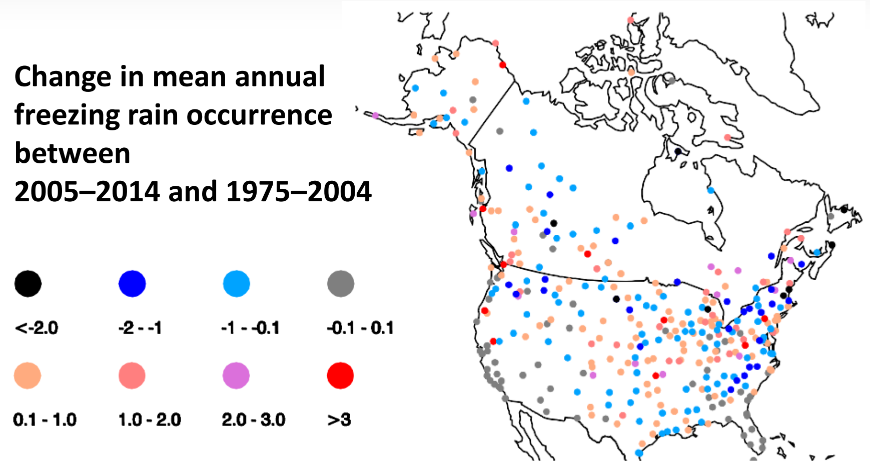
- Studies suggest annual snowfall totals will decrease in many areas, though they may increase near the poles
- Changes in extremes are more variable

Uncertainties

- Parameterization of convection processes in GCMs (as with other storms)
- Competing effects of temperature, precipitation, and humidity



Projected change in 99.9th percentile of daily snowfall between 2091-2100 and 1851-1920



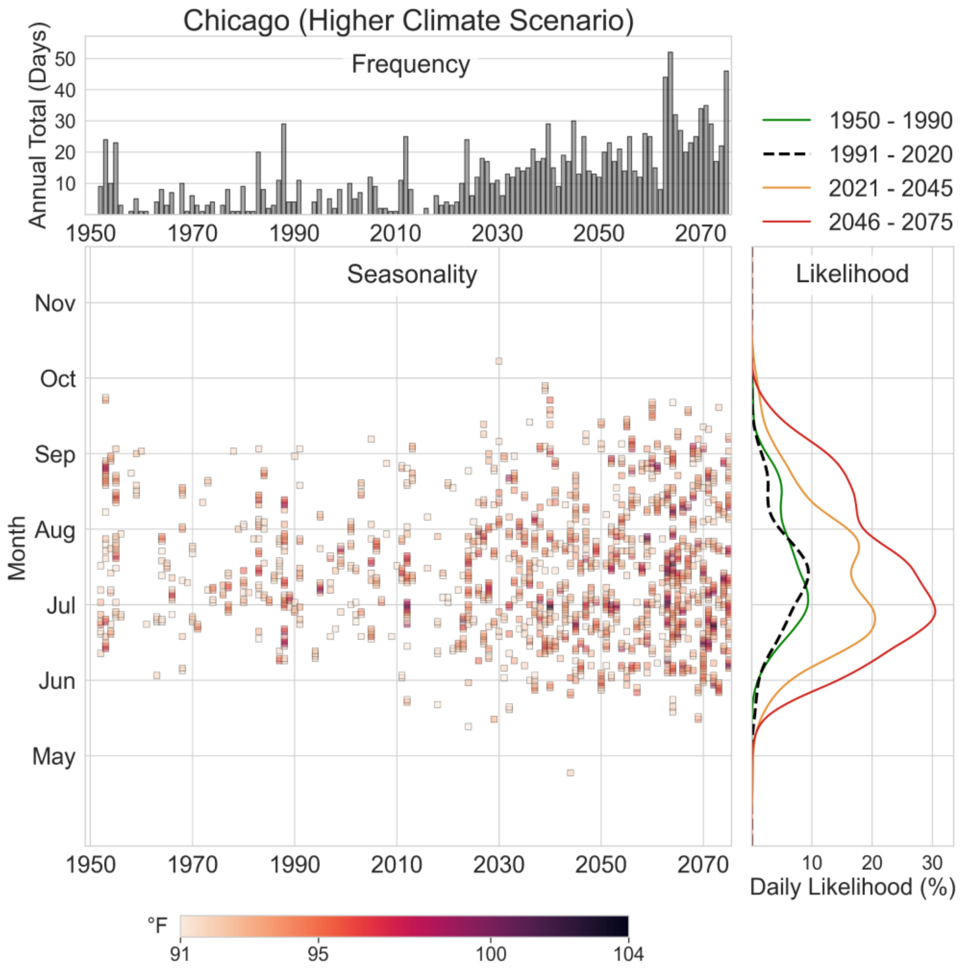
Change in mean annual freezing rain occurrence between 2005–2014 and 1975–2004

Medium understanding/confidence of snow & ice changes

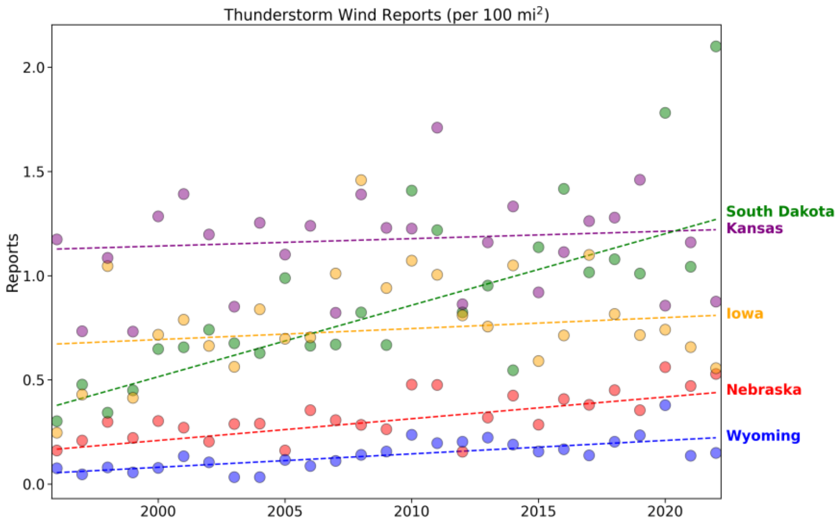
Sources: Quante et al. (2021, top); Groisman et al. (2016, bottom)

