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2022 Building Performance Analysis Conference and SimBuild

Conference Paper
Session #2 Approaches to Modeling Future Weather, Climate and Extreme Events I

Multi-scenario Extreme Weather Simulator Application to Heat Waves

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Learning Objectives

- Evaluate the sensitivity of cooling loads to building envelope parameters under future climate projections
- Analyze building energy performance under different weather datasets for a typical secondary school in a hot and humid climate zone
- Explain the meaning and importance of thermal resilience.
- Describe the evaluation methods for thermal resilience.
- **Understand why a probabilistic approach to extreme weather is important**
- **Elaborate the basic methods used in the Multi-scenario Extreme weather simulator**

Acknowledgements

- John Eddy (Sandia National Laboratories) for approving funding for writing this paper
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- Potential bias: *National Technology & Engineering Solutions of Sandia, LLC*

  Honeywell

Outline

- Context
  - Why extreme events
  - Why a probabilistic approach
- Methods
  - How the multi-scenario extreme weather simulator (software 1) works
  - Building energy modeling demonstration
- Results
  - Electricity
  - Thermal comfort
- Conclusions
  - Just getting started!

Why extreme events?

- **Global Climate Change**

1. **Global Climate Change**

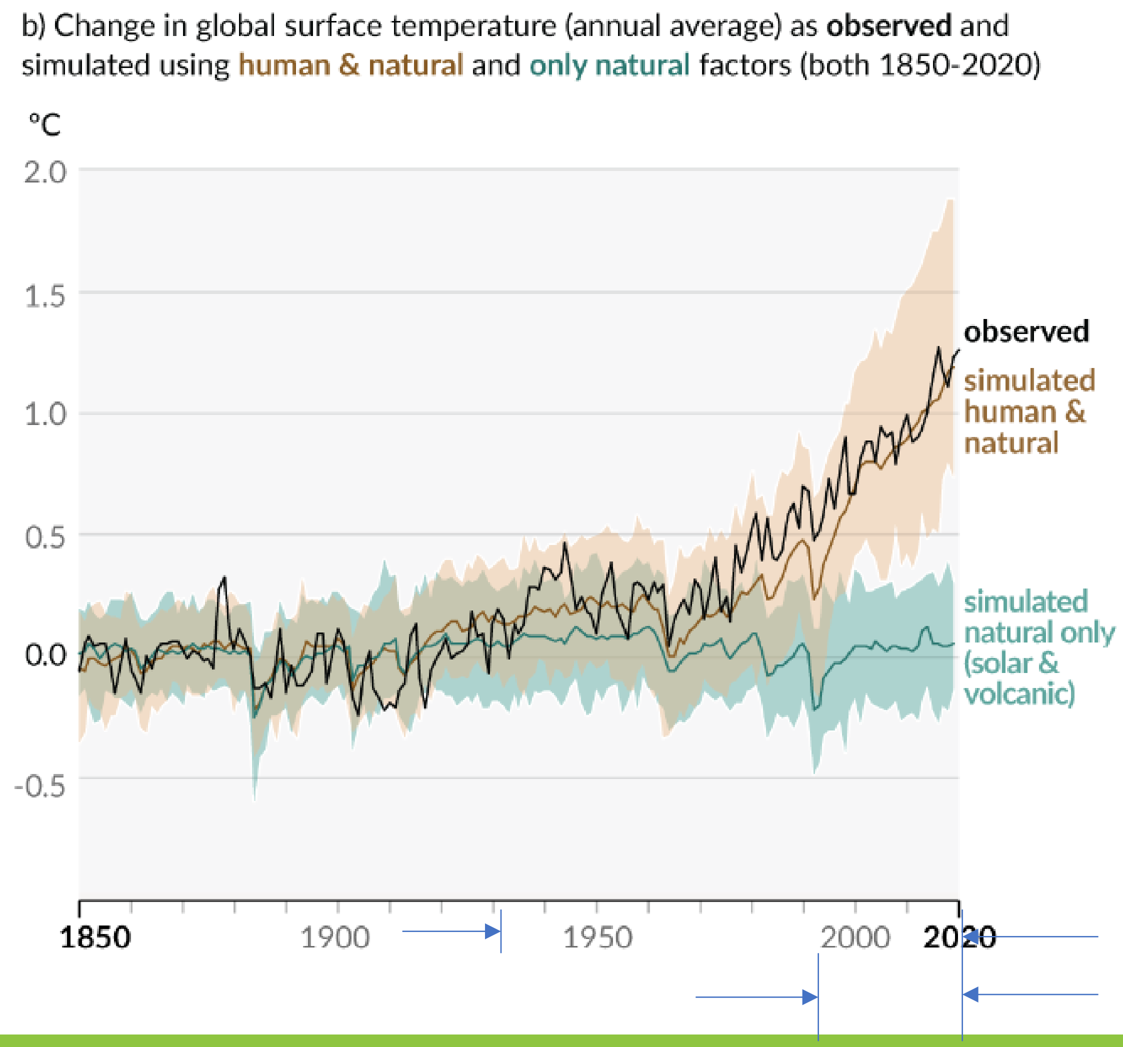


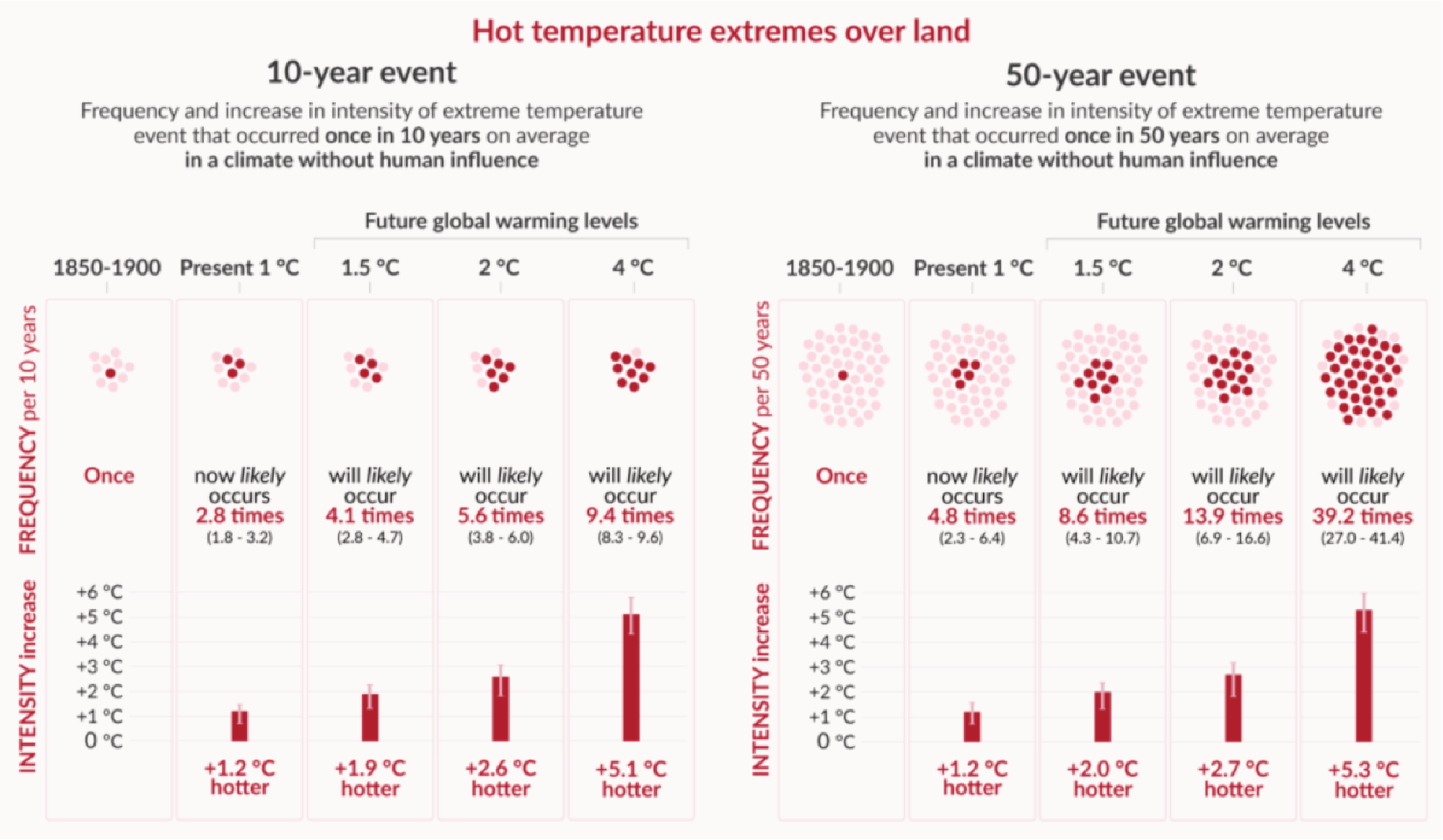
Figure SPM.1 Intergovernmental Panel on Climate Change (IPCC) Working Group I – The Physical Science Basis Sixth Assessment Report (AR6) (approved for release for education on climate change issues to society)

Approximate building & grid equipment timescales

See ASHRAE fundamentals chapter 36 on climate change

Why extreme events?

