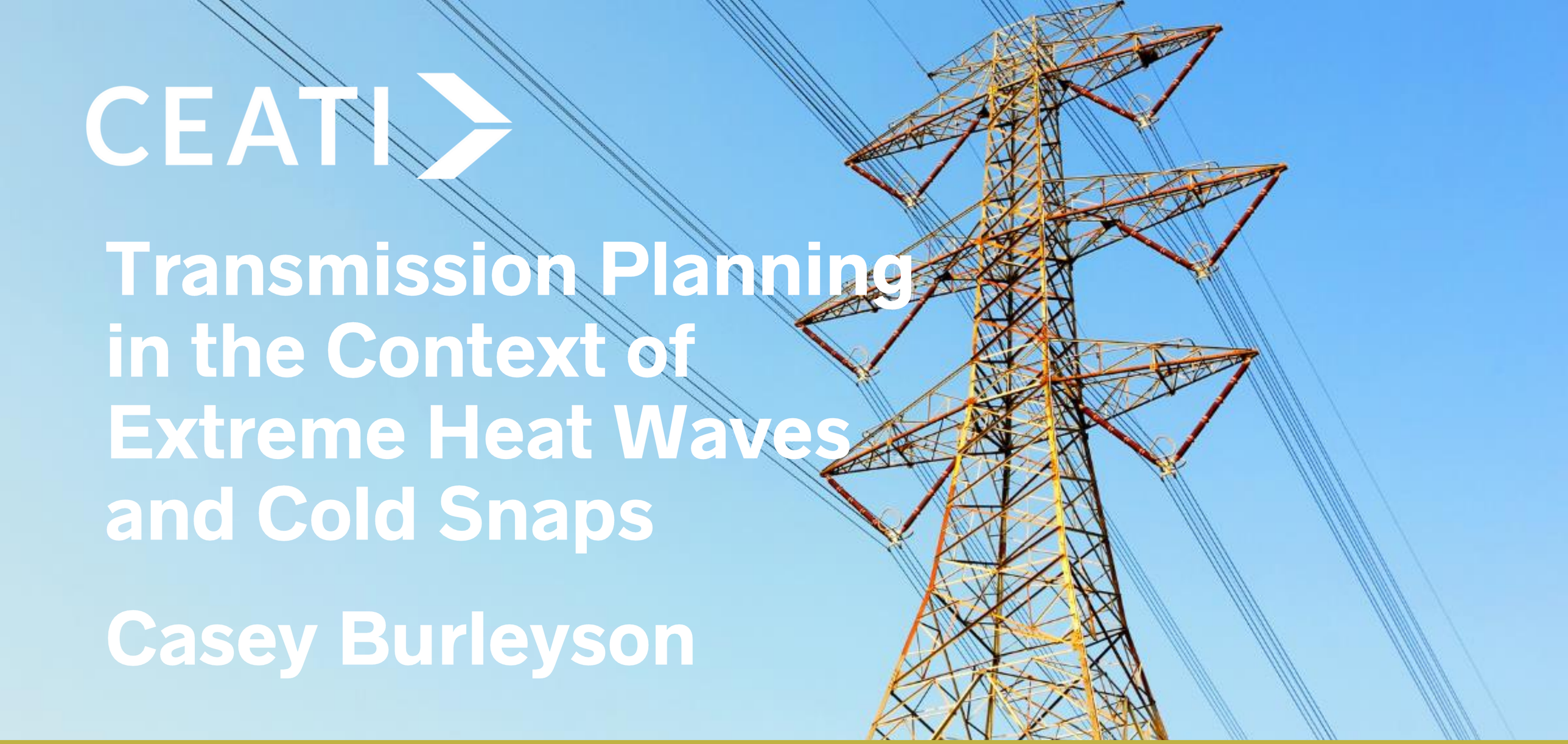


CEATI

Transmission Planning in the Context of Extreme Heat Waves and Cold Snaps

Casey Burleyson

2026 TRANSMISSION & DISTRIBUTION CONFERENCE

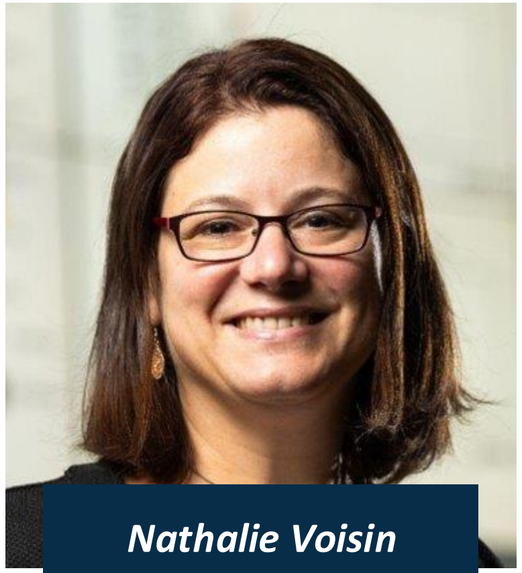
Pacific Northwest
NATIONAL LABORATORY

MEET THE PRESENTERS



Casey Burleyson
Principal Scientist
PNNL

A meteorologist by training, Casey's research focuses on understanding weather impacts on energy systems and long-term grid planning.



Nathalie Voisin
Chief Scientist
PNNL

Nathalie is the Chief Scientist for Regional Climate-Energy Dynamics in the Earth System Predictability group.

Pacific Northwest
NATIONAL LABORATORY

TEAM

- Heng Wan, PNNL
- Osten Anderson, PNNL
- Cameron Bracken, PNNL

CEATI

WHAT WE WILL BE COVERING

- Stress testing: Reliability assurance practices call for using historical events to "stress test" projected infrastructure.
- Event selection: Events from libraries of heat waves and cold snaps evoke diverse grid responses.
- Ranking events: Methods for ranking events by temperature or load do not translate to high rankings for other stress metrics such as dependence on imports.
- Case studies: Events with similar temperatures and loads can produce diverse outcomes based on seasonal resource availability, spatial extent, and duration.
- Data sharing: We are making our data available to support utilities in selecting events for stress testing.

Motivation: NERC TPL-008-1

"The purpose of the TPL-008-1 standard is to establish transmission system planning performance requirements to develop a Bulk Power System (BPS) that will operate reliably during extreme heat and extreme cold temperature events."



R2. Each Planning Coordinator shall identify the zone(s) to which the Planning Coordinator belongs to under Attachment 1 and shall coordinate with all Planning Coordinators within each of its identified zone(s), to identify one common extreme heat benchmark temperature event and one common extreme cold benchmark temperature event for each of its identified zone(s) when completing the Extreme Temperature Assessment. The benchmark temperature events shall be obtained from the benchmark library maintained by the ERO or developed by the Planning Coordinators. Each benchmark temperature event identified by the Planning Coordinators shall: *[Violation Risk Factor: High] [Time Horizon: Long-term Planning]*

2.1. Consider no less than a 40-year period of temperature data ending no more than five years prior to the time the benchmark temperature events are selected; and

2.2. Represent one of the 20 most extreme temperature conditions based on the three-day rolling average of daily maximum (heat) or daily minimum (cold) temperature across the zone.

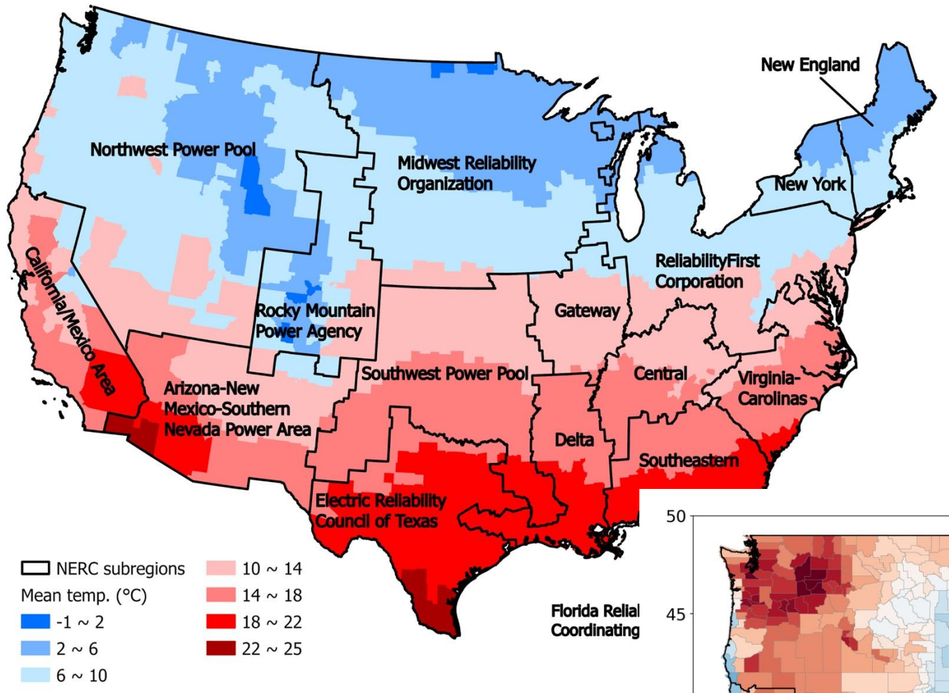
Motivation: NERC TPL-008-1

"The purpose of the TPL-008-1 standard is to establish transmission system planning performance requirements to develop a Bulk Power System (BPS) that will operate reliably during extreme heat and extreme cold temperature events."

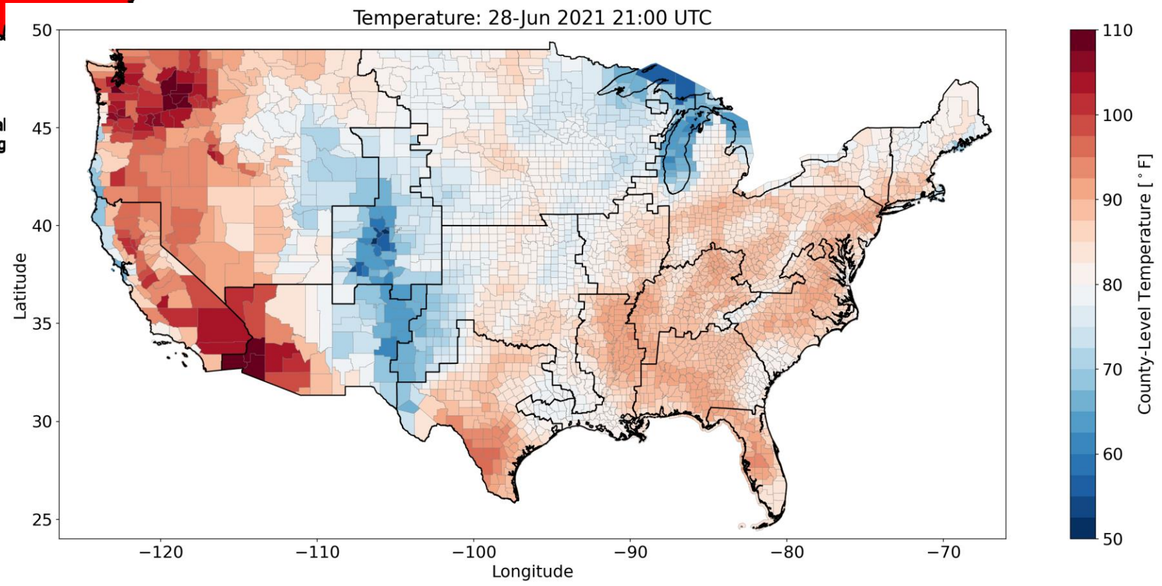
Topic One: Does it matter how you define heat waves and cold snaps for use in reliability assessments?