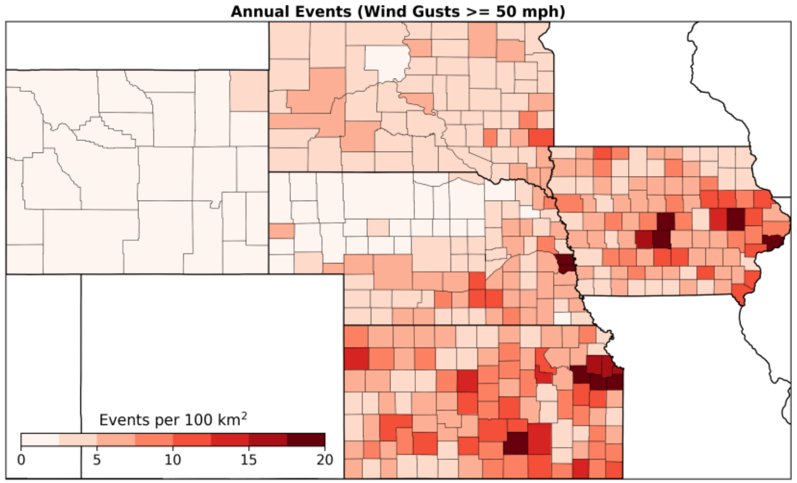
Example climate hazard assessments

Observed historical and simulated projected extreme heat events (95th percentile, 91°F/33°C)



Historical extreme wind events (gusts >=50 mph / 22 m/s)





Source: EPRI analysis of ERA5 and ISIMIP (left) and NOAA Storm Event Database (right)

Summary of potential climate hazards

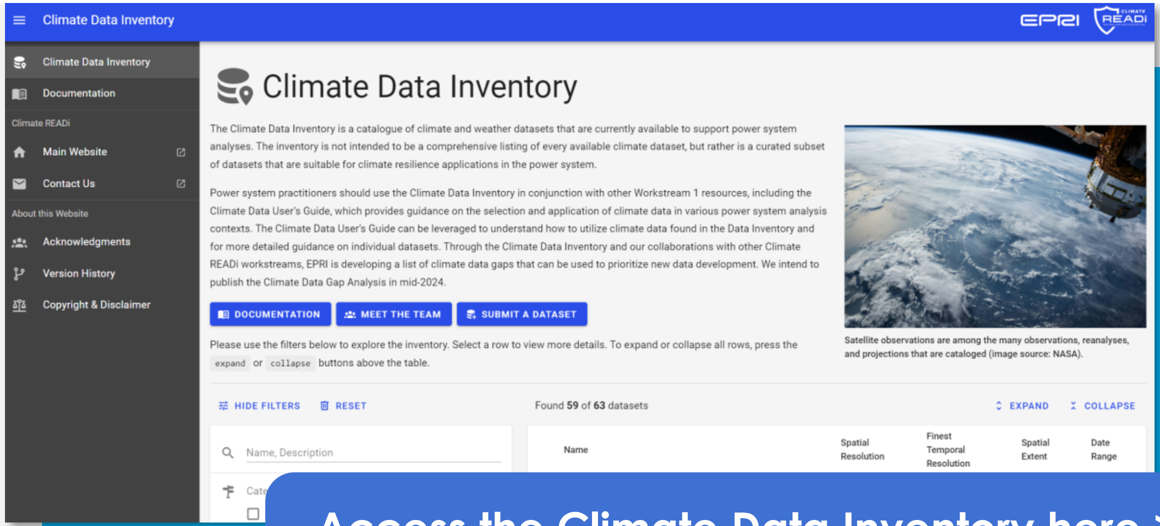
Climate Variable	Quality of Observational Record	Ability of Models to Simulate	Understanding of Physical Drivers of Changes	Confidence in Projected Changes
Air Temperature	High	High	High	High
Precipitation	High	Medium	Medium	Medium
Wind	Medium	Medium	Low	Medium
Solar	Medium	Medium	Medium	Medium
Drought (meteorological)	High	Medium	Medium	Medium
Wildfires	Medium	Low	Medium	Medium
Severe & Convective Storms	Low	Low	Low	Low
Hurricanes	Medium	Medium	Medium	Medium
Inland Flooding	Low	Low	Medium	Medium
Coastal Flooding	High	High	High	High

Tip for practical application

For some hazards, it may be difficult to complete an assessment or produce site-specific data. EPRI's Climate Data Gap Assessment can help companies explain why their evaluations of some hazards are more robust compared to others.

For more information on climate hazards, please see the Climate Data User Guide.

How to apply Physical Climate Data and Guidance resources



Climate Data Inventory

The Climate Data Inventory is a catalogue of climate and weather datasets that are currently available to support power system analyses. The inventory is not intended to be a comprehensive listing of every available climate dataset, but rather is a curated subset of datasets that are suitable for climate resilience applications in the power system.