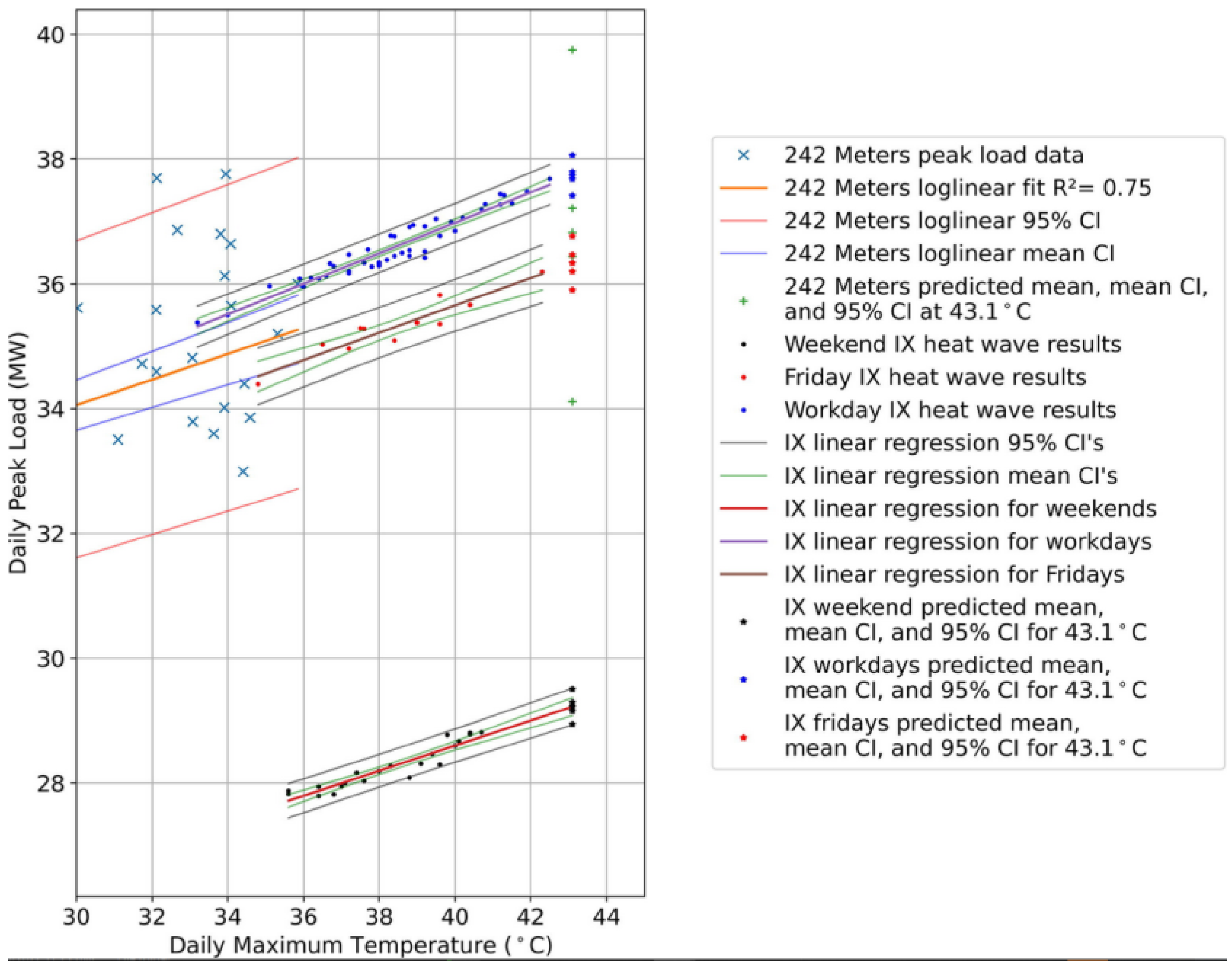
- **Increased frequency, and intensity of extreme heat waves**



Why a probabilistic approach?

• Scenario approach

- Create a set of heat wave scenarios
    - Safety factors
    - Success criteria
- Apply these scenarios to engineering analysis of grid and buildings
    - Evaluate design criteria
    - Uncertainty due to operations and equipment
    - No weather based uncertainty
- Hopefully worst case!

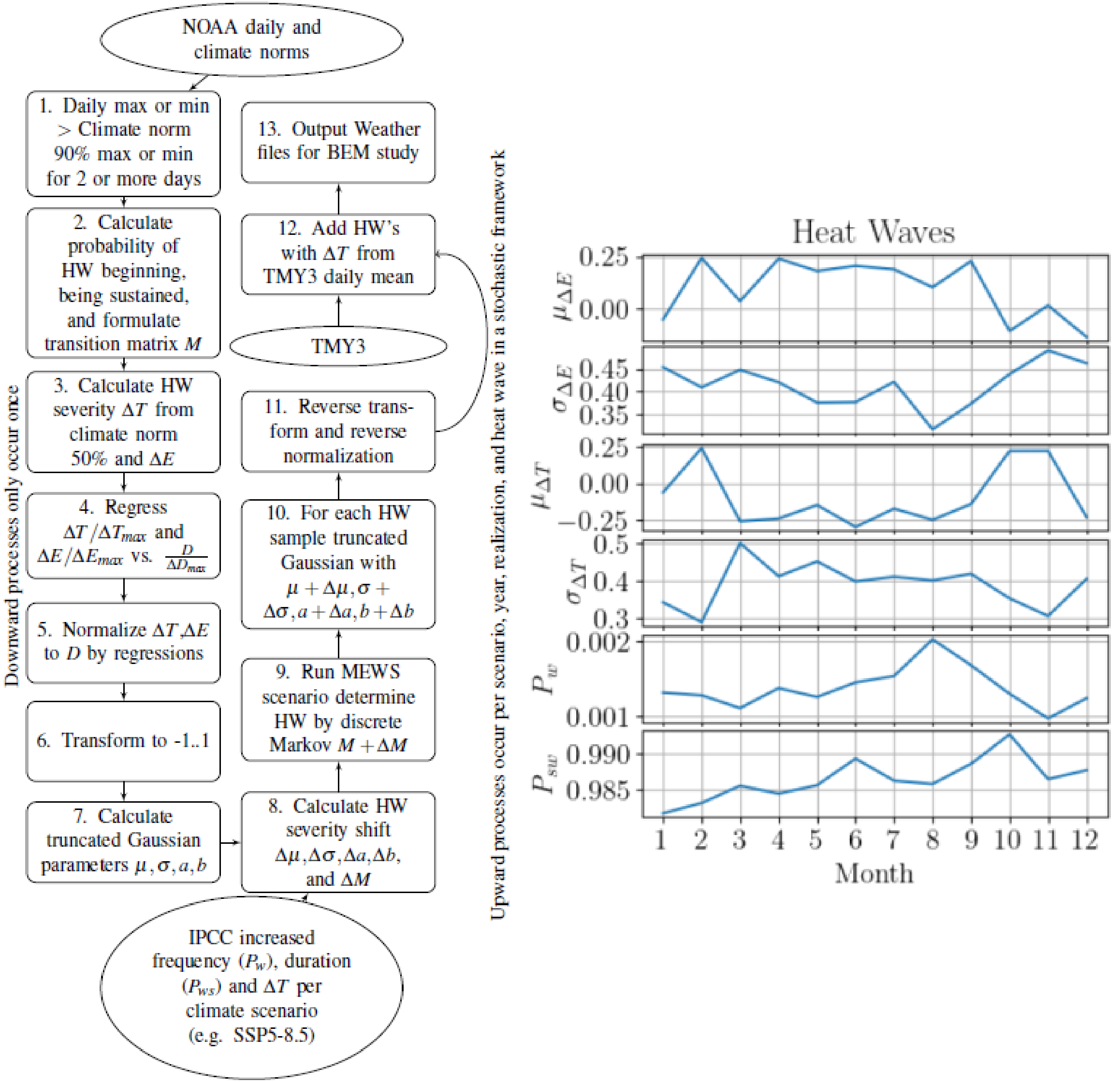


Used with permission (Villa, 2021a)

Why a probabilistic approach?

• Probabilistic approach

- Propagate statistical properties of extreme weather events
- Difficulties
  - Insufficient historical data
    - Poor statistics of distribution tails
  - Duration of data needed can be non-stationary
  - Complexity
- Validation
  - Verify historic accuracy
  - Verify ensemble model based accuracy
- Advantages
  - Natural blending of normal conditions versus extreme event conditions



Comparison

- **Probabilistic vs. Scenario**

Hybrid Scenario/Probabilistic approaches can also work.

Scenario		Probabilistic	
Advantages	**Disadvantages**	**Advantages**	**Disadvantages**
Simple	Indirect comparison of normal vs. resilience	Direct comparison of normal vs. resilience	Complex
Shorter run time	May be unconservative or overly conservative	Quantifies chance of worst case, samples possibilities	Often requires unavailable data
Facilitates higher fidelity models		Consistent with probability based resilience metrics	Longer run time
		Fair playing field for other random, correlated processes	Simplified models needed

Why a probabilistic approach?

- **Fair comparison of normal vs. resilience conditions**

We cannot "future proof" all tech! Who is going to pay the bill?

"Tornado proof"

The TIV (Tornado Intercept Vehicle) built from a Ford F-450 (2006) Creative commons Wikimedia Creative Commons Attribution 2.0 Generic license.