Topic Two: Does it matter which events you select from among the top-20 heat waves or cold snaps?

We leverage a large historical meteorology dataset

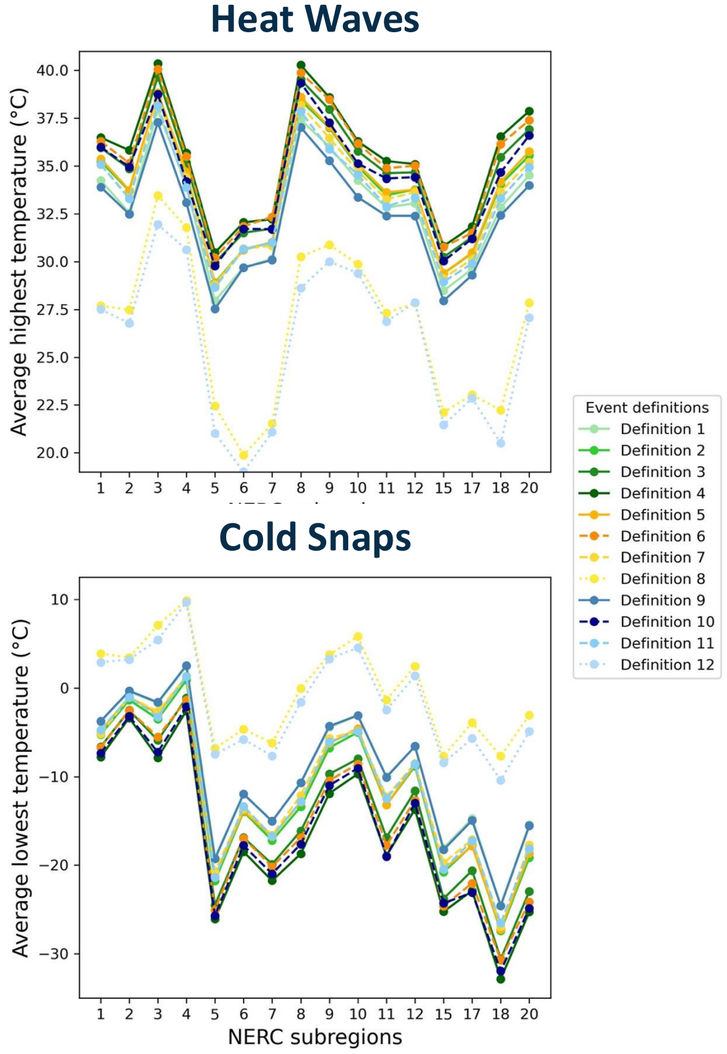


Reuse this data!



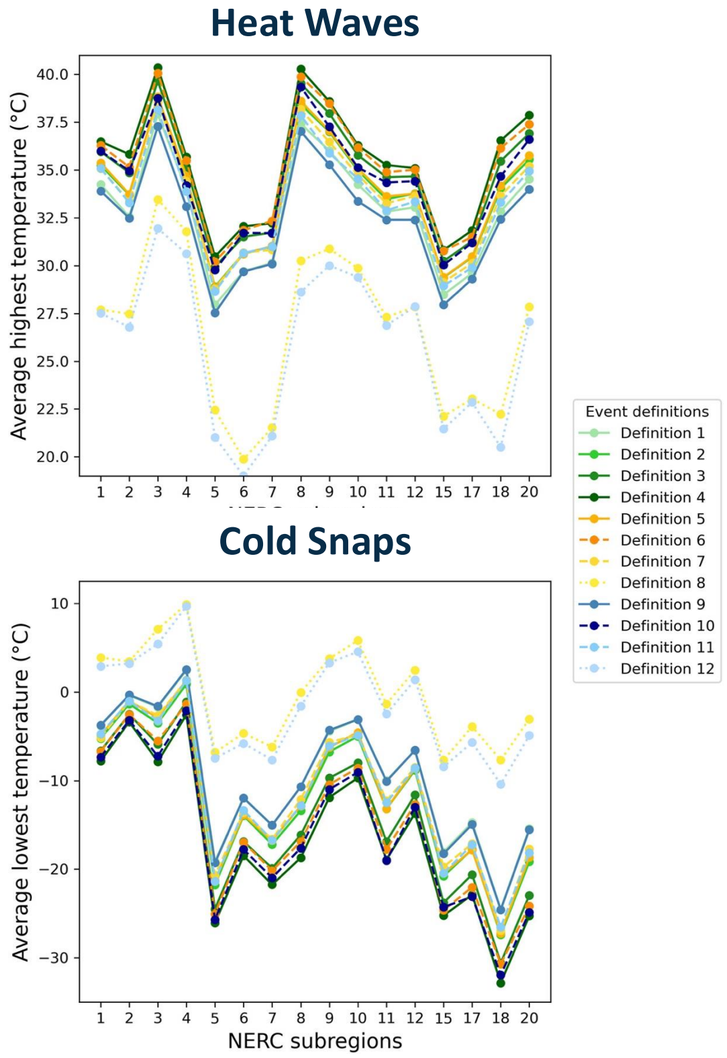
- Historic data reproduces observed sequence of past events (1980–2025)
- 1/8 deg (12 km) resolution over the U.S.
- 25 hourly and 250+ three-hourly variables
- Output is first spatially-averaged by county then population-weighted to create annual 8760-hr meteorology time series for each region

Topic One: Comparing event definitions



	Temperature Metric	Heat Wave Threshold	Cold Snap Threshold	Duration	References
Def 1	Daily mean	> 90th percentile	< 10th percentile	2+ consecutive days	Anderson and Bell, 2011
Def 2	Daily mean	> 95th percentile	< 5th percentile	2+ consecutive days	Anderson and Bell, 2011; Barnett et al., 2012
Def 3	Daily mean	> 98th percentile	< 2nd percentile	2+ consecutive days	Anderson and Bell, 2011; Barnett et al., 2012
Def 4	Daily mean	> 99th percentile	< 1st percentile	2+ consecutive days	Anderson and Bell, 2011; Barnett et al., 2012
Def 5	Daily maximum	> 95th percentile	< 5th percentile	2+ consecutive days	Anderson and Bell, 2011
Def 6	Daily maximum	T1 > 97.5th percentile; T2 > 81st percentile	T1 < 2.5th percentile; T2 < 19th percentile	Everyday > T2; 3+ consecutive days > T1; Average Tmax > T1 for whole period	Peng et al., 2011; Meehl and Tebaldi, 2004
Def 7	Daily maximum	T1 > 90th percentile; T2 > 75th percentile	T1 < 10th percentile; T2 < 25th percentile	Everyday > T2; 3+ consecutive days > T1; Average Tmax > T1 for whole period	Lau and Nath, 2014; Luo and Lau, 2017
Def 8	Daily maximum	> 90th percentile (15-day moving window)	< 10th percentile (15-day moving window)	3+ consecutive days	Chen and Zhai, 2017
Def 9	Daily minimum	> 95th percentile	< 5th percentile	2+ consecutive days	Anderson and Bell, 2011
Def 10	Daily minimum	T1 > 97.5th percentile; T2 > 81st percentile	T1 < 2.5th percentile; T2 < 19th percentile	Everyday > T2; 3+ consecutive days > T1; Average Tmin > T1 for whole period	Liao et al., 2018
Def 11	Daily minimum	T1 > 90th percentile; T2 > 75th percentile	T1 < 10th percentile; T2 < 25th percentile	Everyday > T2; 3+ consecutive days > T1; Average Tmin > T1 for whole period	Liao et al., 2018
Def 12	Daily minimum	> 90th percentile (15-day moving window)	< 10th percentile (15-day moving window)	3+ consecutive days	Chen and Zhai, 2017

Topic One: Comparing event definitions

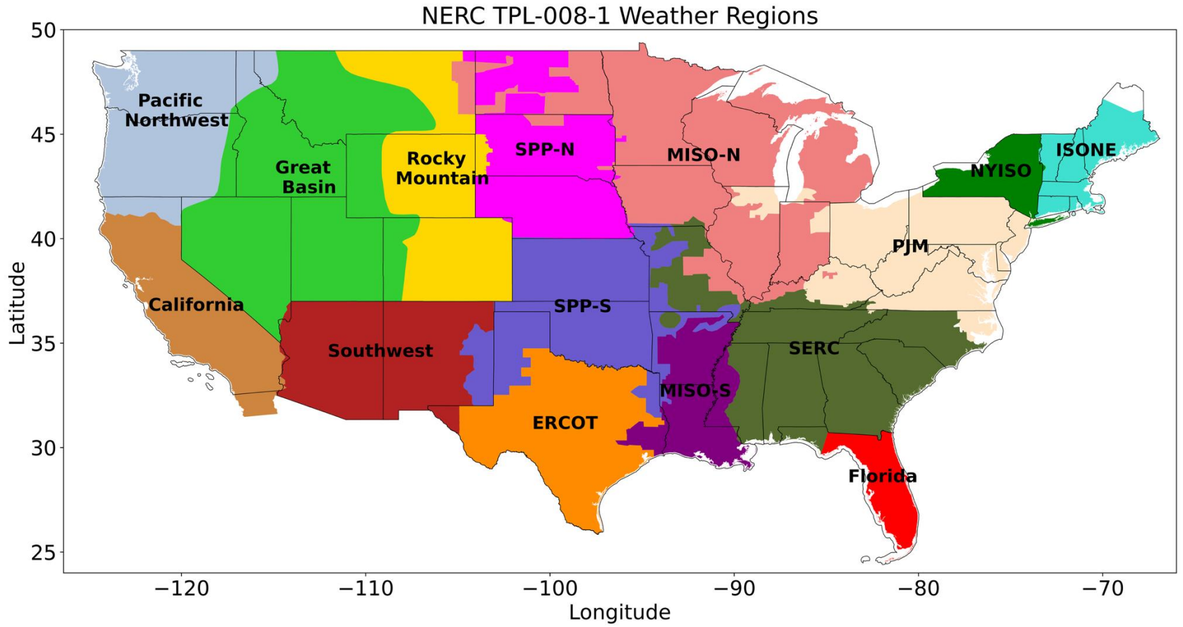


Key Results

- Definitions with looser thresholds tend to produce higher event frequencies and broader spatial coverage, but not necessarily longer event durations.
- Definitions have minimal impact on the overall ranking (e.g., top-20) of extreme events. All definitions find mostly the same ”most extreme” events.