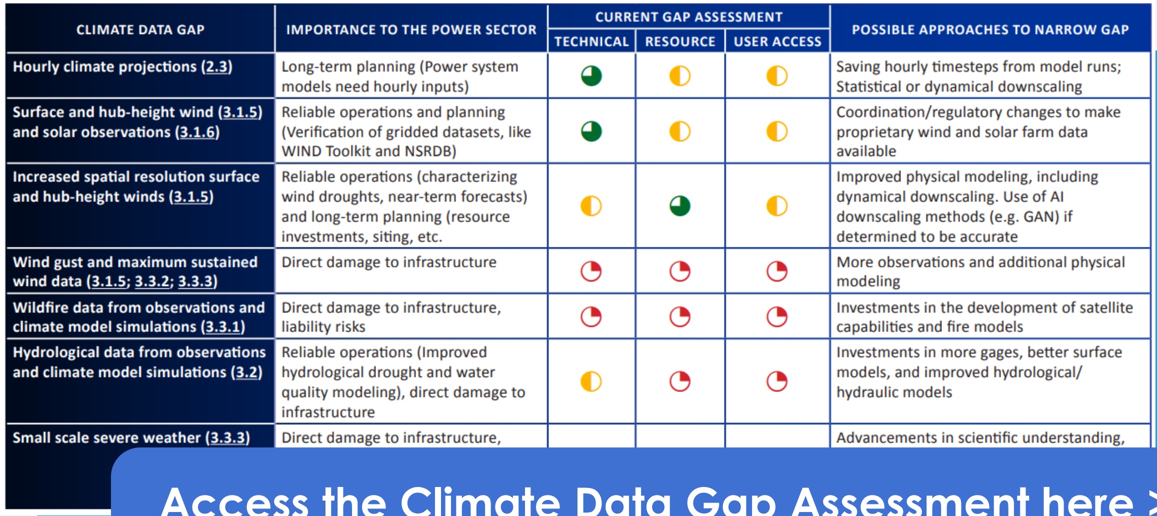
Power system practitioners should use the Climate Data Inventory in conjunction with other Workstream 1 resources, including the Climate Data User's Guide, which provides guidance on the selection and application of climate data in various power system analysis contexts. The Climate Data User's Guide can be leveraged to understand how to utilize climate data found in the Data Inventory and for more detailed guidance on individual datasets. Through the Climate Data Inventory and our collaborations with other Climate READi workstreams, EPRI is developing a list of climate data gaps that can be used to prioritize new data development. We intend to publish the Climate Data Gap Analysis in mid-2024.

Please use the filters below to explore the inventory. Select a row to view more details. To expand or collapse all rows, press the `expand` or `collapse` buttons above the table.

Satellite observations are among the many observations, reanalyses, and projections that are cataloged (image source: NASA).

Found **59** of **63** datasets

Access the Climate Data Inventory here >>



CLIMATE DATA GAP	IMPORTANCE TO THE POWER SECTOR	CURRENT GAP ASSESSMENT			POSSIBLE APPROACHES TO NARROW GAP
		TECHNICAL	RESOURCE	USER ACCESS	
Hourly climate projections (2.3)	Long-term planning (Power system models need hourly inputs)	◕	◐	◐	Saving hourly timesteps from model runs; Statistical or dynamical downscaling
Surface and hub-height wind (3.1.5) and solar observations (3.1.6)	Reliable operations and planning (Verification of gridded datasets, like WIND Toolkit and NSRDB)	◕	◐	◐	Coordination/regulatory changes to make proprietary wind and solar farm data available
Increased spatial resolution surface and hub-height winds (3.1.5)	Reliable operations (characterizing wind droughts, near-term forecasts) and long-term planning (resource investments, siting, etc.	◐	◕	◐	Improved physical modeling, including dynamical downscaling. Use of AI downscaling methods (e.g. GAN) if determined to be accurate
Wind gust and maximum sustained wind data (3.1.5; 3.3.2; 3.3.3)	Direct damage to infrastructure	◔	◔	◔	More observations and additional physical modeling
Wildfire data from observations and climate model simulations (3.3.1)	Direct damage to infrastructure, liability risks	◔	◔	◔	Investments in the development of satellite capabilities and fire models
Hydrological data from observations and climate model simulations (3.2)	Reliable operations (Improved hydrological drought and water quality modeling), direct damage to infrastructure	◐	◔	◔	Investments in more gages, better surface models, and improved hydrological/ hydraulic models
Small scale severe weather (3.3.3)	Direct damage to infrastructure,				Advancements in scientific understanding,

Access the Climate Data Gap Assessment here >>

1 Discover changes in relevant climate hazards

2 Identify suitable climate data. Justify data choices.

3 Generate climate data for other Framework activities

Climate READi's climate data resources facilitate more confident application of climate data.

Climate Data Gap Assessment

Download here.


CLIMATE READi
RESILIENCE AND ADAPTATION INITIATIVE
EPRI
TECHNICAL REPORT
CLIMATE DATA GAPS ASSESSMENT
September 2024

Gap Assessment

Provides a snapshot reference for the power sector to take stock of existing climate data gaps relevant to electricity sector planning and operations and characterizes present-day limitations impacting climate data.

Key Takeaways

Observational gaps linked to small volume of historical measurements and lack of public access to proprietary measurements.

Data gaps of climate model simulations at spatial scales are mostly driven by technical and resource constraints. Temporal gaps are driven more by misalignment of use cases and reconciling what data are needed with what data are possible.

Observational data on severe weather events are constrained by limited observations in the historical period. Climate model data for the phenomena are limited by the models’ relatively coarse spatial and temporal resolution.

Key Takeaways

Efforts to improve climate literacy in the power sector are valuable to improve understanding of available climate data and potential data applications.