"Flood proof"

https://commons.wikimedia.org/wiki/File:Car_Boat_%3F_(3830832878).jpg
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Objectives

1. Provide extreme weather files that contain statistically realistic increases in severity and frequency based on climate model predictions and historical data

- Extreme temperature (heat waves and extreme cold)
- Future:

  Extreme Precipitation, Drought, Hurricanes, …

2. Quickly generate files with reasonable output with a data-driven approach

Data here includes climate model outputs

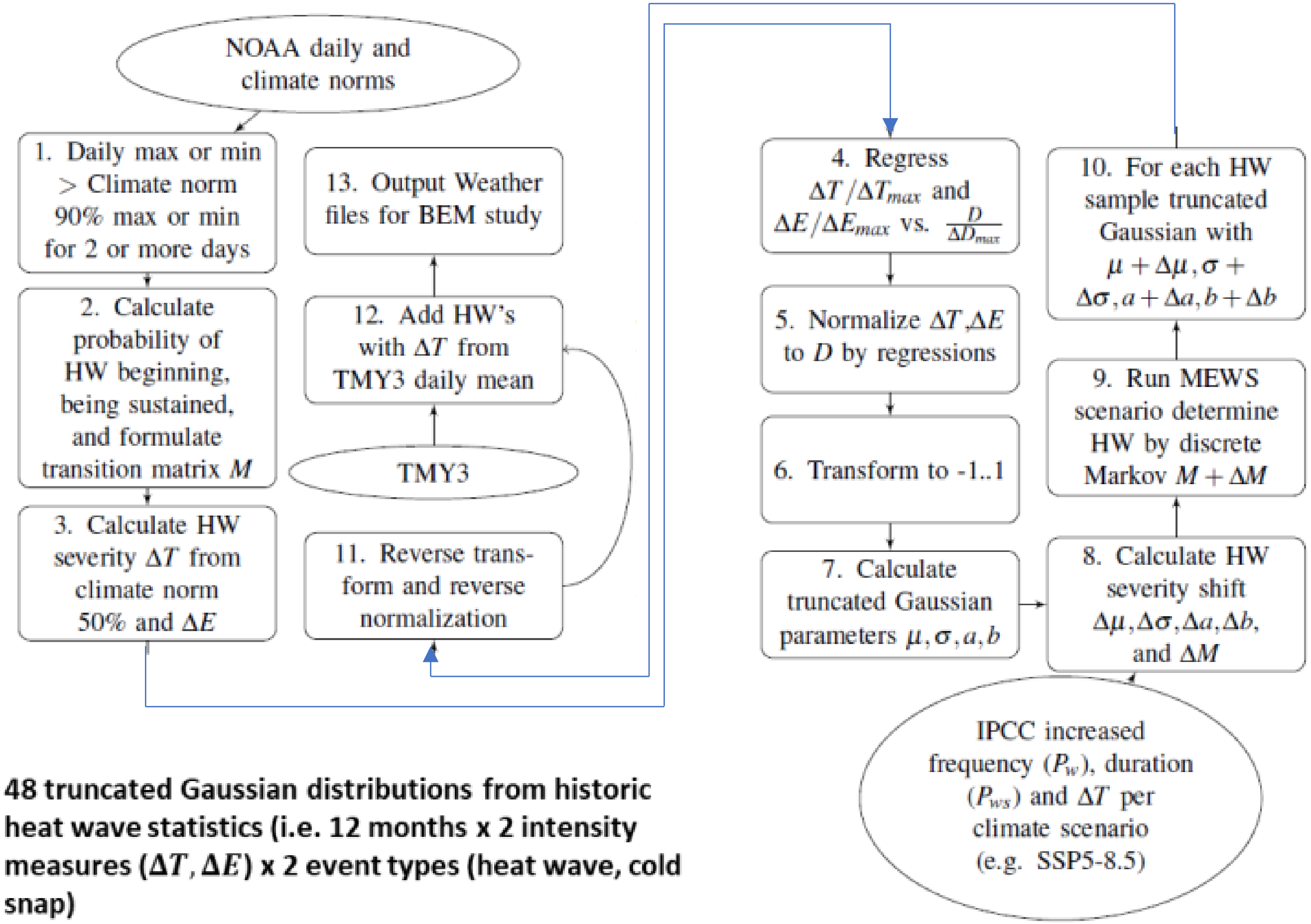
- Fuse historical data and climate projections into "best-guess" sampling distributions and Markov processes

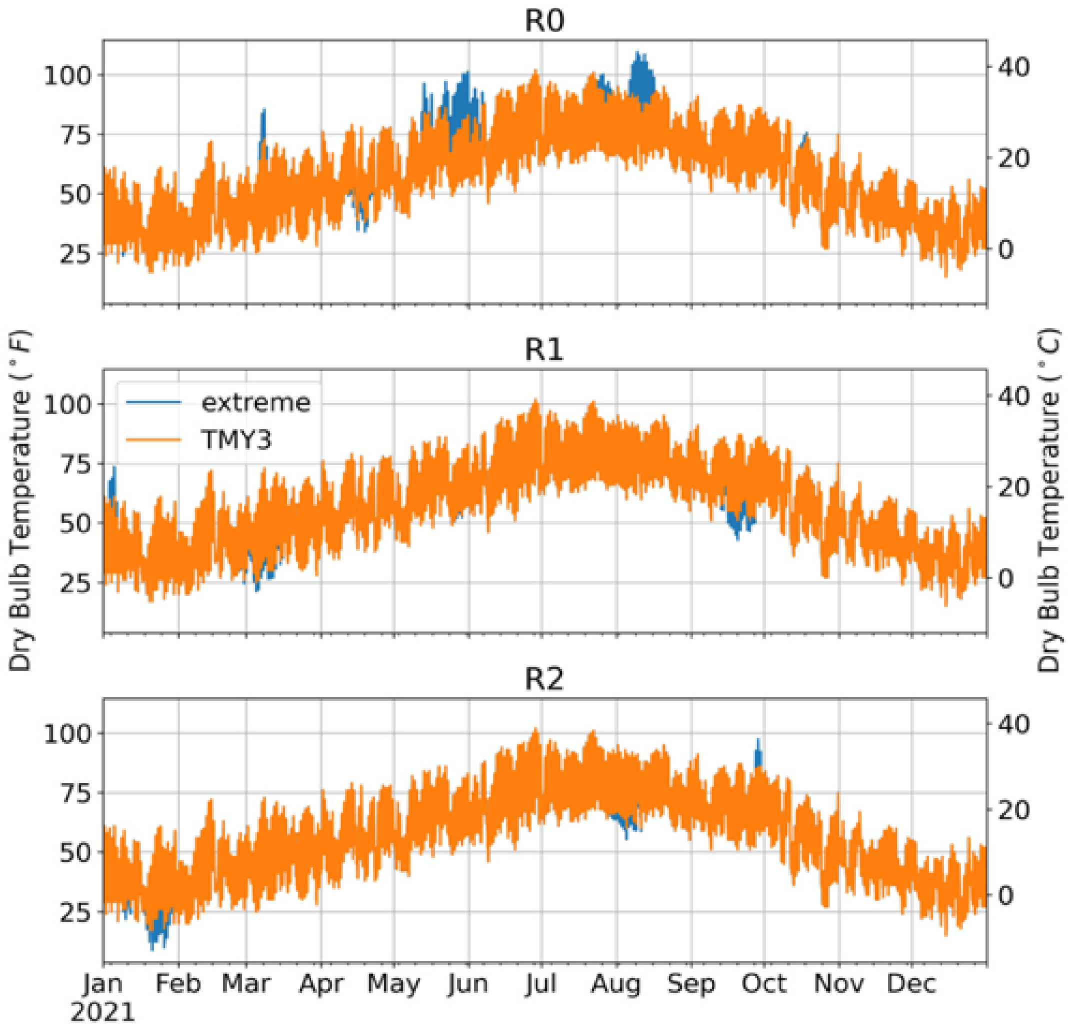
3. Keep the algorithm simple (as possible!)

4. Make it freely available:

- Software 1 is open source and listed in the bibliography (Villa, 2021b)

Methods: software 1





- **48 truncated Gaussian distributions from historic heat wave statistics (i.e. 12 months x 2 intensity measures (ΔT, ΔE) x 2 event types (heat wave, cold snap)**

Step 1: Data and extreme temperature definition

National Oceanic and Atmospheric Association (NOAA)