Topic Two: Selecting stress events

Topic Two: Does it matter which events you select from among the top-20 heat waves or cold snaps?

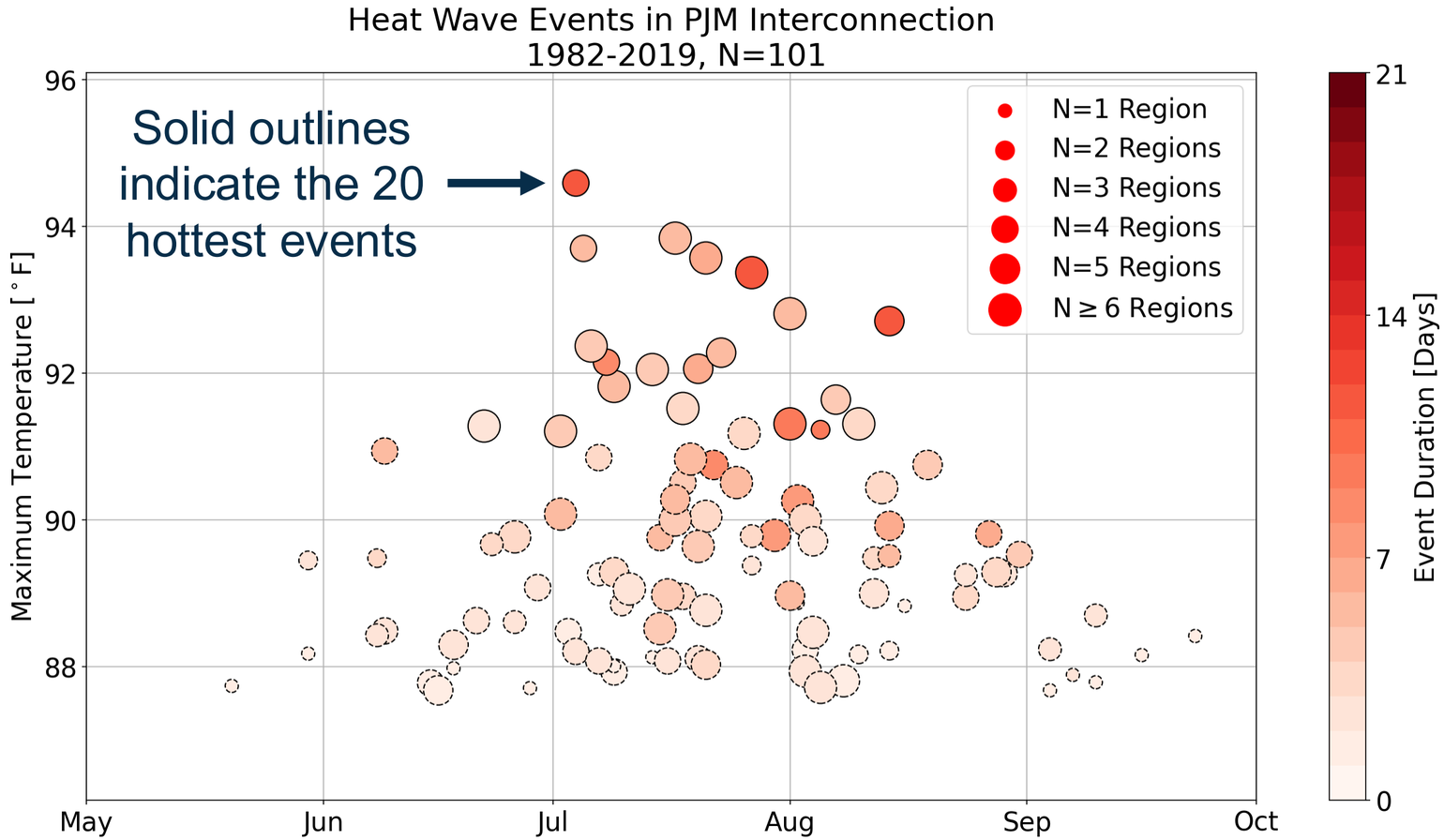


R2. Each Planning Coordinator shall identify the zone(s) to which the Planning Coordinator belongs to under Attachment 1 and shall coordinate with all Planning Coordinators within each of its identified zone(s), to identify one common extreme heat benchmark temperature event and one common extreme cold benchmark temperature event for each of its identified zone(s) when completing the Extreme Temperature Assessment. The benchmark temperature events shall be obtained from the benchmark library maintained by the ERO or developed by the Planning Coordinators. Each benchmark temperature event identified by the Planning Coordinators shall: *[Violation Risk Factor: High] [Time Horizon: Long-term Planning]*

2.1. Consider no less than a 40-year period of temperature data ending no more than five years prior to the time the benchmark temperature events are selected; and

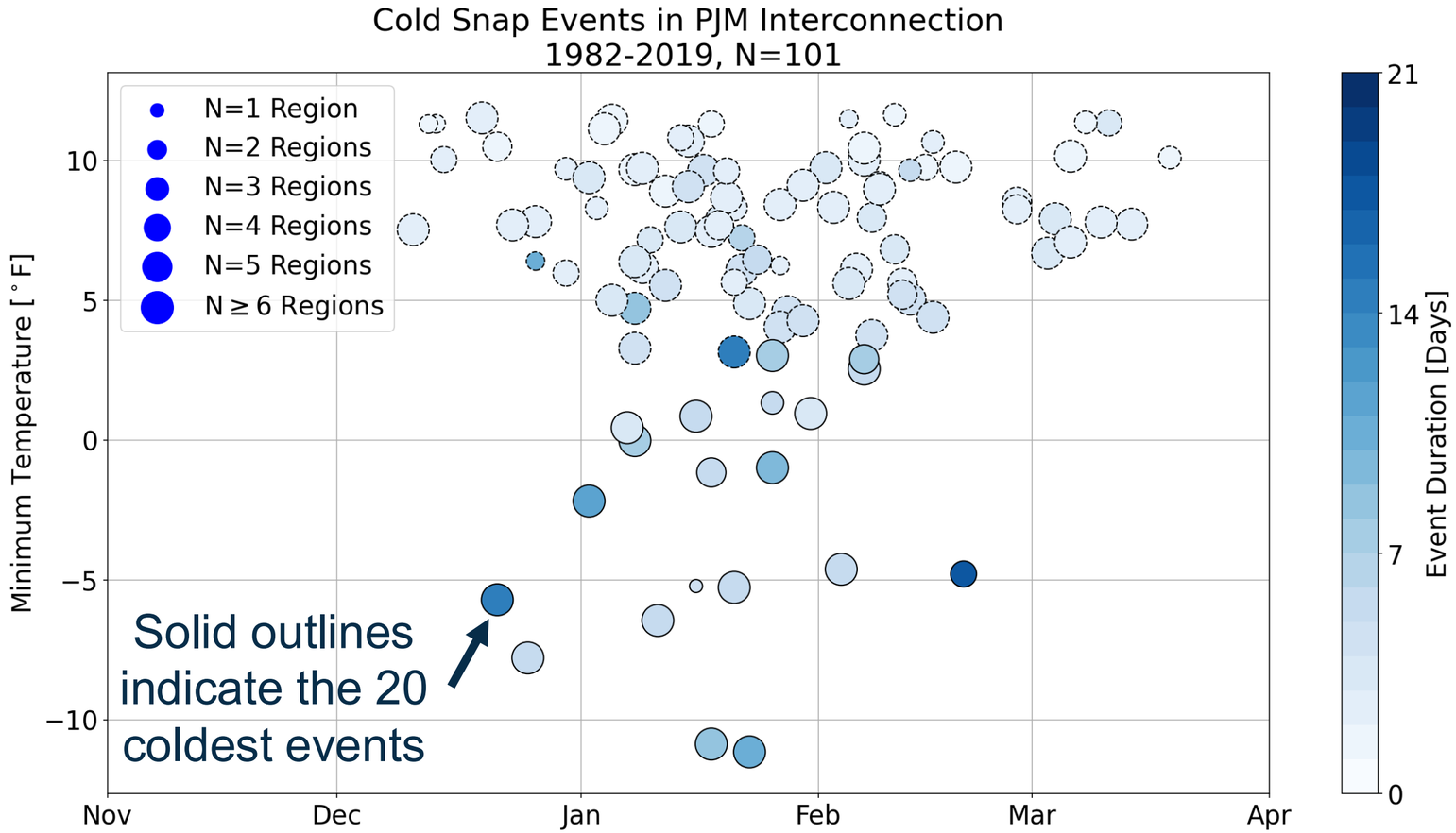
2.2. Represent one of the 20 most extreme temperature conditions based on the three-day rolling average of daily maximum (heat) or daily minimum (cold) temperature across the zone.

We built historical heat wave and cold snap libraries



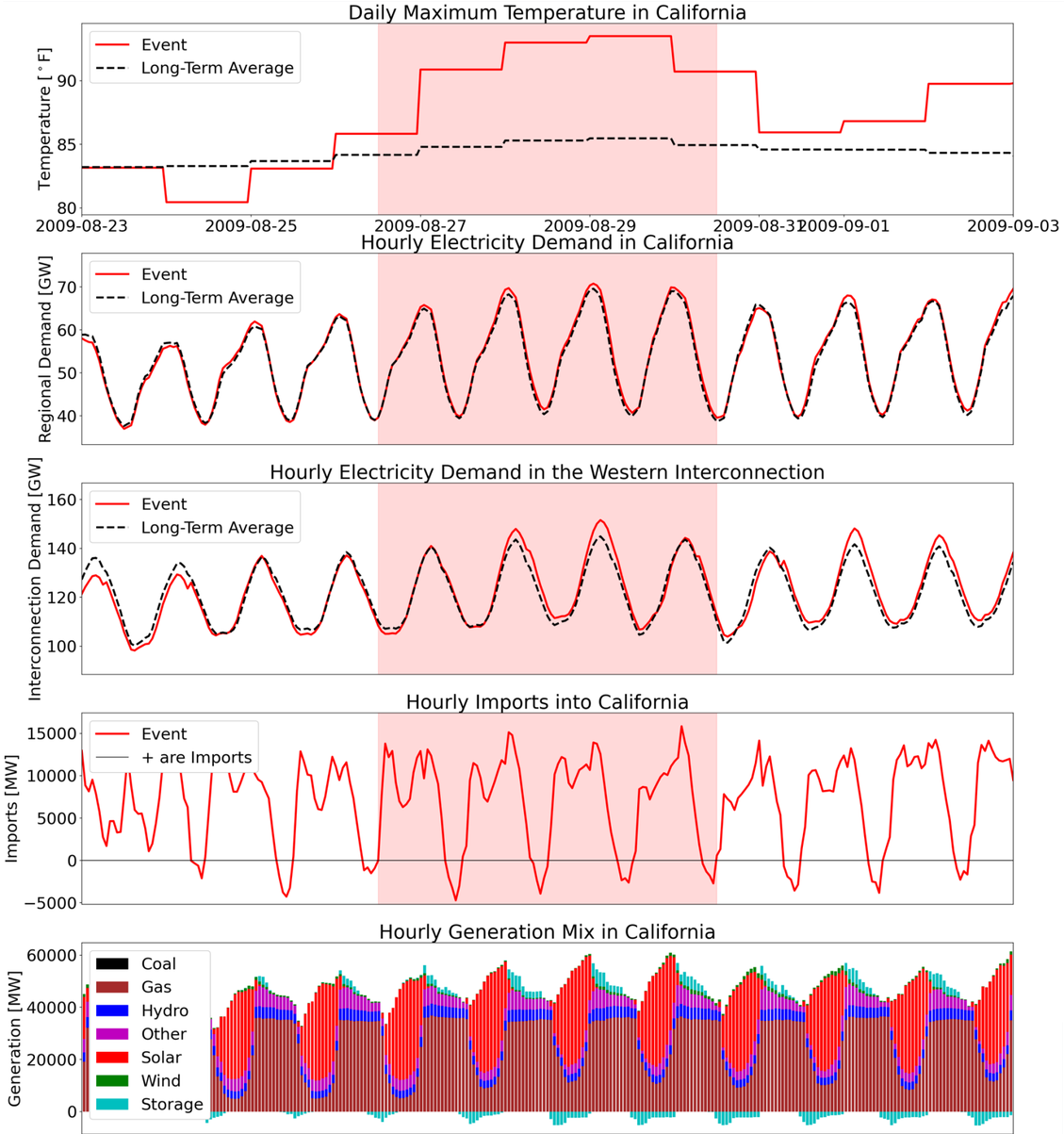
The thermal events in the catalogue have significant variability in severity, time of year, spatial extent, and duration.