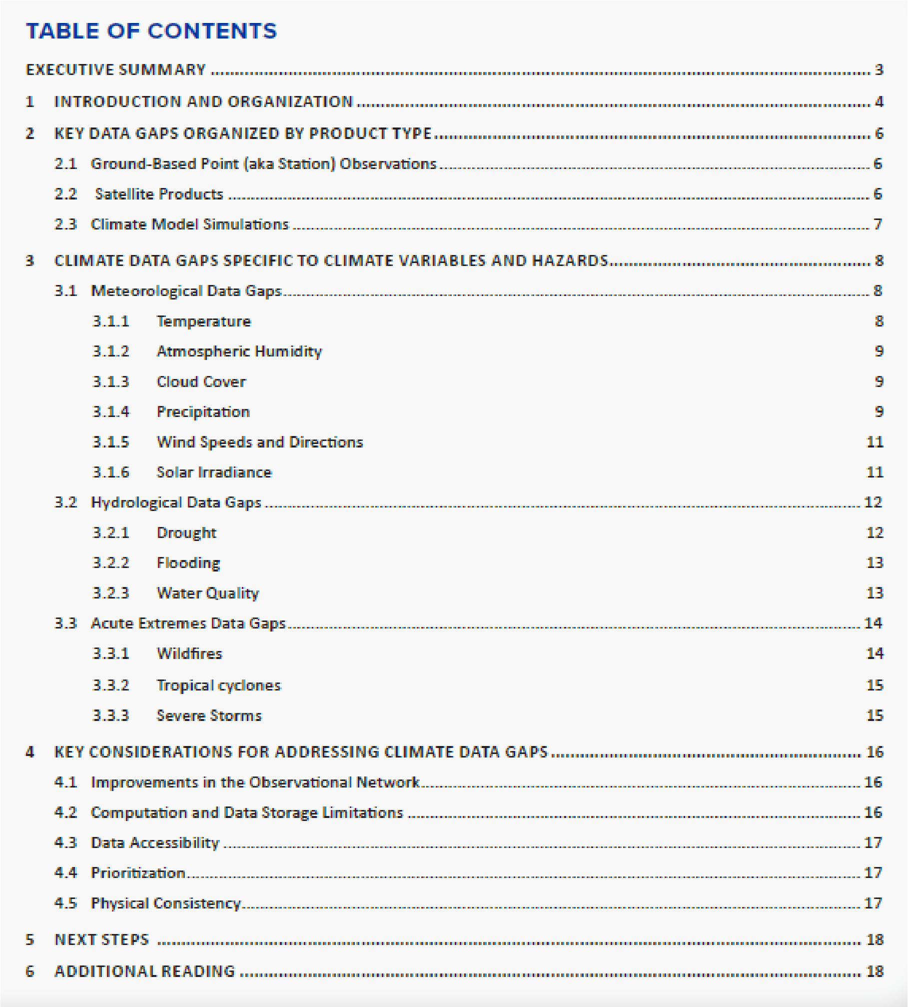
Collaborations between climate data providers and power system practitioners are ongoing.

Organizations seeking to assess climate risks should proactively engage relevant climate specialists rather than simply taking data/tools off the shelf and relying on a non-specialist to analyze them.

How to use the Climate Data Gap Assessment

Data gaps outlined by product type

Data gaps outlined by specific climate variable



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Informed Stakeholder Response

Respond to intervener or stakeholder inquiries on scope and limitations of your company’s hazard assessment

Research Dialogue

Identify strategic opportunities to support new climate data development

Confident Climate Data Application

Evaluate data availability for multiple climate variables and events

Climate data gaps have multiple drivers

01

Technical Gap

Advances in scientific understanding are needed to address the gap

02

Resource Gap

Observational equipment or computing power are needed to address the gap

03

User Access Gap

Barriers exist related to cost or effort needed to obtain and process data gaps

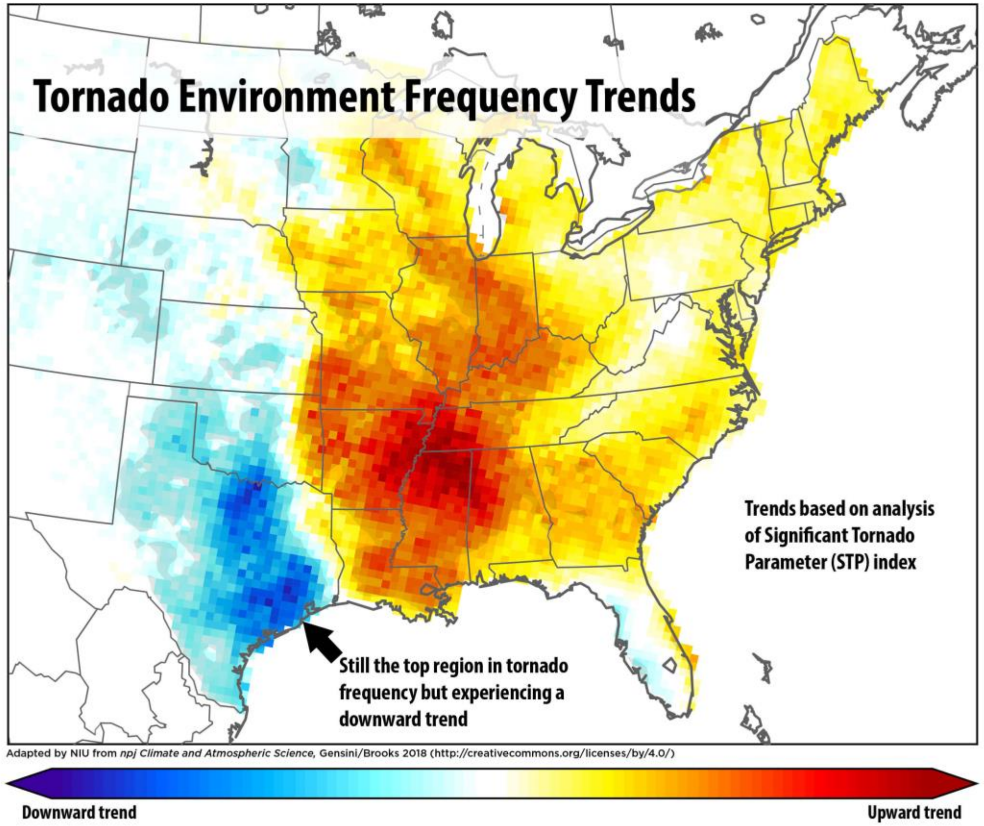
Climate data gaps have multiple drivers

Severe weather example

01

Technical Gap

Advances in scientific understanding are needed to address the gap



Adapted by NIU from *npj Climate and Atmospheric Science*, Gensini/Brooks 2018 (http://creativecommons.org/licenses/by/4.0/)

https://www.nature.com/articles/s41612-018-0048-2

Climate models generally don’t represent variables associated with severe weather because the temporal and spatial resolution are too coarse and there are many uncertainties associated with the small-scale processes that drive these phenomena.