- Climate norms (1991-2020)
- Daily summaries

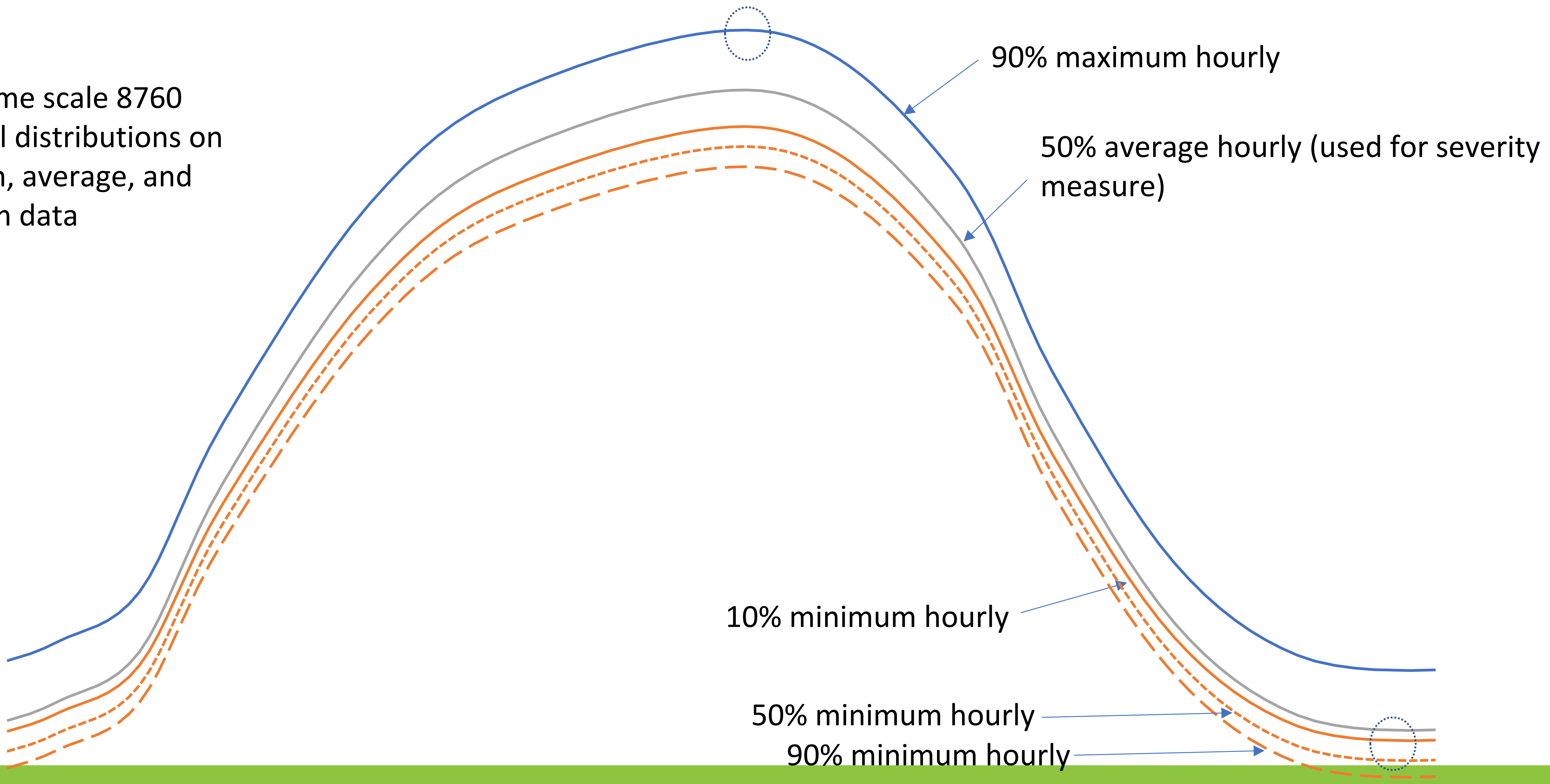
Definition

Heat wave: 2 days of either daily maximum temperature greater than 90% climate norm maximum temperature or daily minimum temperature greater than climate norm daily 10 % minimum temperature

Cold snap: 2 days of either daily minimum temperature less than 10% climate norm minimum temperature or daily maximum temperature less than climate norm 10% daily maximum

Climate norms data

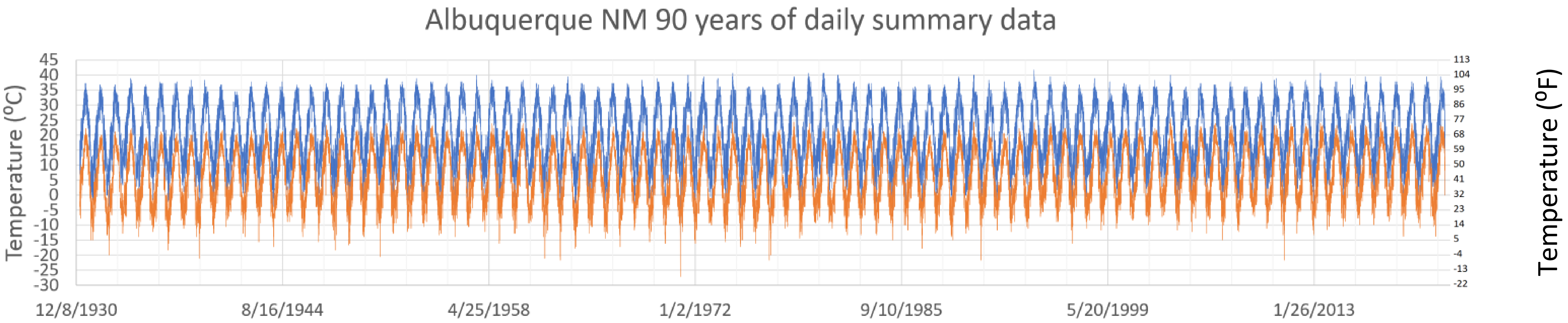
- Hourly time scale 8760
- Statistical distributions on minimum, average, and maximum data



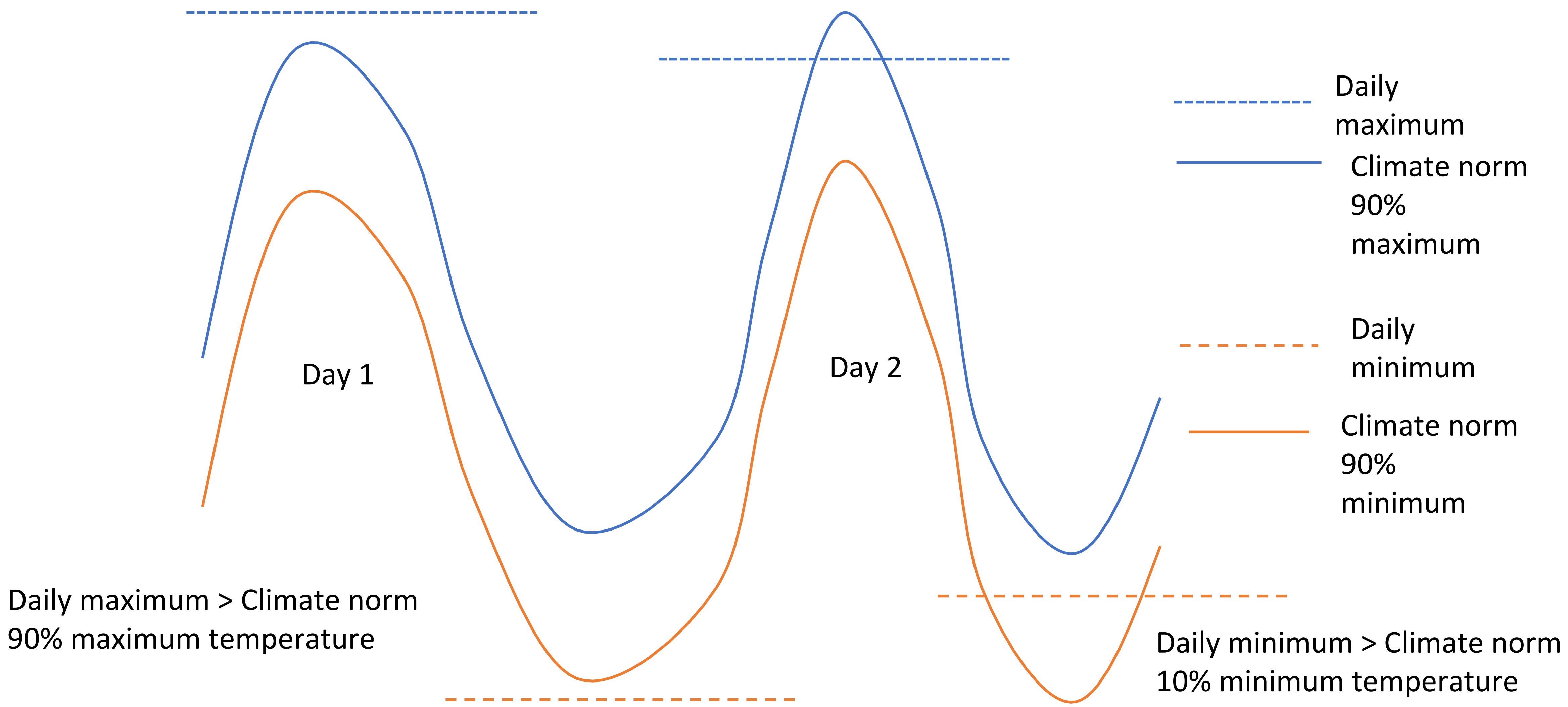
Daily summaries

Chosen because longest historical records available

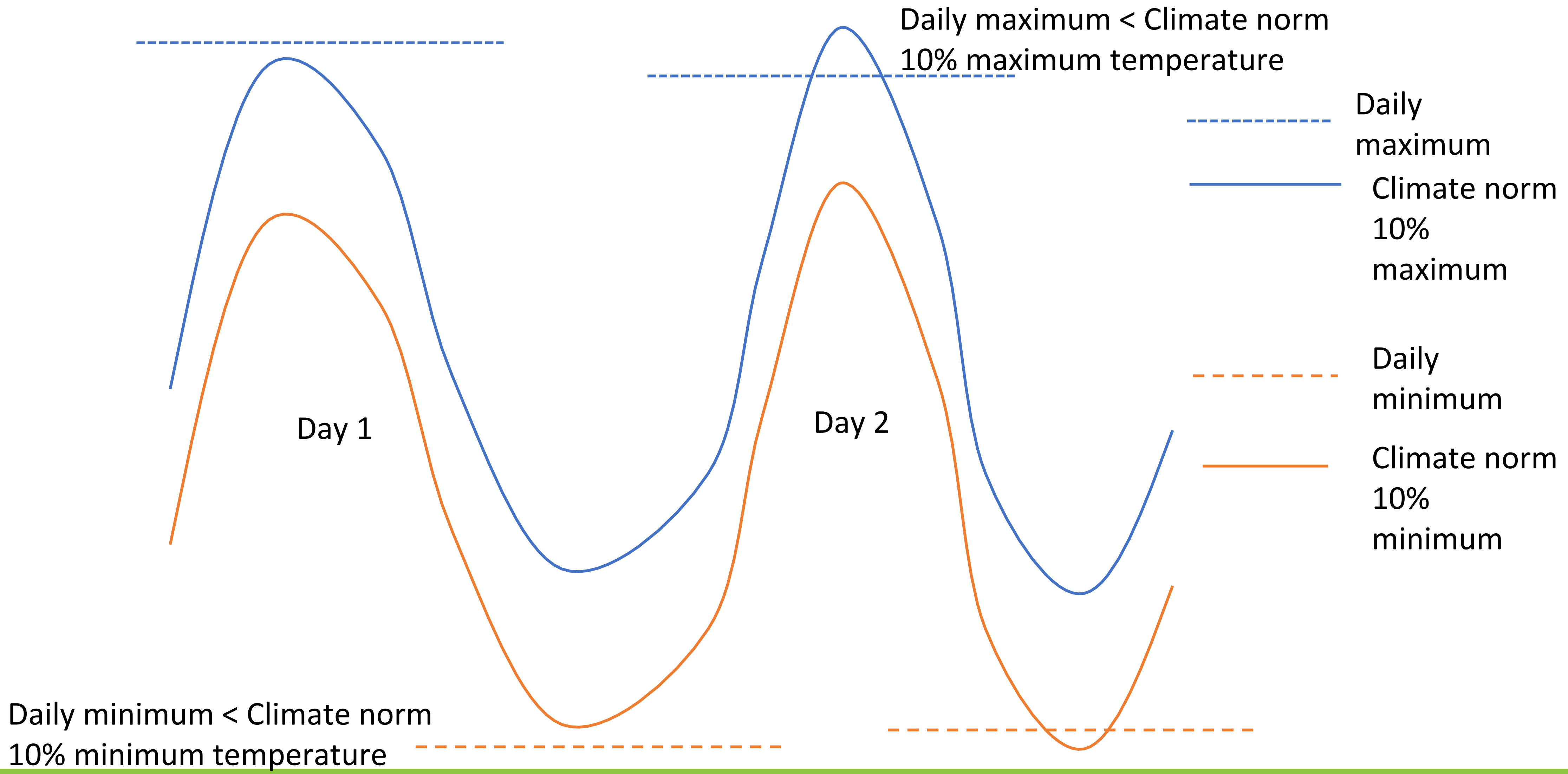
Daily maximum, minimum, and average temperatures