We built historical heat wave and cold snap libraries



The thermal events in the catalogue have significant variability in severity, time of year, spatial extent, and duration.

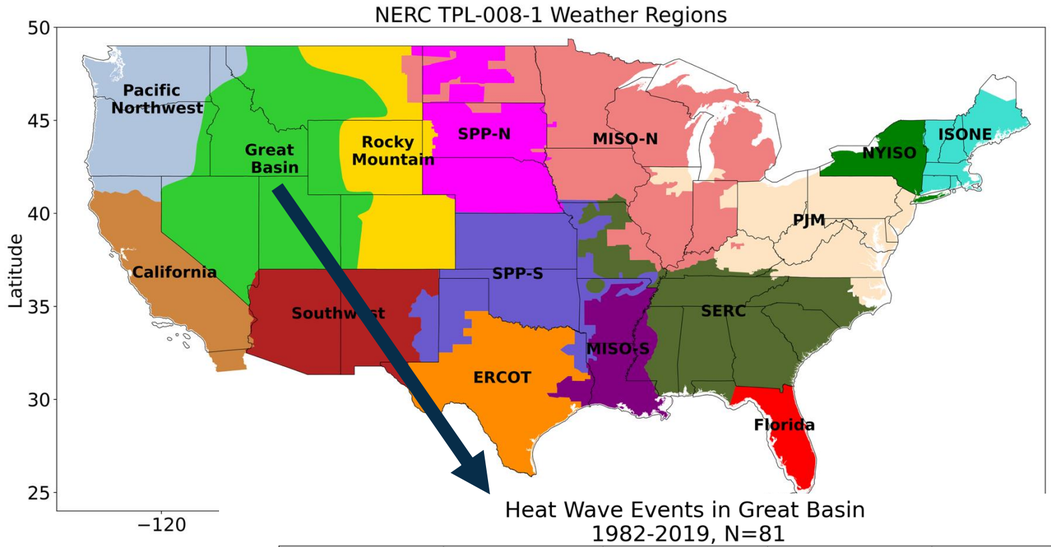
Studying the BPS response to extreme heat and cold events

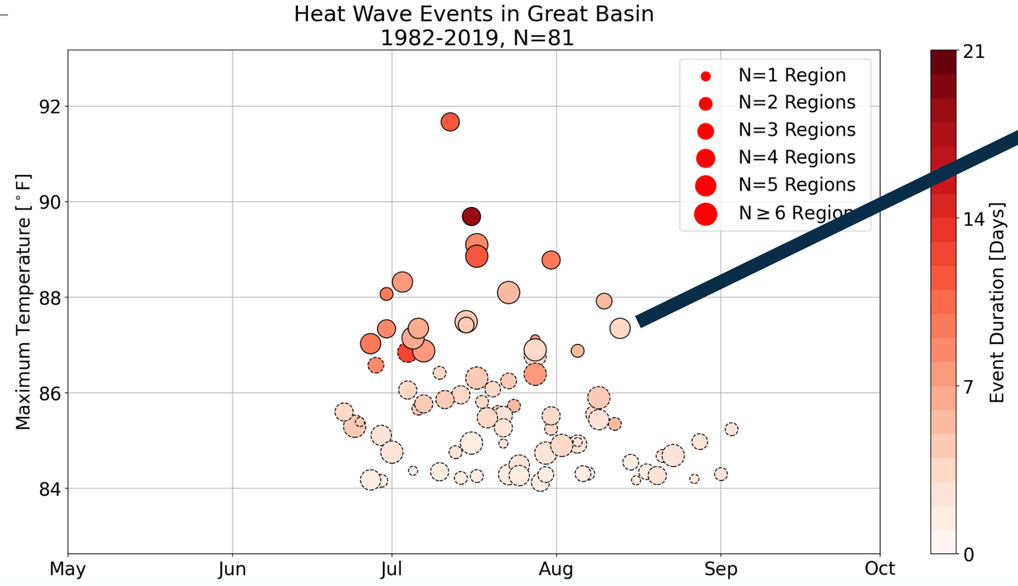


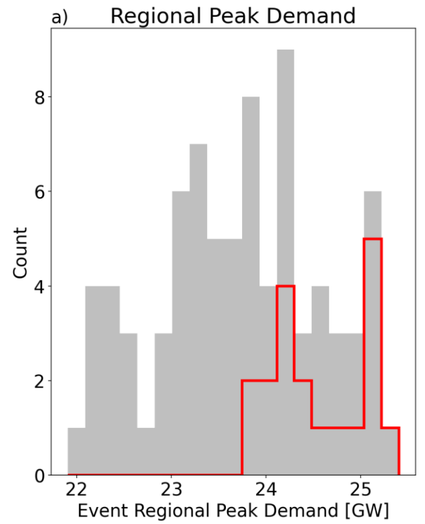
We simulated all 38 historical weather years to understand heat wave and cold snap impacts.

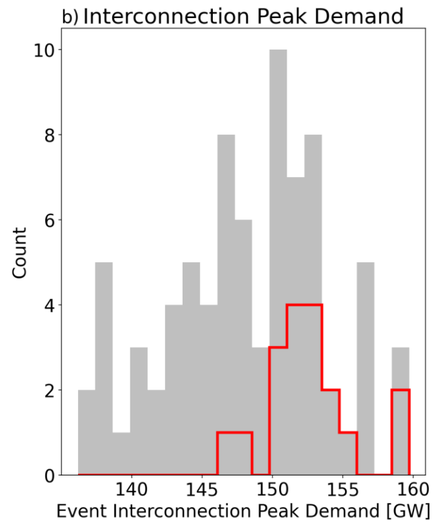
- Hourly meteorology was converted into coincident hourly load, wind, solar, and hydropower potential
- We projected variables onto the WECC 2032 Anchor Data Set system to reflect how each event might impact a future grid
- Hourly simulations were conducted using the GridView Production Cost Model to measure the response of the BPS to the events

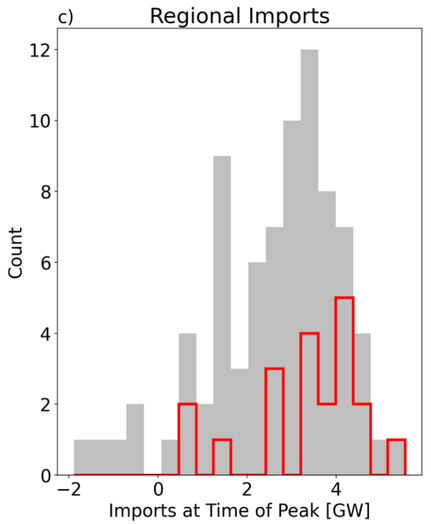
Heat waves and cold snaps create diverse stress responses