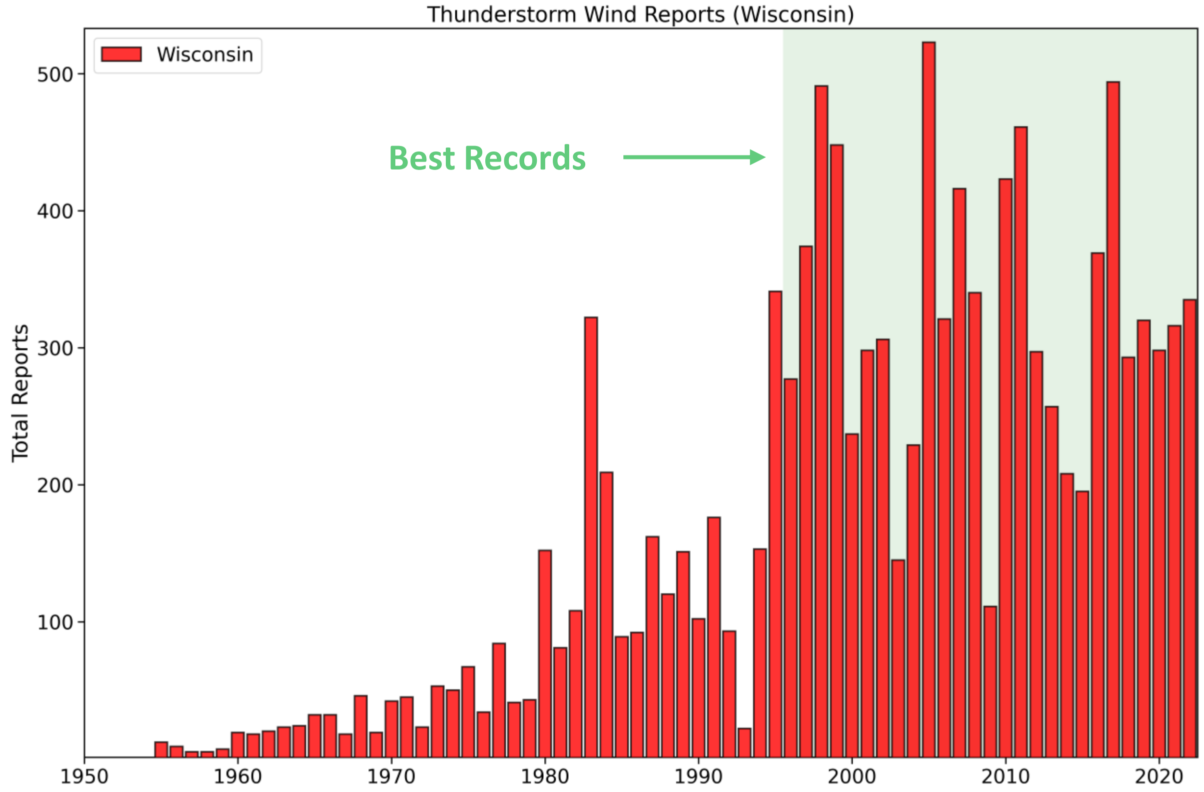
Climate data gaps have multiple drivers

Severe weather example

02

Resource Gap

Observational equipment or computing power are needed to address the gap



Source: EPRI analysis of NOAA storm event database

NOAA's Storm Event Database logs information on severe storms, including thunderstorms, hail/ice storms, and straight-line winds. Reporting criteria have changed over time with the best records available since 1996. Reports can be inconsistent across space and correlate with areas of high population.

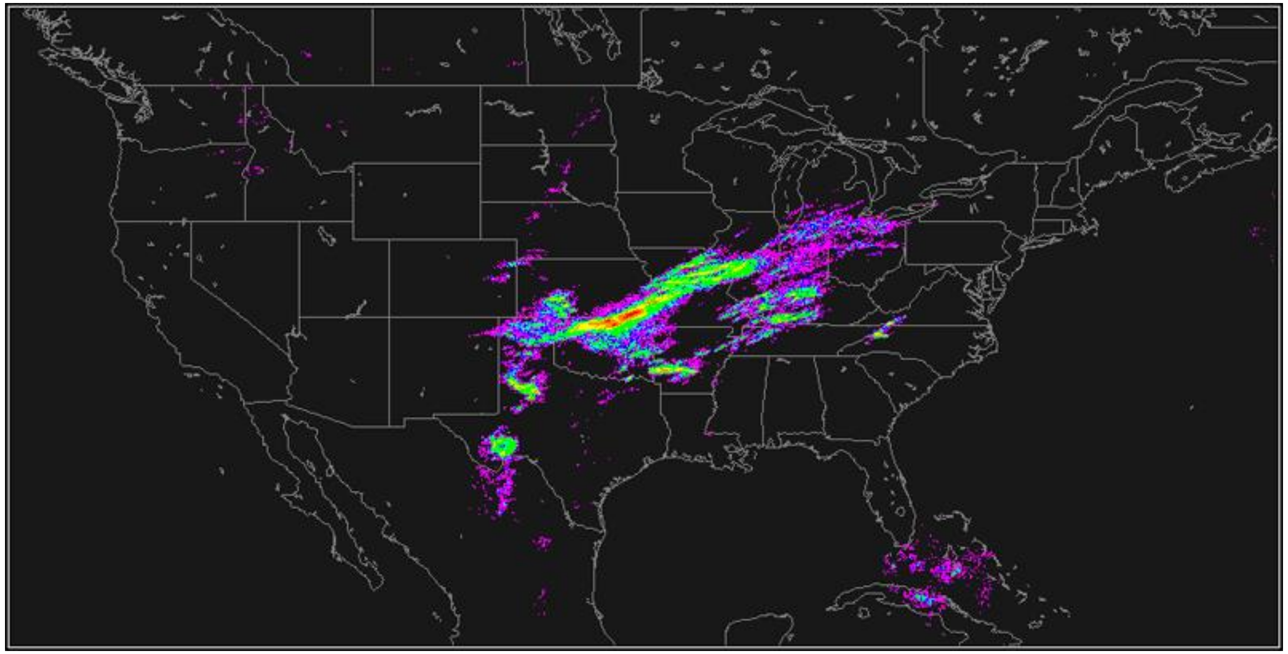
Climate data gaps have multiple drivers

Severe weather example

03

User Access Gap

Barriers exist related to cost or effort needed to obtain and process data gaps



Vaisala US NLDN Lightning Flash Data. Source: NASA GHRC: https://ghrc.nsstc.nasa.gov/home/lightning/index/data_nldn

Lightning data for the United States is available through the Vaisala National Lightning Detection Network (NLDN) since 1991. NOAA's Geospatial Lightning Mapper 7 is a recently launched satellite product (2017) designed to capture lightning strikes across much of North America.