2 Day heat wave example



2 Day cold snap example



Step 2: Calculate the Markov probabilities for heat waves and cold snaps (Frequency and Duration)

1. Probability of heat wave P_{hw_m} ~ number of heat waves in historic record for month m / total hours in historic record for month m
2. Probability of sustaining a heat wave when in a heat wave P_{hws_m} find via regression of $P_{hws_m}^{D_{HW}}$ probability a heat wave is of a given duration divided by the sum of all heat wave's duration
3. Similar reasoning for cold snaps

$$M_m = \begin{bmatrix} 1 - P_{hw_m} - P_{cs_m} & P_{cs_m} & P_{hw_m} \\ 1 - P_{css_m} & P_{css_m} & 0 \\ 1 - P_{hws_m} & 0 & P_{hws_m} \end{bmatrix}$$

Steps 3-7: Characterize extreme temperature event severity

Heat wave severity is magnitude measured above daily average of climate norms. Each heat wave has a ΔT_{hw} peak.

Forms a set $\{\Delta T_{hw_m}\}$ for each month of the year.

The difference between the heat wave daily maximum temperature and daily average of climate norms is also integrated to form the total energy ΔE_{hw} in $℃ \cdot day$ added by each heat waves.

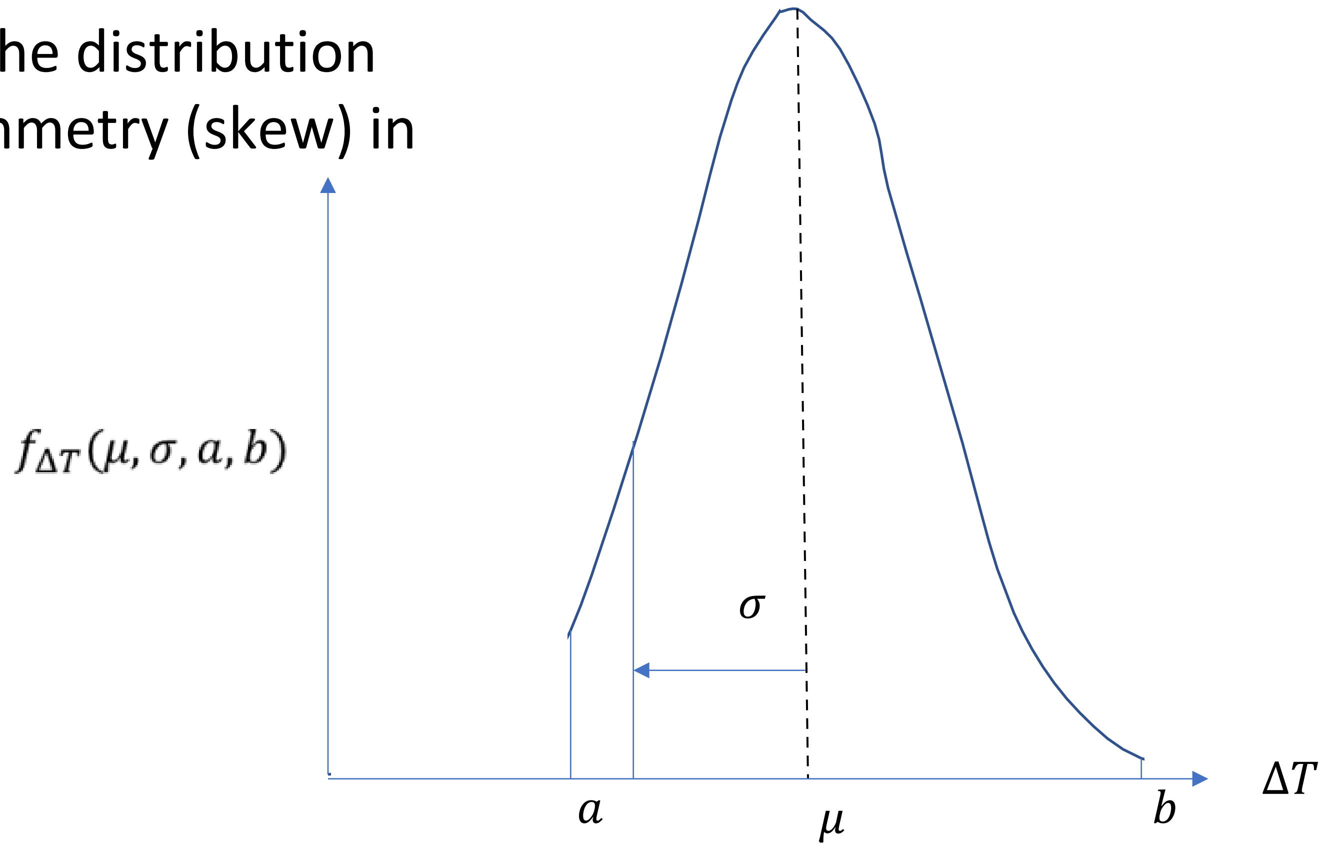
Form a second set $\{\Delta E_{hw_m}\}$ for each month of the year.

Perform several statistical steps to form truncated Gaussian distributions of $\Delta T \sim \mathcal{N}_{\Delta T}(\mu_{\Delta T}, \sigma_{\Delta T}, a_{\Delta T}, b_{\Delta T})$, normalize the results by D and scale to -1…1

Truncated Gaussian

Enables

1. Maximum and minimum historic cases to be the bounds of the distribution
2. Fitting asymmetry (skew) in data



Step 8: Calculate shift in all parameters based on IPCC data

For each IPCC climate scenario, year, and month each year, calculate shifts $\Delta M, \Delta\mu, \Delta\sigma, \Delta a, \Delta b$

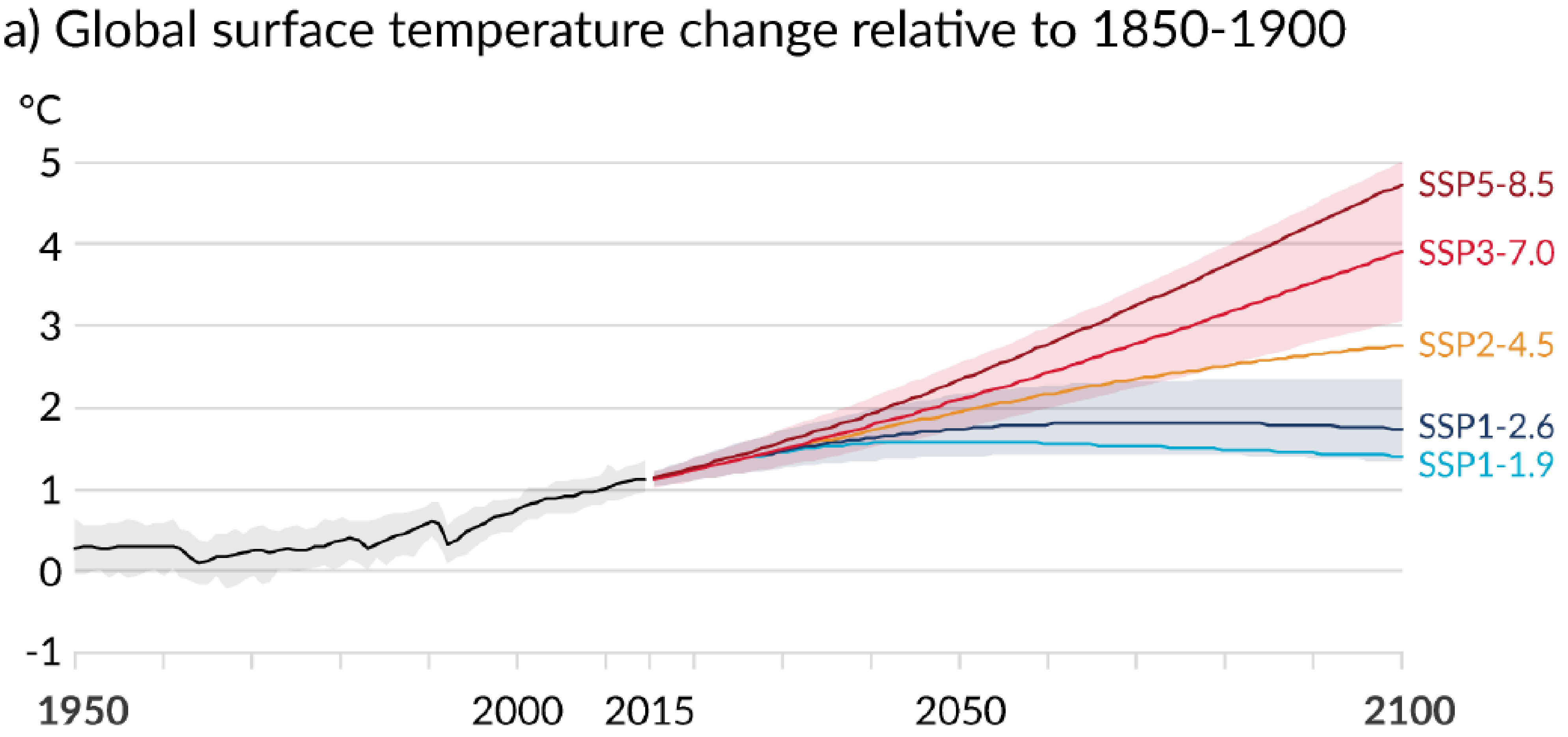
$$\Delta M_m = \begin{bmatrix} P_{hw_m} + P_{cs_m} - P'_{hw_m} - P'_{cs_m} & P'_{cs_m} - P_{cs_m} & P'_{hw_m} - P_{hw_m} \\ P_{css_m} - P'_{css_m} & P'_{css_m} - P_{css_m} & 0 \\ P_{hws_m} - P'_{hws_m} & 0 & P'_{hws_m} - P_{hws_m} \end{bmatrix}$$