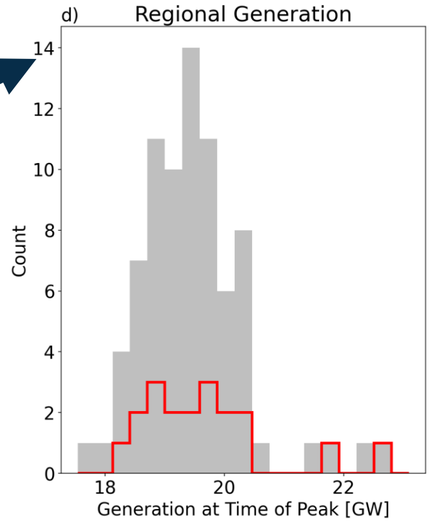


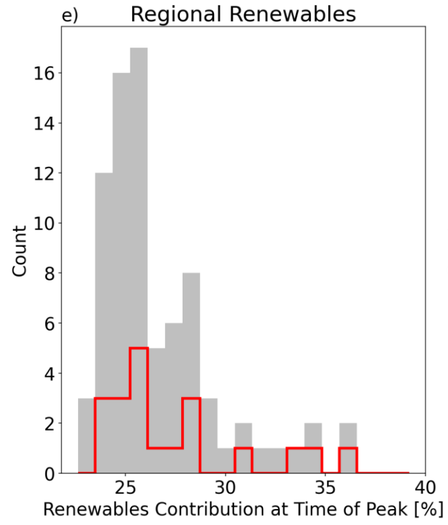


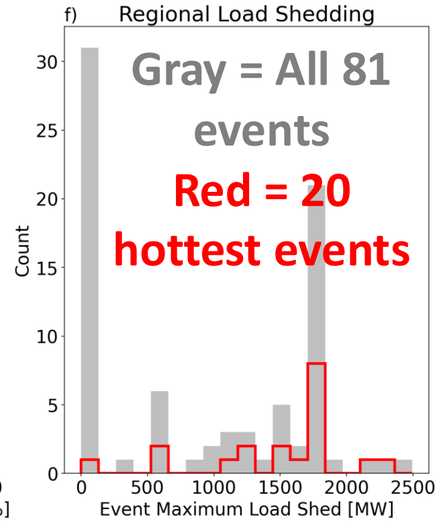




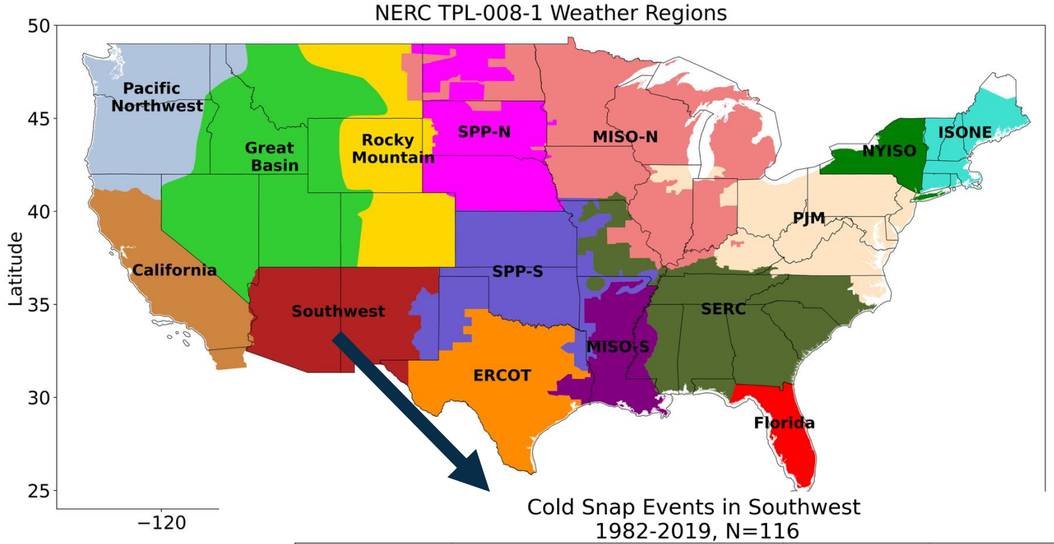


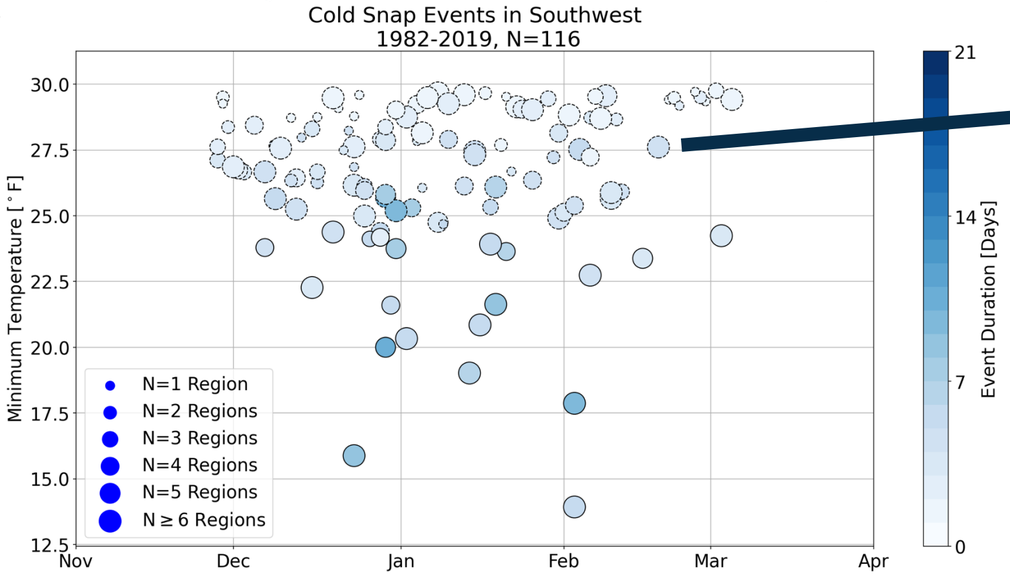


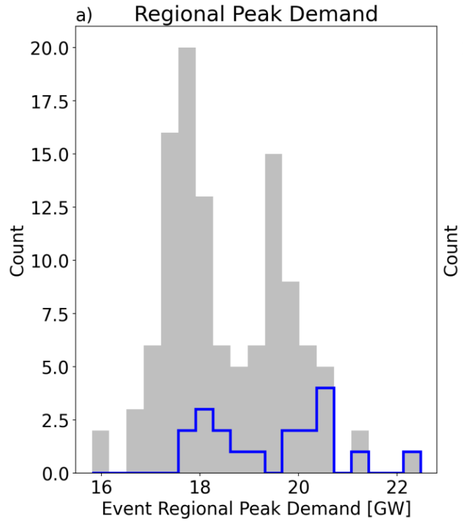


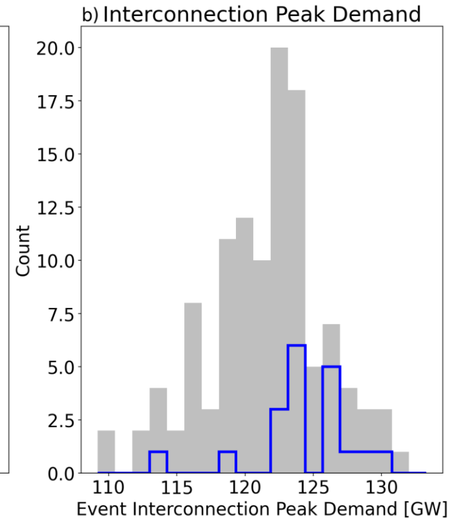


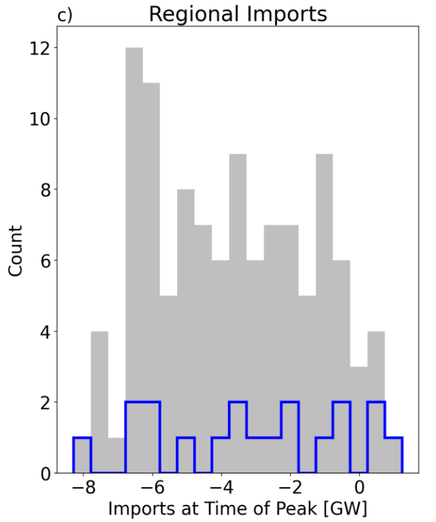
Heat waves and cold snaps create diverse stress responses

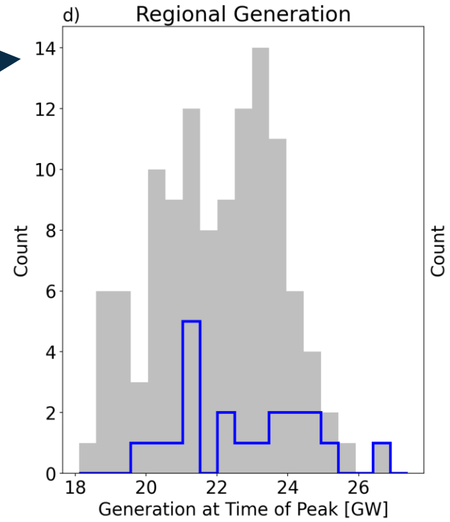


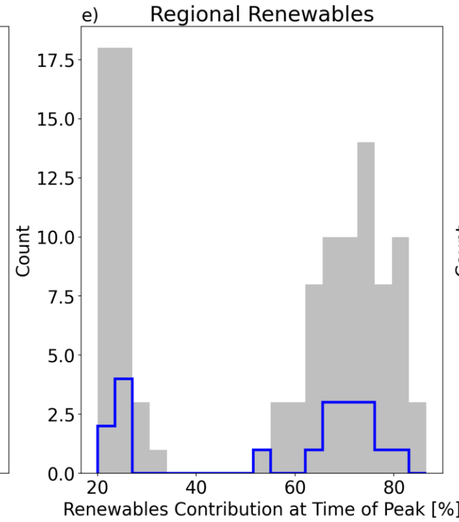


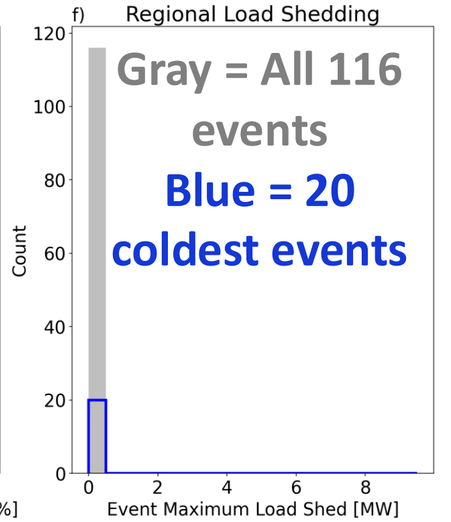












Top-N rankings depend on which variable you rank on

PNNL

Heat Waves Impacting the California Region, 1982-2019, N=86

Start Day	Maximum Temp. Ranking	Maximum Temp. (°F)	Region Peak Load Ranking	Region Peak Load (GW)	WECC Peak Load Ranking	WECC Peak Load (GW)	Imports at Peak Ranking	Imports at Peak (GW)
7/20/06	1	98.7	3	71.7	1	161.0	28	12.2
8/26/17	2	97.5	4	71.7	7	156.0	65	7.8
9/2/88	3	96.6	13	70.7	43	148.1	10	14.5
8/4/97	4	95.6	37	66.6	37	149.0	52	9.0
8/3/98	5	95.4	28	67.9	24	151.2	71	7.4
7/5/89	6	94.9	70	62.3	28	150.8	77	6.9
7/16/88	7	94.4	16	70.6	32	150.1	17	13.3
8/9/96	8	94.1	38	66.5	23	151.4	68	7.5
7/31/93	9	94.1	55	64.6	50	147.0	78	6.2
6/28/13	10	94.0	35	66.9	9	156.0	54	8.9

CEATI

Top-N rankings depend on which variable you rank on

PNNL

Heat Waves Impacting the California Region, 1982-2019, N=86

Start Day	Maximum Temp. Ranking	Maximum Temp. (°F)	Region Peak Load Ranking	Region Peak Load (GW)	WECC Peak Load Ranking	WECC Peak Load (GW)	Imports at Peak Ranking	Imports at Peak (GW)
7/20/06	1	98.7	3	71.7	1	161.0	28	12.2
8/26/17	2	97.5	4	71.7	7	156.0	65	7.8
9/2/88	3	96.6	13	70.7	43	148.1	10	14.5
8/4/97	4	95.6	37	66.6	37	149.0	52	9.0
8/3/98	5	95.4	28	67.9	24	151.2	71	7.4
7/5/89	6	94.9	70	62.3	28	150.8	77	6.9
7/16/88	7	94.4	16	70.6	32	150.1	17	13.3
8/9/96	8	94.1	38	66.5	23	151.4	68	7.5
7/31/93	9	94.1	55	64.6	50	147.0	78	6.2
6/28/13	10	94.0	35	66.9	9	156.0	54	8.9