Many characteristics of lightning, like intensity, are proprietary to the company Vaisala and not available to the public.

Selection of climate data gaps

CLIMATE DATA GAP	IMPORTANCE TO THE POWER SECTOR	CURRENT GAP ASSESSMENT			POSSIBLE APPROACHES TO NARROW GAP
		TECHNICAL	RESOURCE	USER ACCESS	
Hourly climate projections (2.3)	Long-term planning (Power system models need hourly inputs)	◕	◑	◑	Saving hourly timesteps from model runs; Statistical or dynamical downscaling
Surface and hub-height wind (3.1.5) and solar observations (3.1.6)	Reliable operations and planning (Verification of gridded datasets, like WIND Toolkit and NSRDB)	◕	◑	◑	Coordination/regulatory changes to make proprietary wind and solar farm data available
Increased spatial resolution surface and hub-height winds (3.1.5)	Reliable operations (characterizing wind droughts, near-term forecasts) and long-term planning (resource investments, siting, etc.	◑	◕	◑	Improved physical modeling, including dynamical downscaling. Use of AI downscaling methods (e.g. GAN) if determined to be accurate
Wind gust and maximum sustained wind data (3.1.5; 3.3.2; 3.3.3)	Direct damage to infrastructure	◔	◔	◔	More observations and additional physical modeling
Wildfire data from observations and climate model simulations (3.3.1)	Direct damage to infrastructure, liability risks	◔	◔	◔	Investments in the development of satellite capabilities and fire models
Hydrological data from observations and climate model simulations (3.2)	Reliable operations (Improved hydrological drought and water quality modeling), direct damage to infrastructure	◑	◔	◔	Investments in more gages, better surface models, and improved hydrological/ hydraulic models
Small scale severe weather (3.3.3)	Direct damage to infrastructure, reliable operations	◔	◔	◔	Advancements in scientific understanding, improvements in modeling conditions conducive to severe weather. Better industry reporting of severe weather impacts.

Selection of climate data gaps

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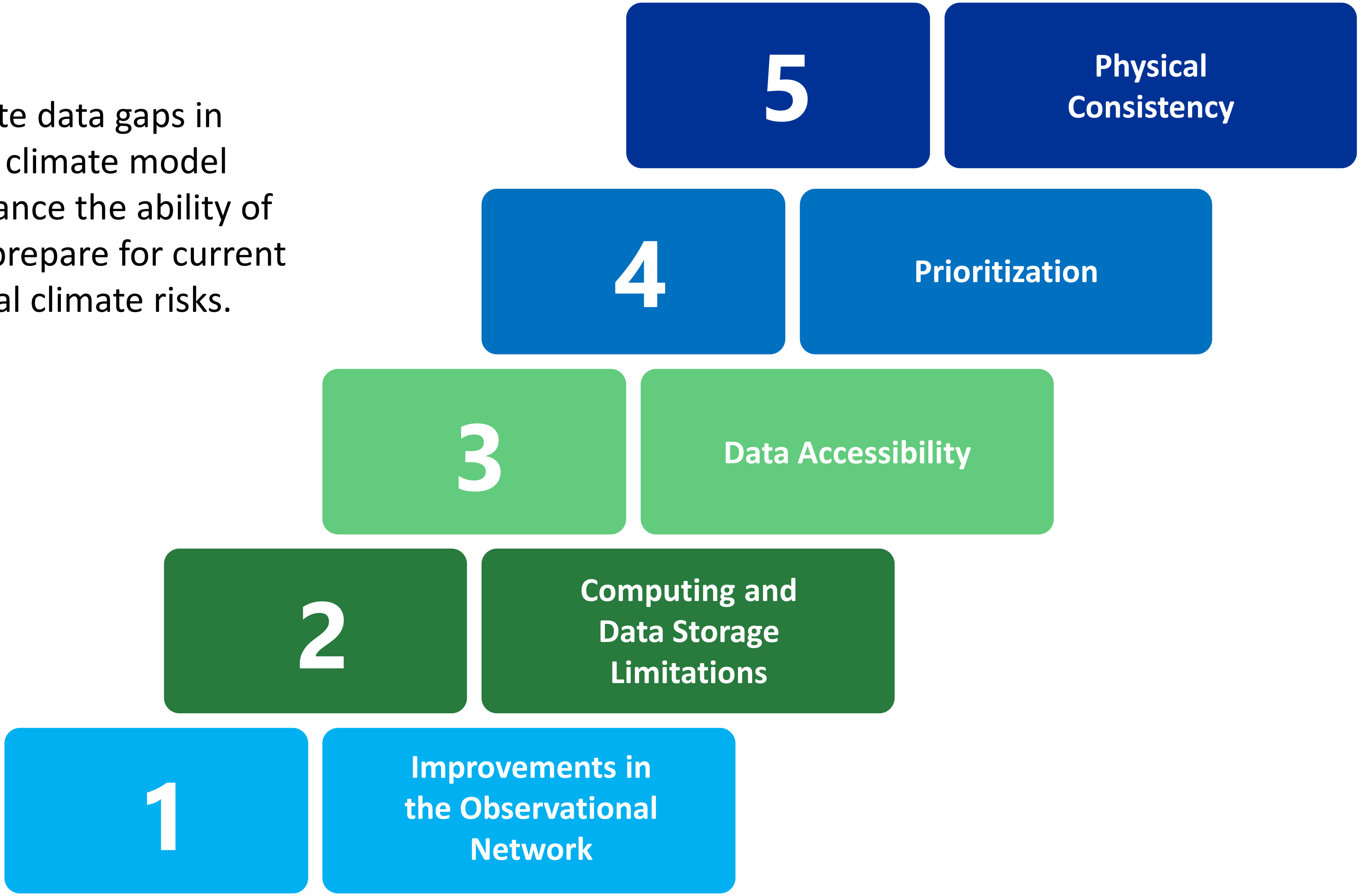
◕ Slight gap that can be overcome with modest effort or means

◐ Medium gap that requires concerted effort, institutional funding, or open-source access tools to overcome

◔ Major gap that requires transformational method, substantial collaborative funding, or innovative user tools to overcome

Key considerations for addressing climate data gaps

Addressing climate data gaps in observations and climate model simulations can advance the ability of the power sector to prepare for current and future physical climate risks.