Several assumptions needed here so that IPCC data provided for 10 and 50 year extreme temperature events is adequate:

1. Assume increase in ΔT is proportional to ΔE
2. Weighted averages for modified sustained heat wave probabilities (cannot meet 10 and 50 year events exactly with single Markov parameters)

IPCC scenarios (global average here)

IPCC scenarios drive how severe extreme temperature events become in future years



IPCC AR6 Physical Basis Report 2021 Figure SPM.8

Steps: 9-11 Produce stochastic realizations

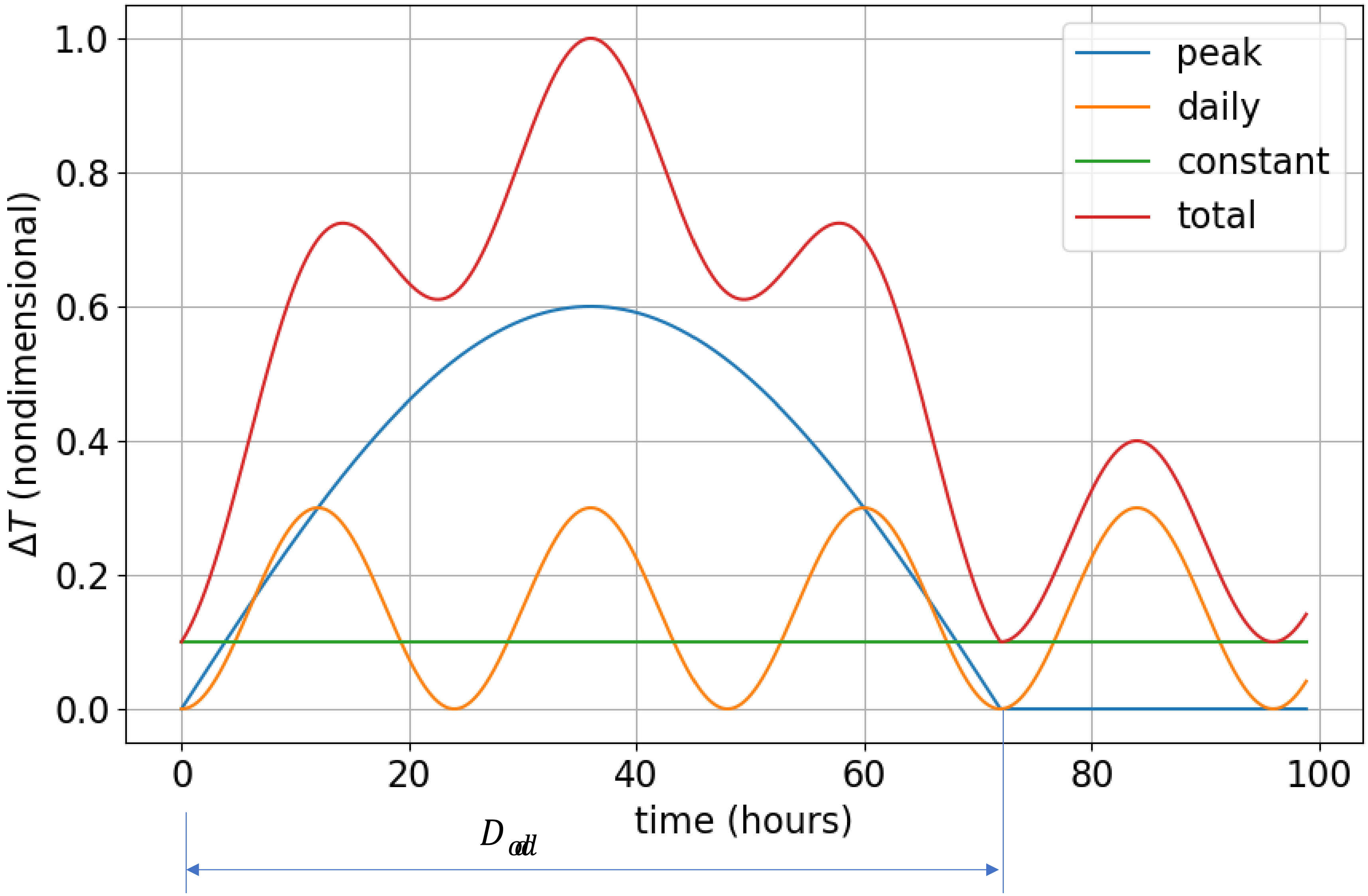
1. Calculate extreme event initiation and duration for many future years from stochastic sampling of the $M + \Delta M$ Markov process.
2. Sample extreme event duration normalized temperature and energy increases
3. Retrieve durations for each heat wave, reverse transform from -1...1 and denormalize duration to produce physical ΔT and ΔE for each extreme event
4. Solve for heat wave functional form parameters A,B,C

$$\Delta T(t, D, \Delta t_{min}) = \begin{cases} A \sin\left(\frac{\pi t}{D_{odd}}\right) + B\left(1 - \cos\left(\frac{2\pi t}{\Delta t_{min}}\right)\right) + C & t \leq D_{odd} \\ B\left(1 - \cos\left(\frac{2\pi t}{\Delta t_{min}}\right)\right) + C & t > D_{odd} \end{cases}$$

$$\Delta E = \frac{2AD_{odd}}{\pi} + BD - \frac{B\Delta t_{min}}{2\pi} \sin\left(\frac{2\pi D}{\Delta t_{min}}\right)$$

$$D_{odd} = \Delta t_{min}\left[\left\lfloor \frac{D}{\Delta t_{min}} \right\rfloor - \delta\left(\left\lfloor \frac{D}{\Delta t_{min}} \right\rfloor \mod 2\right)\right]$$

Extreme event functional form



Building Performance Demonstration

US DOE prototype EnergyPlus model (DOE, 2021)

- Total building area: 4,982 m^2
- ASHRAE 90.1 2019 model in climate zone
- 18 thermal zones

Typical meteorological year version 3 weather input for baseline weather

100 weather instances from software 1

5 socioeconomic pathway (SSP) mean temperature rise scenarios

9 years (2020,2025,…2060)

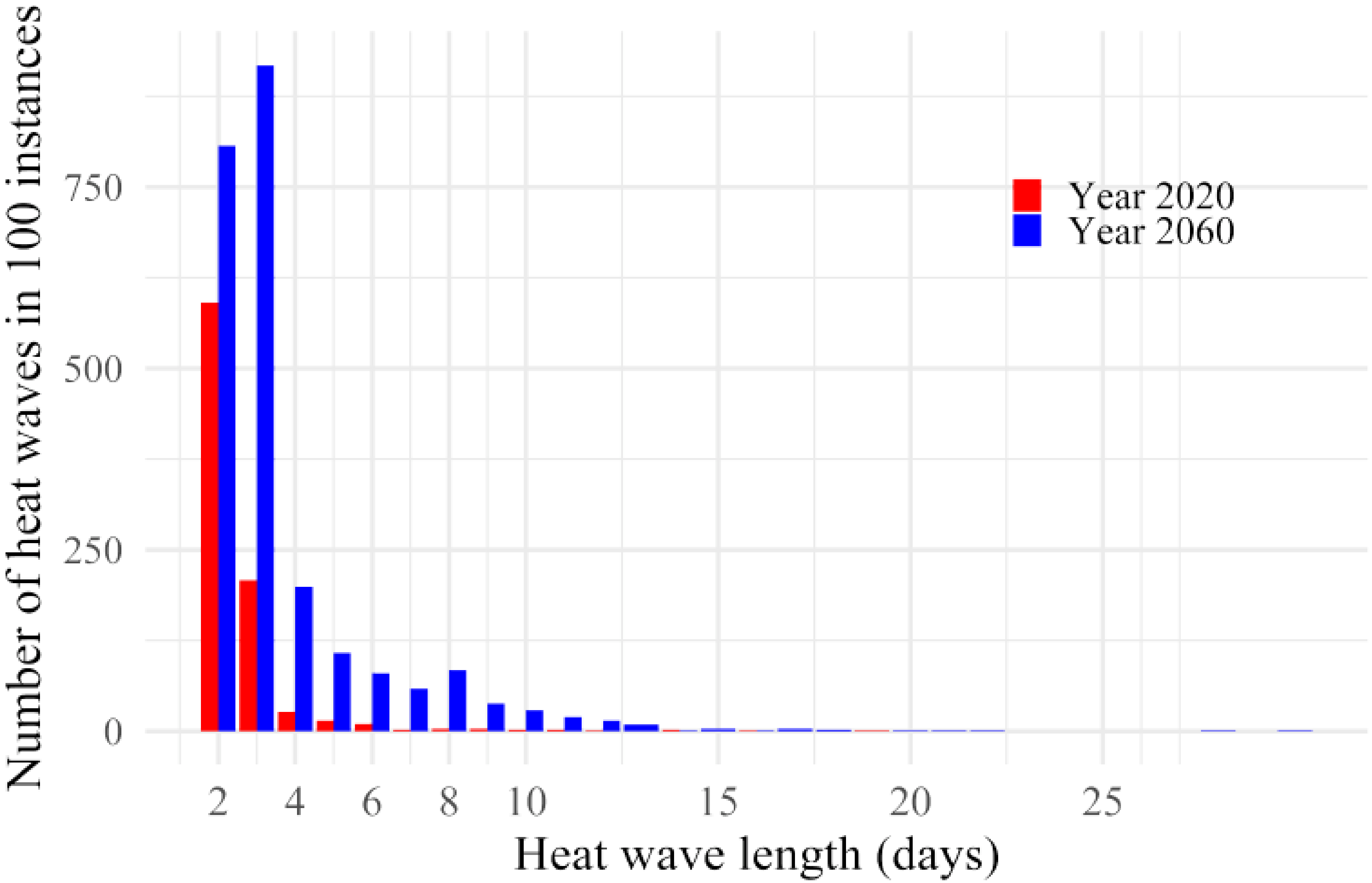
Heat waves characterized by station ID USW0002305 (Albuquerque airport)