CEATI

Top-N rankings depend on which variable you rank on

PNNL

Heat Waves Impacting the California Region, 1982-2019, N=86

Start Day	Maximum Temp. Ranking	Maximum Temp. (°F)	Region Peak Load Ranking	Region Peak Load (GW)	WECC Peak Load Ranking	WECC Peak Load (GW)	Imports at Peak Ranking	Imports at Peak (GW)
7/27/95	30	92.6	1	72.1	3	158.9	23	12.4
7/16/98	27	92.6	2	72.0	2	159.1	48	9.3
7/20/06	1	98.7	3	71.7	1	161.0	28	12.2
8/26/17	2	97.5	4	71.7	7	156.1	65	7.8
7/16/03	49	91.7	5	71.5	5	157.7	32	11.5
7/15/06	59	91.3	6	71.4	14	154.5	18	13.1
7/26/16	43	91.9	7	70.9	8	156.1	20	13.0
7/12/84	24	93.1	8	70.9	44	147.9	22	12.6
8/29/07	38	92.2	9	70.8	19	152.4	11	14.3
8/27/09	26	92.7	10	70.8	21	151.6	14	14.0

CEATI

Top-N rankings depend on which variable you rank on

PNNL

Heat Waves Impacting the California Region, 1982-2019, N=86

Start Day	Maximum Temp. Ranking	Maximum Temp. (°F)	Region Peak Load Ranking	Region Peak Load (GW)	WECC Peak Load Ranking	WECC Peak Load (GW)	Imports at Peak Ranking	Imports at Peak (GW)
7/20/06	1	98.7	3	71.7	1	161.0	28	12.2
7/16/98	27	92.6	2	72.0	2	159.1	48	9.3
7/27/95	30	92.6	1	72.1	3	158.9	23	12.4
7/14/05	61	91.2	11	70.8	4	158.5	29	12.1
7/16/03	49	91.7	5	71.5	5	157.7	32	11.5
7/17/09	32	92.5	12	70.7	6	156.2	47	9.3
8/26/17	2	97.5	4	71.7	7	156.1	65	7.8
7/26/16	43	91.9	7	70.9	8	156.1	20	13.0
6/28/13	10	94.0	35	66.9	9	155.9	54	8.9
7/23/18	18	93.5	15	70.6	10	155.5	25	12.3

CEATI

Top-N rankings depend on which variable you rank on

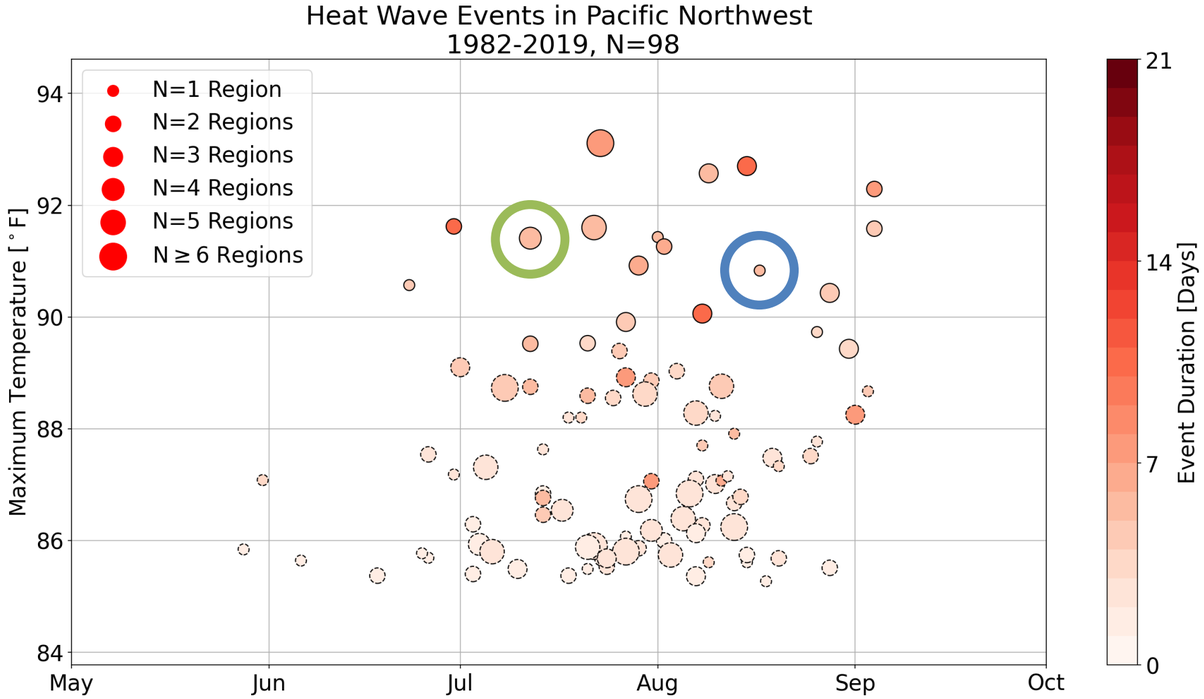
PNNL

Heat Waves Impacting the California Region, 1982-2019, N=86

Start Day	Maximum Temp. Ranking	Maximum Temp. (°F)	Region Peak Load Ranking	Region Peak Load (GW)	WECC Peak Load Ranking	WECC Peak Load (GW)	Imports at Peak Ranking	Imports at Peak (GW)
5/28/84	50	91.6	83	58.5	84	121.7	1	19.9
6/25/93	72	90.8	76	61.4	81	131.0	2	17.0
9/9/15	54	91.4	32	67.2	66	140.8	3	16.6
7/1/96	68	91.0	66	63.1	75	136.4	4	16.4
8/28/08	74	90.6	18	70.3	65	140.9	5	15.9
9/26/09	82	90.3	56	64.5	80	131.5	6	15.1
9/4/84	63	91.2	25	68.6	77	133.7	7	15.0
6/25/06	65	91.1	78	60.9	72	136.8	8	15.0
6/28/94	81	90.4	44	65.7	48	147.1	9	14.5
9/2/88	3	96.6	13	70.7	43	148.1	10	14.5

CEATI

Case studies: Does it matter which events you select?



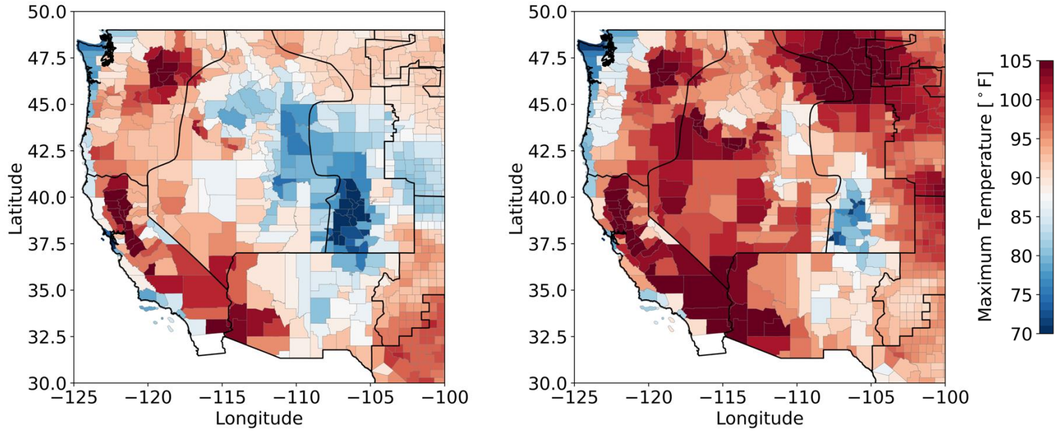
We compare pairs of events with equivalent temperature and load peaks but differences in other key aspects.

Event One: Regional heat wave impacting primarily the Pacific Northwest

- Region max temp: 90.8°F/30.7°C (12th hottest)
- Region peak load: 27.0 GW (27th highest)
- Interconnection peak load: 142.6 GW (80th highest)

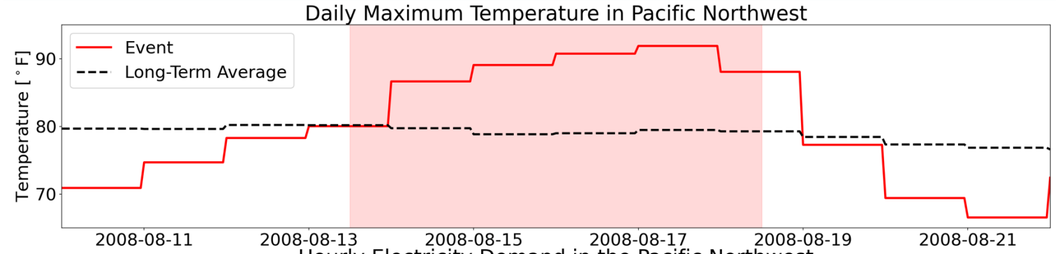
Event Two: Widespread heat wave impacting the entire western interconnection

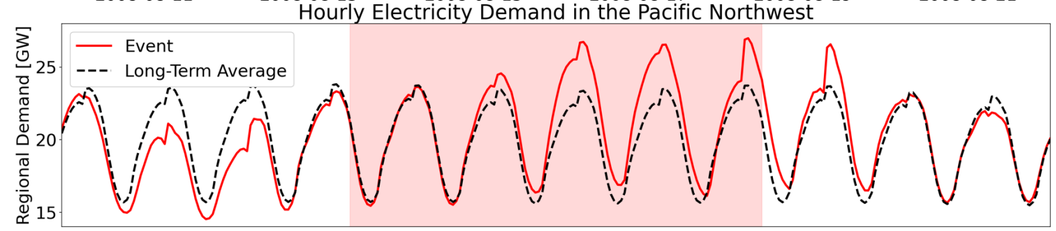
- Region max temp: 91.4°F/33.0°C (9th hottest)
- Region peak load: 27.1 GW (22nd highest)
- Interconnection peak load: 152.4 GW (20th highest)

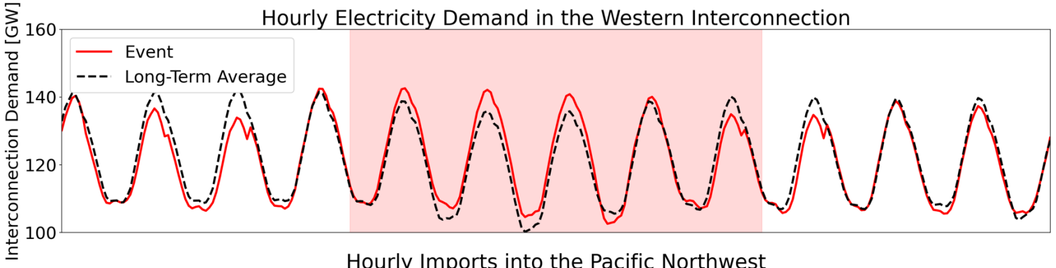


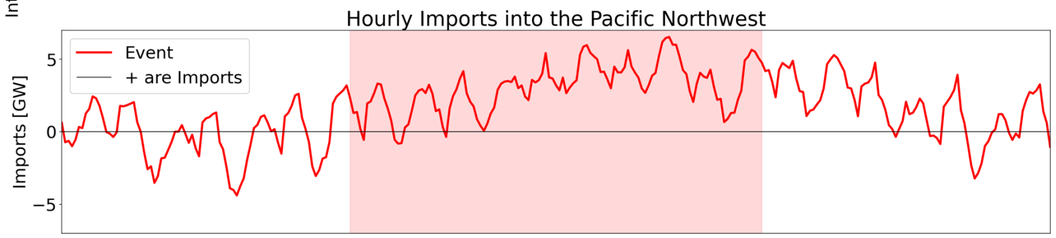
Case studies: Does it matter which events you select?