5 **Physical Consistency**

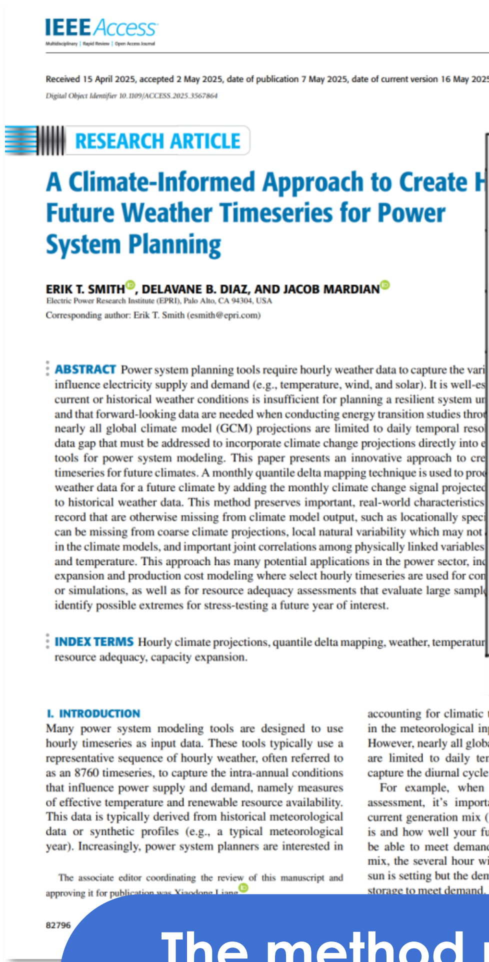
4 **Prioritization**

3 **Data Accessibility**

2 **Computing and Data Storage Limitations**

1 **Improvements in the Observational Network**

How to apply Physical Climate Data and Guidance resources



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RESEARCH ARTICLE

A Climate-Informed Approach to Create H
Future Weather Timeseries for Power
System Planning

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ABSTRACT Power system planning tools require hourly weather data to capture the vari
influence electricity supply and demand (e.g., temperature, wind, and solar). It is well-es
current or historical weather conditions is insufficient for planning a resilient system ur
and that forward-looking data are needed when conducting energy transition studies thro
nearly all global climate model (GCM) projections are limited to daily temporal reso
data gap that must be addressed to incorporate climate change projections directly into e
tools for power system modeling. This paper presents an innovative approach to cre
timeseries for future climates. A monthly quantile delta mapping technique is used to pro
weather data for a future climate by adding the monthly climate change signal projected
to historical weather data. This method preserves important, real-world characteristics
record that are otherwise missing from climate model output, such as locationally speci
can be missing from coarse climate projections, local natural variability which may not
in the climate models, and important joint correlations among physically linked variables
and temperature. This approach has many potential applications in the power sector, in
expansion and production cost modeling where select hourly timeseries are used for con
or simulations, as well as for resource adequacy assessments that evaluate large sampl
identify possible extremes for stress-testing a future year of interest.

INDEX TERMS Hourly climate projections, quantile delta mapping, weather, temperatur
resource adequacy, capacity expansion.

I. INTRODUCTION

Many power system modeling tools are designed to use hourly timeseries as input data. These tools typically use a representative sequence of hourly weather, often referred to as an 8760 timeseries, to capture the intra-annual conditions that influence power supply and demand, namely measures of effective temperature and renewable resource availability. This data is typically derived from historical meteorological data or synthetic profiles (e.g., a typical meteorological year). Increasingly, power system planners are interested in accounting for climatic trends and potential extreme events in the meteorological inputs to their simulation models [1]. However, nearly all global climate model (GCM) projections are limited to daily temporal resolution, which does not capture the diurnal cycle critical for power system planning.

For example, when conducting a resource adequacy assessment, it's important to know how sufficient your current generation mix (wind, solar, gas, coal, nuclear, etc.) is and how well your future proposed generation mix may be able to meet demand. If transitioning to a solar heavy mix, the several hour window after peak heating where the sun is setting but the demand is still high will require battery storage to meet demand. It would be impossible to accurately

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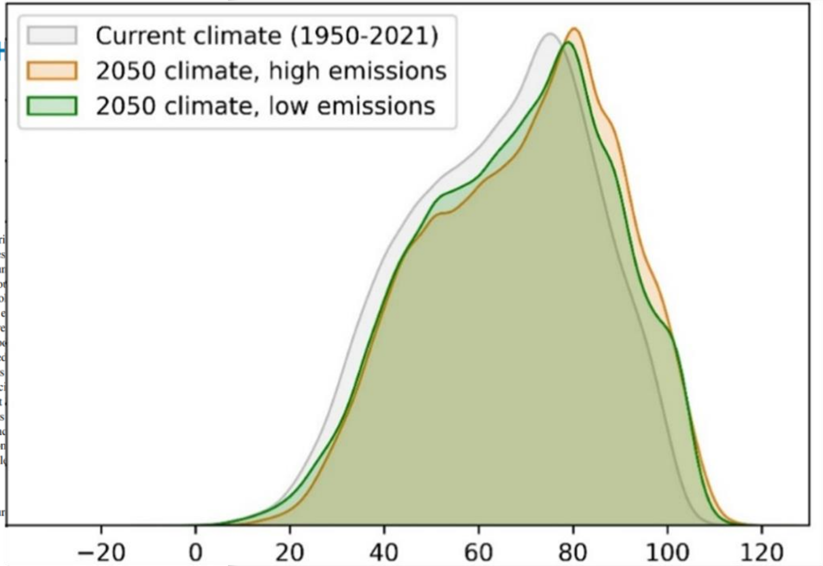


Source: *Climate READi Texas Case Study Story Map*

The method produces forward-looking climate data at hourly temporal resolution, suitable for use in power system models.