- Climate norms 1991-2020
- Daily summaries 1931-2021

Verification

- Post processing of output showed heat waves were found to have accurate multiplication factors for increased frequency of heat waves

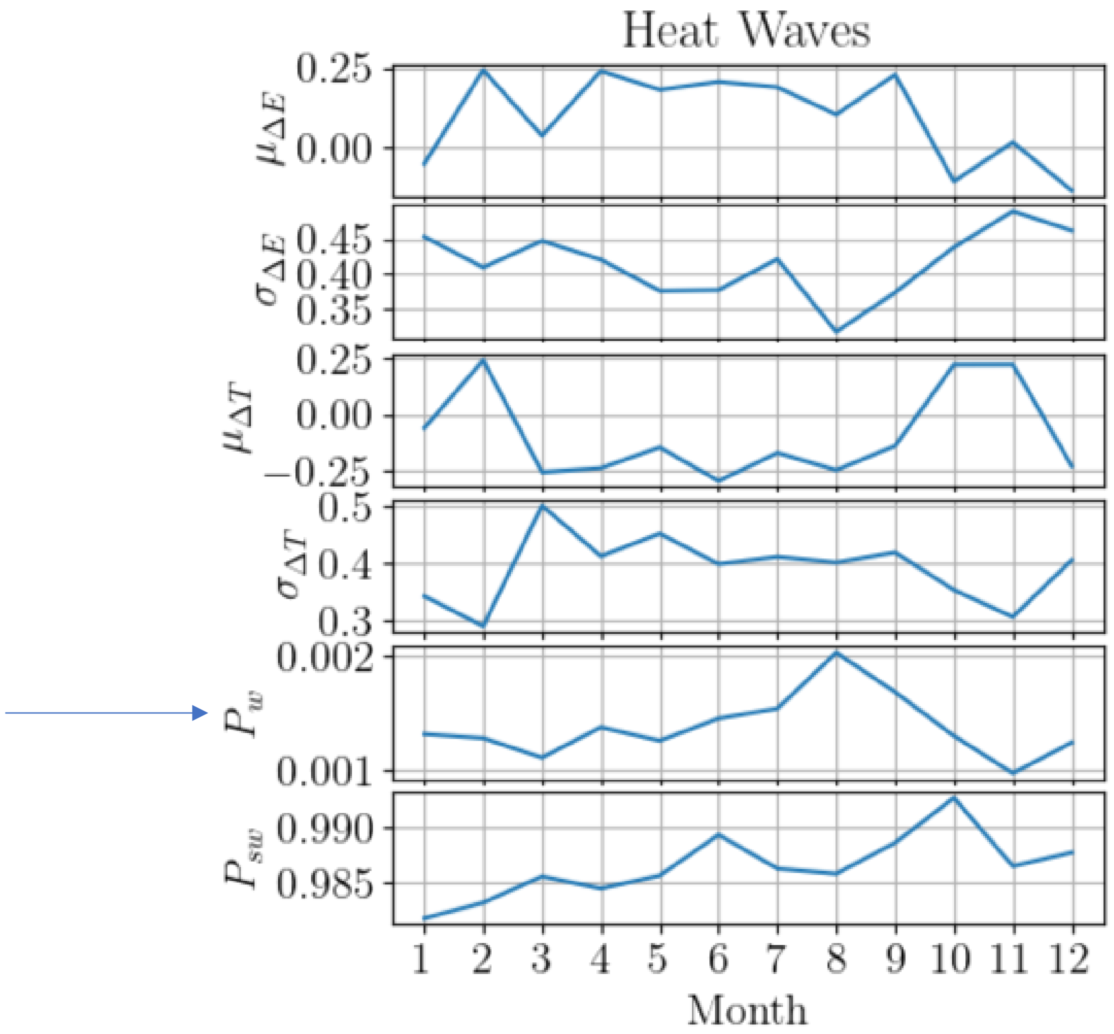
Event	IPCC	Software 1
10 yr, SSP8.5	2.5	2.8