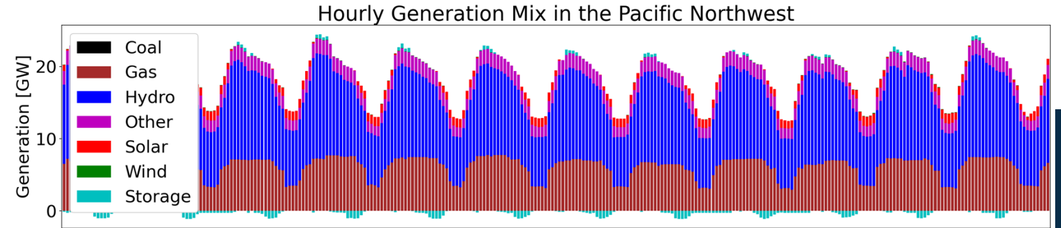
PNNL





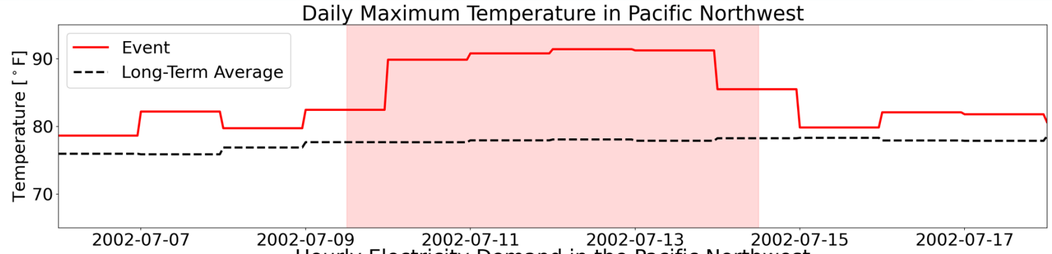


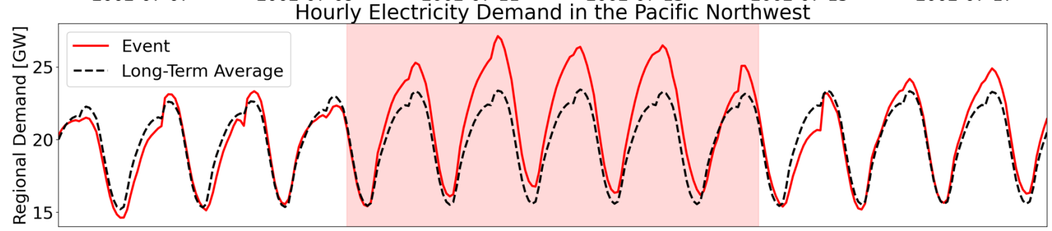


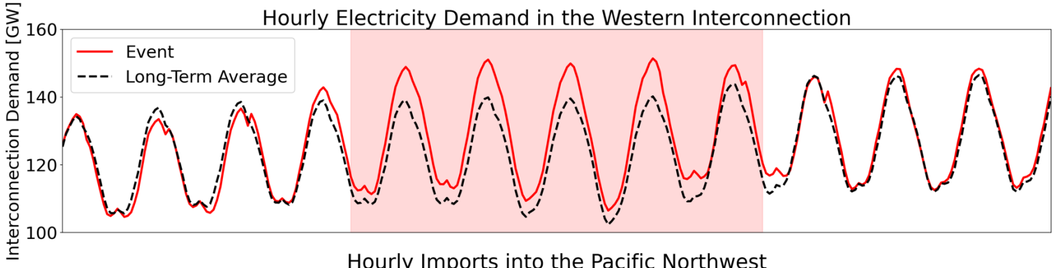


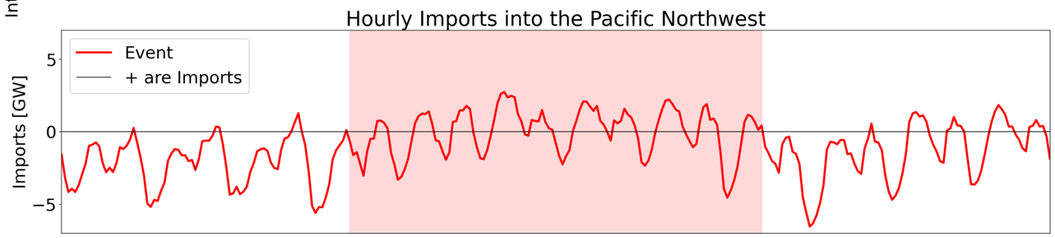
Event One: Regional heat wave

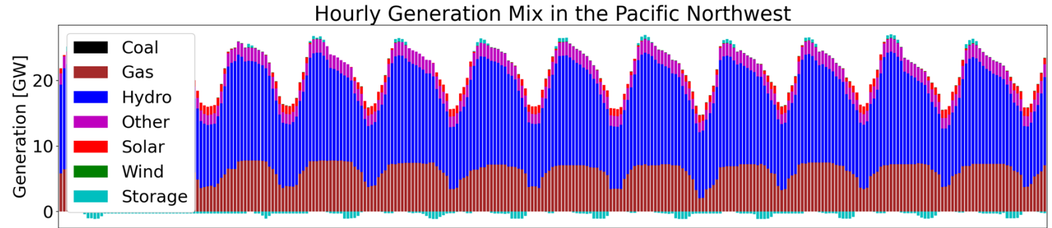
Event Two: Widespread heat wave











Case studies: Does it matter which events you select?

Taken in isolation, Event One might suggest that the region depends on its neighbors to ensure reliability during heat waves. In contrast, during Event Two the Pacific Northwest imported only half as much power at the time of peak demand and was a net exporter for many hours during the heat wave.

Event One: Regional heat wave impacting primarily the Pacific Northwest

- Region max temp: 90.8°F/30.7°C (12th hottest)
- Region peak load: 27.0 GW (27th highest)
- Interconnection peak load: 142.6 GW (80th highest)

→

- Peak LMP: $1950/MW
- Imports at peak demand: 5.1 GW
- Hydropower dispatch at peak: 12.2 GW

Event Two: Widespread heat wave impacting the entire western interconnection

- Region max temp: 91.4°F/33.0°C (9th hottest)
- Region peak load: 27.1 GW (22nd highest)
- Interconnection peak load: 152.4 GW (20th highest)

→

- Peak LMP: <$500/MW
- Imports at peak demand: 2.6 GW
- Hydropower dispatch at peak: 15.5 GW

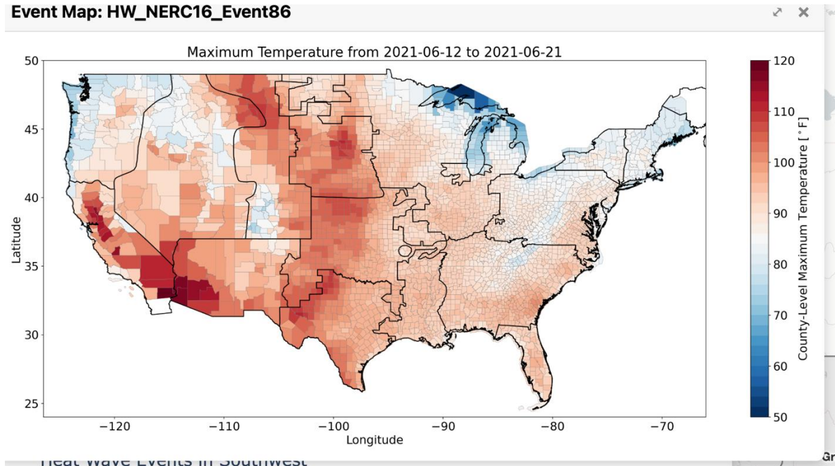
What matters and where for selecting stress events?

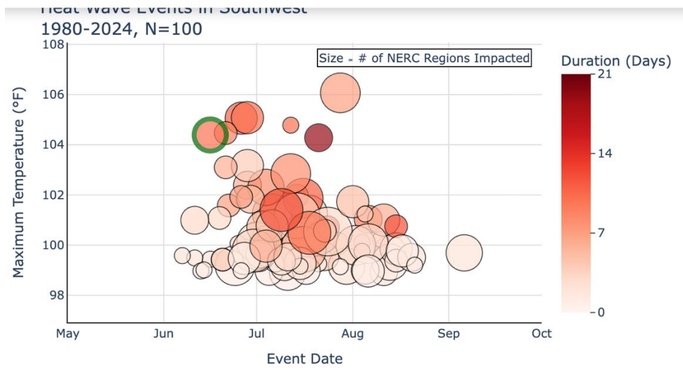
The variables that have the strongest correlations with critical stress metrics during heat waves vary for each of the regions.