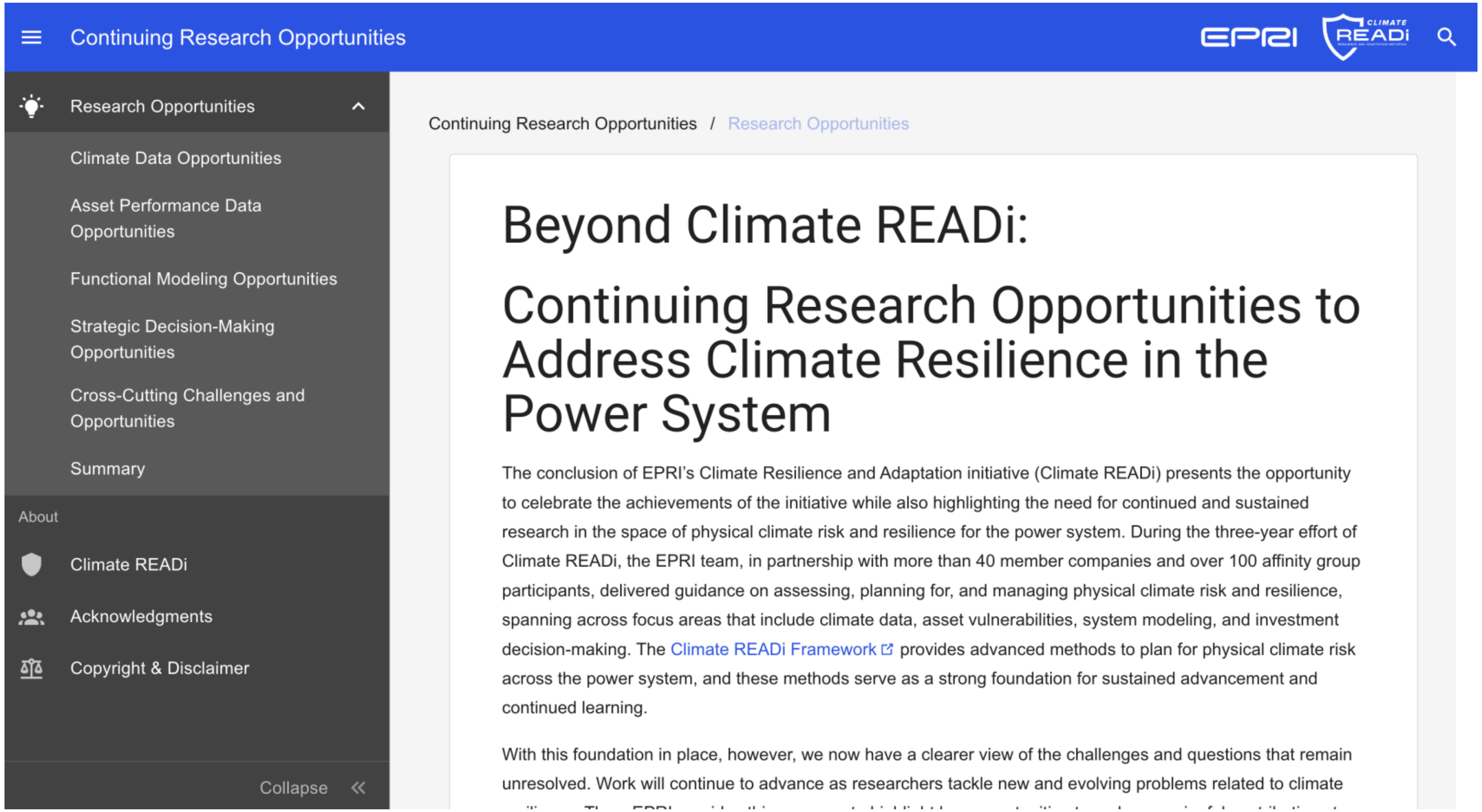
1 Discover changes in relevant climate hazards

2 Identify suitable climate data. Justify data choices.

3 Generate climate data for other Framework activities

Through Climate READi, EPRI developed an innovative approach for creating physically consistent, climate change-adjusted hourly meteorological datasets.

Climate READi Continuing Research Opportunities



Beyond Climate READi:

Continuing Research Opportunities to Address Climate Resilience in the Power System

The conclusion of EPRI's Climate Resilience and Adaptation initiative (Climate READi) presents the opportunity to celebrate the achievements of the initiative while also highlighting the need for continued and sustained research in the space of physical climate risk and resilience for the power system. During the three-year effort of Climate READi, the EPRI team, in partnership with more than 40 member companies and over 100 affinity group participants, delivered guidance on assessing, planning for, and managing physical climate risk and resilience, spanning across focus areas that include climate data, asset vulnerabilities, system modeling, and investment decision-making. The Climate READi Framework provides advanced methods to plan for physical climate risk across the power system, and these methods serve as a strong foundation for sustained advancement and continued learning.

With this foundation in place, however, we now have a clearer view of the challenges and questions that remain unresolved. Work will continue to advance as researchers tackle new and evolving problems related to climate

https://apps.epri.com/climate-readi-research-opportunities/

Today's Agenda

Motivations

- Regulators and state energy offices are being asked to evaluate analyses and investment justifications built on complex climate data.
- Climate READi resources can help decision-makers understand what climate data are available, how they should (and should not) be used for power system planning, and where important gaps remain.
- Participants will gain practical insight into:
  - Interpreting climate data and modeling in utility filings
  - Setting realistic expectations around uncertainty and extremes
  - Identifying priority areas for future data and research investments that support resilient, reliable energy systems

Relevance of Climate READi for state energy officials

Introduction to Climate READi Framework

Key insights from Climate READi climate data resources

Discussion and Q&A

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