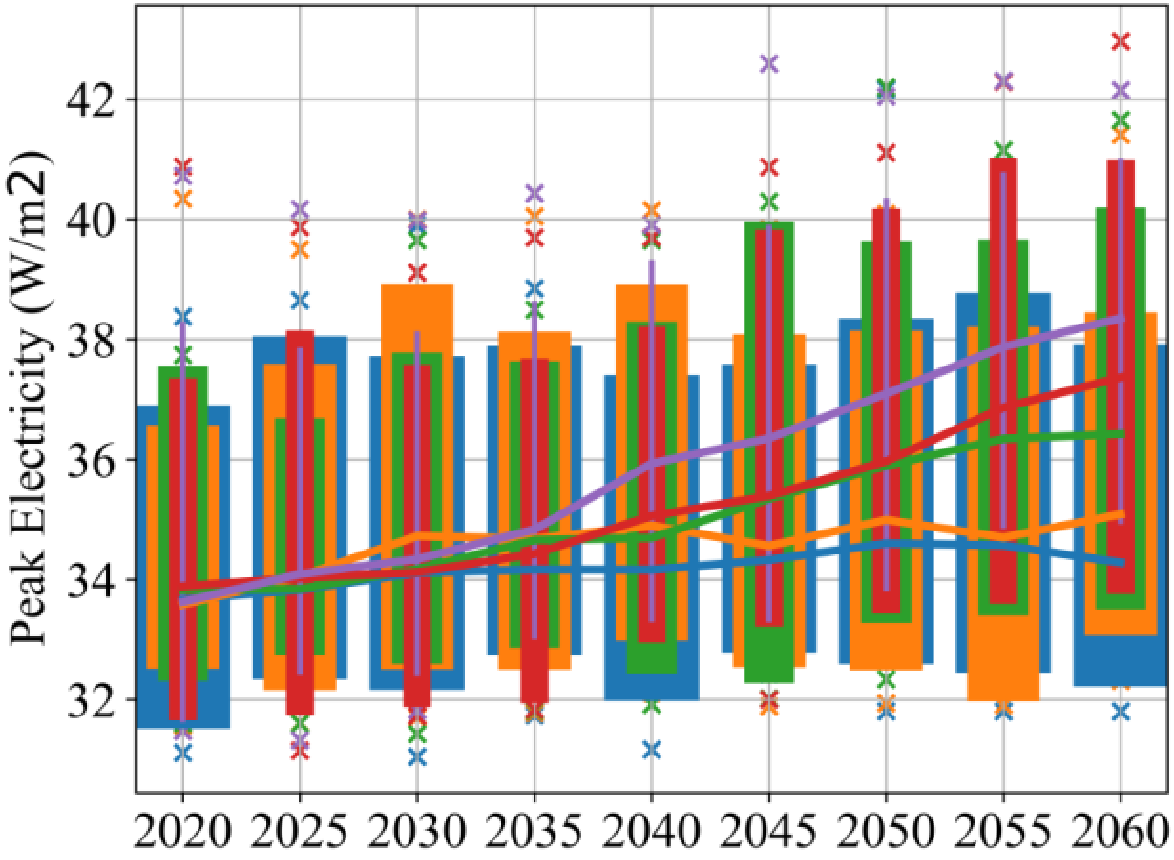
• **Verification**

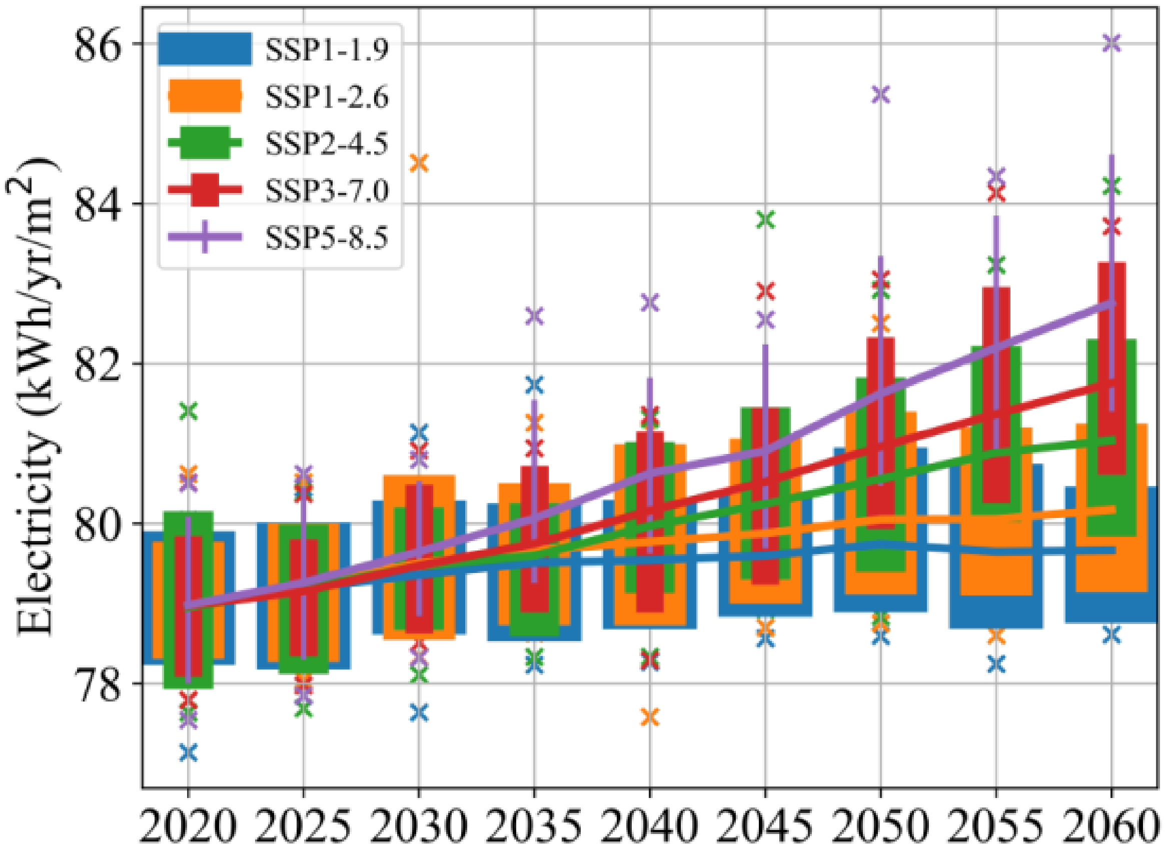
Probability of a heat wave increases in summer as expected

Duration peak lags



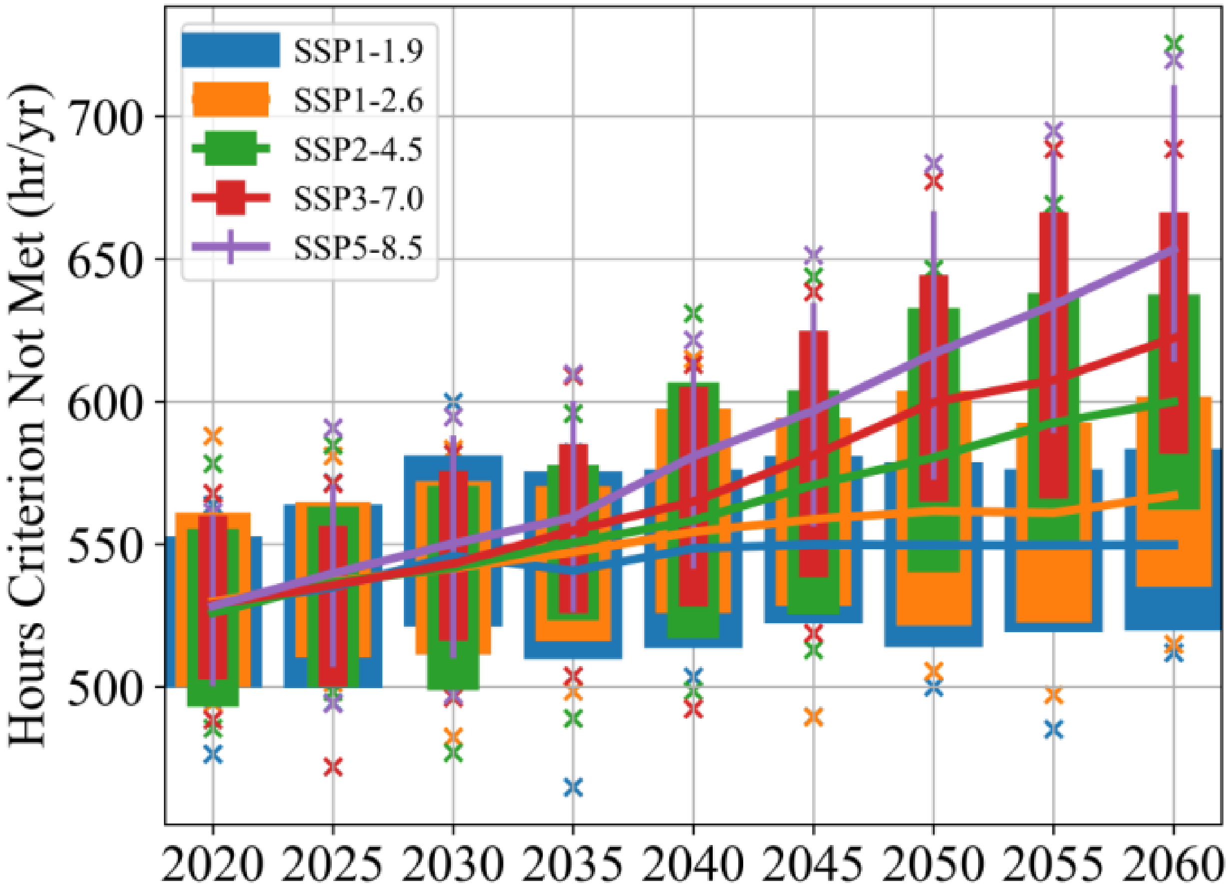
Results: Increase in Electric Load



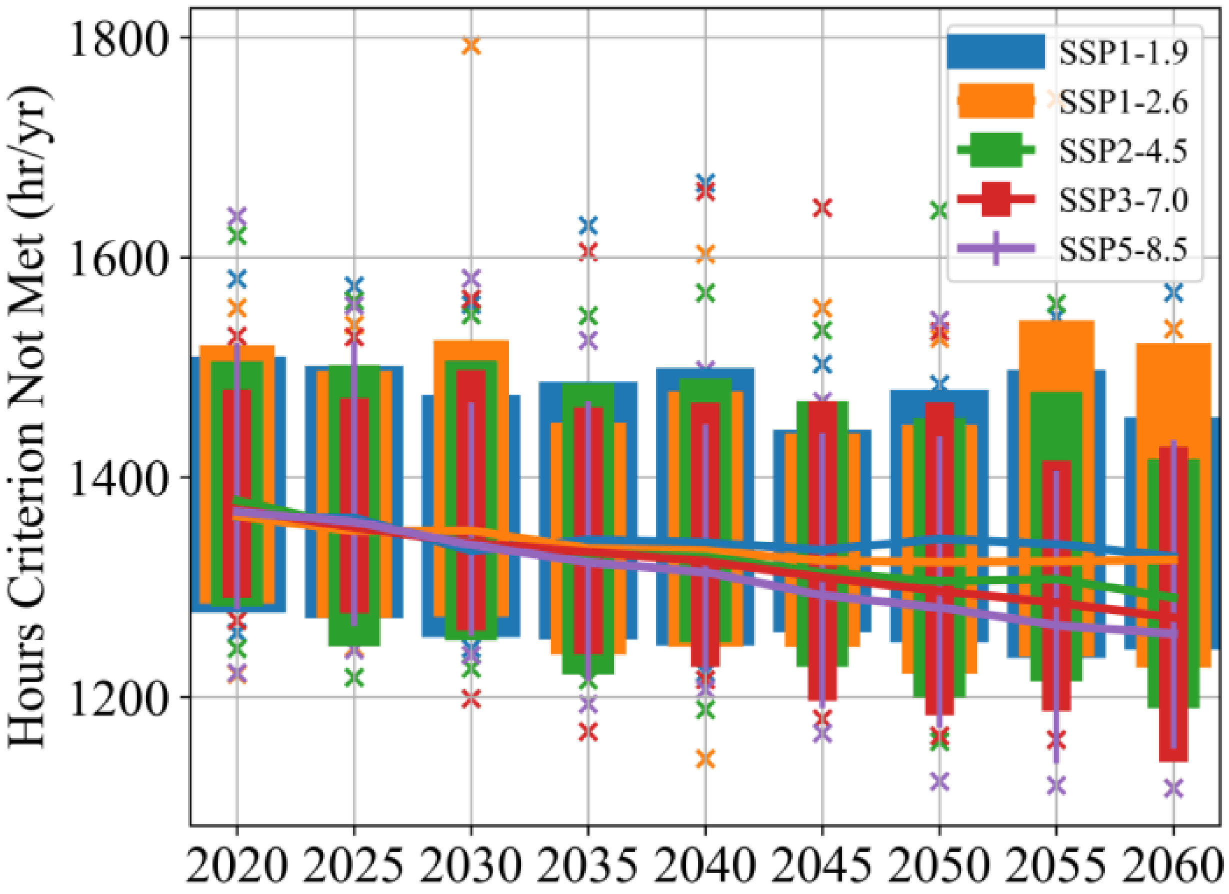


Thermal Comfort

Hours cooling setpoint not met



Hours not comfortable based on simple ASHRAE 55-2004 criterion



Conclusions

- An algorithm for shifting extreme events in a probabilistic context has been successfully applied to building energy modeling
- Future studies need to combine extreme weather with power outages and building system failures
- Significant enhancements are envisioned:

1. Validate MEWS against climate model future weather for several cases
2. Show convergence of multi-parameter stochastic resilience analysis
3. Generalize heat wave definition and functional form and show that it mimic weather
4. Extend heat waves to include humidity, pressure, wind, cloud, and other effects

Bibliography

DOE. 2021. Department of Energy Commercial Prototype Models website. https://www.energycodes. gov/prototype-building-models.
DOE. 2022. Energy Plus website. https://energyplus. net/

Villa, Daniel L. 2021b. "Institutional heat wave analysis by building energy modeling fleet and meter data." Energy and Buildings 237:110774.

Villa, Daniel. 2021a. Multi-scenario Extreme Weather Simulator GitHub repository. https://github.com/ sandialabs/MEWS.

QUESTIONS?

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