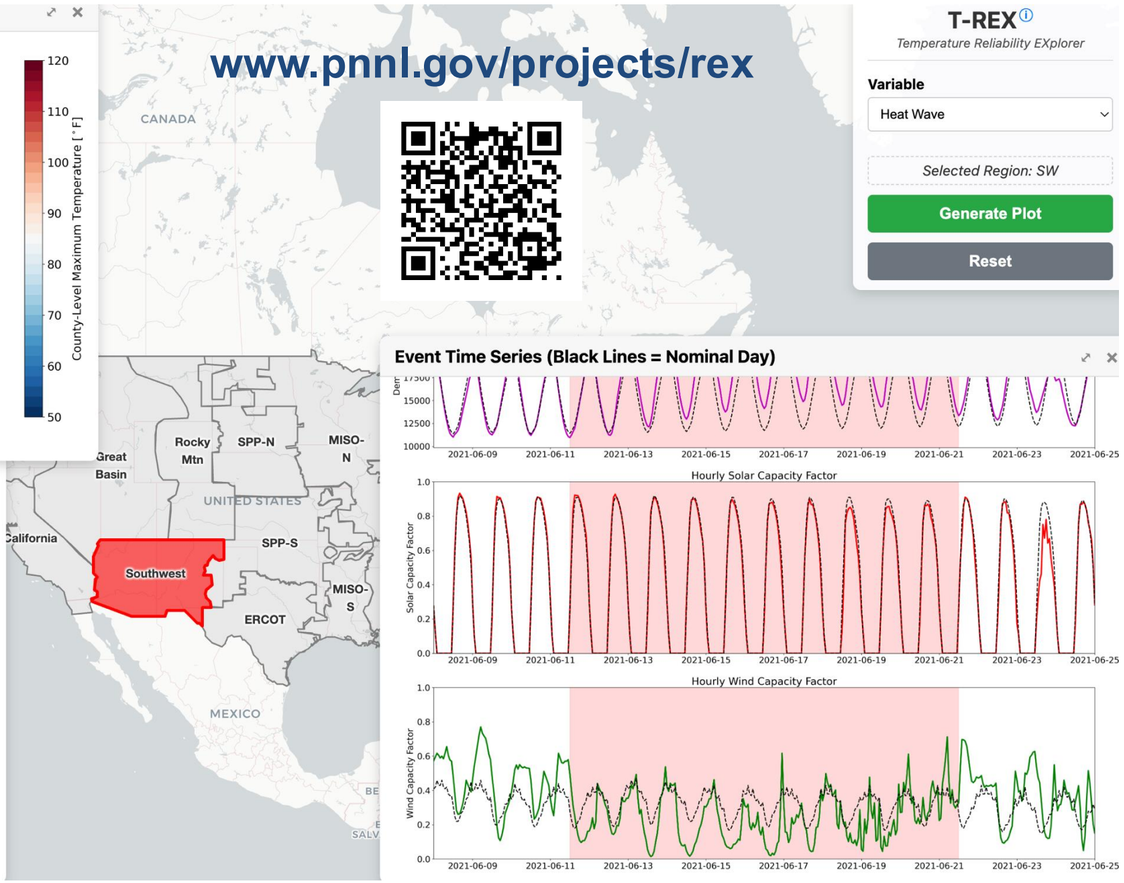
	California	Great Basin	Pacific Northwest	Rocky Mountains	Southwest
Regional Peak Demand	Temperature and Spatial Extent	Temperature and Spatial Extent	Temperature	Temperature and Spatial Extent	Temperature and Day of Year
Interconnection Peak Demand	Spatial Extent and Temperature	Temperature and Spatial Extent	Temperature and Spatial Extent	Temperature and Spatial Extent	Day of Year and Temperature
Maximum LMP	Gas at Peak Demand and Spatial Extent	Other at Peak Demand and Temperature	Temperature and Hydropower at Peak Demand	Temperature and Gas at Peak Demand	Temperature and Day of Year
LMP at Peak Demand	Gas at Peak Demand and Spatial Extent	Other at Peak Demand and Day of Year	Day of Year and Hydropower at Peak Demand	Gas at Peak Demand and Temperature	Temperature and Day of Year
Maximum Load Shed	Temperature and Spatial Extent	Other at Peak Demand and Temperature	Temperature and Day of Year	Temperature and Gas at Peak Demand	Day of Year and Temperature
Load Shed at Peak Demand	Spatial Extent	Other at Peak Demand and Temperature	Temperature and Day of Year	Gas at Peak Demand and Day of Year	Day of Year and Temperature
Maximum Imports	No Viable Correlations	Temperature and Day of Year	Hydropower at Peak Demand and Day of Year	Day of Year and Temperature	Temperature and Coal at Peak Demand
Imports at Peak Demand	Gas and Other at Peak Demand	Wind and Gas at Peak Demand	Hydropower at Peak Demand and Day of Year	Day of Year and Gas at Peak Demand	Temperature and Coal at Peak Demand

Sharing data and insights

PNNL’s Reliability EXplorer (REX) dashboard allows users to explore historical heat wave and cold snap responses. It supports utilities in selecting events for stress testing.



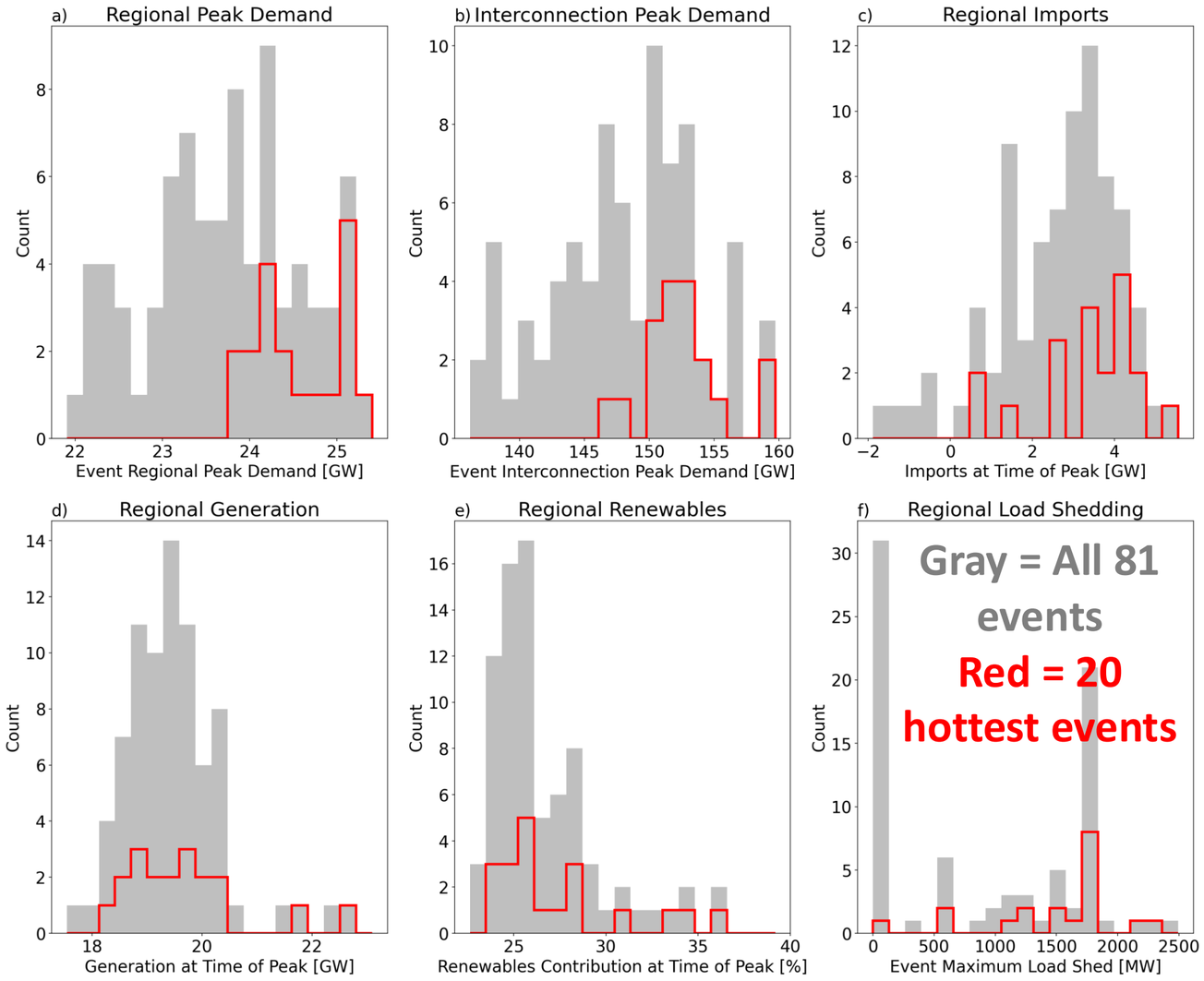




These foundational datasets need to be revised and extended. Practitioners don’t want terabytes of data. They want curated insights they can use to inform decisions.

Future work: Supplementing the historical event library

- Even with 40 years of meteorology, there are a relatively limited (O100) of heat waves and cold snaps in the historical record.
- These historical events represent one draw from the sample of what could have occurred or what might occur in the future.
- Synthetic weather generators and AI weather models can now quickly produce many more samples that can more adequately sample the tails of the distribution of planning risk.



Conclusions

1. Individual historical heat waves or cold snaps should not be treated as representative of all such events for stress testing. Thermal events are diverse from both a meteorological perspective and how they create grid stress.
2. The most extreme temperature events may not impose the most stress on the system. Event intensity, duration, and spatial extent all need to be considered, with each characteristic weighted appropriately for the reliability components being tested (e.g., capacity, storage and generation, and utilization of the transmission system).
3. More efforts are needed to generalize event definitions to consider regional characteristics and a broad range of intensity metrics.

Reliability Aspect	Event Selection Strategy	Key Variables to Use in Selecting Events
Risk from extreme loads	Events with the highest regional loads	Minimum or maximum temperature and peak regional load
Risk from inadequate storage capacity	Long duration events or events with low renewable contributions	Event duration, date, climatological seasonal wind and solar potential
Risk from inadequate intra- and inter-regional transmission	Events with broad spatial coverage	Number of regions experiencing a coincident event, peak interconnection load

Resources

Papers

- Burleyson, C. D., O. Anderson, C. Bracken, H. Wan, and N. Voisin, 2026: Characterizing diversity in heat wave responses for assessing grid reliability. In revision in *Applied Energy* – November 2026.
- Wan, H., C. Burleyson, and N. Voisin, 2026: What technical choices matter to characterize thermal events in support of bulk power grid reliability studies? *Earth's Future*, 14, e2025EF006623. https://doi.org/10.1029/2025EF006623.

Datasets

- Anderson, O., & Voisin, N. (2026). Weather-grid GridView operations dataset. PNNL's DataHub. https://data.pnnl.gov/group/nodes/dataset/34876.
- Burleyson, C., Voisin, N., Anderson, O., Wan, H., & Bracken, C. (2026). Supporting data for Burleyson et al. 2026 - Applied Energy [Dataset]. Zenodo. https://doi.org/10.5281/zenodo.23024498.
- Jones, A. D., and Coauthors (2022). IM3/HyperFACETS Thermodynamic Global Warming (TGW) Simulation Datasets (v1.0.0) [Data set]. MSD-LIVE Data Repository. https://doi.org/10.57931/1885756
- Wan, H., C. Burleyson, C., and N. Voisin, 2025: Heat wave and cold snap event library under various technical choices for NERC subregions in the conterminous U.S. (1980 - 2024). https://doi.org/10.5281/zenodo.15306963.

Dashboards

- www.pnnl.gov/projects/rex

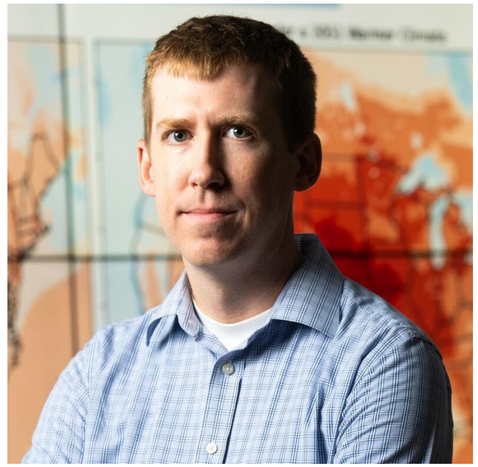


CONNECT WITH US

casey.burleyson@pnnl.gov

https://www.linkedin.com/in/caseyburleyson/

https://www.pnnl.gov/projects/rex



Pacific Northwest
NATIONAL LABORATORY