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The One Where Two Models Actually Agree on Something: Simulations of Building Electricity Consumption Under Climate and Population Change

Casey Burleyson, Gokul Iyer, Mohamad Hejazi, Sonny Kim, Page Kyle, Jennie Rice, Amanda Smith, Todd Taylor, Nathalie Voisin, and Yulong Xie

U.S. DEPARTMENT OF ENERGY BATTELLE

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Casey 101

New York City
Population: ~8,500,000

Richland, WA
Population: ~55,000

Mt. Pleasant, NC
Population: ~1,000

NC State University
Student Population: ~35,000

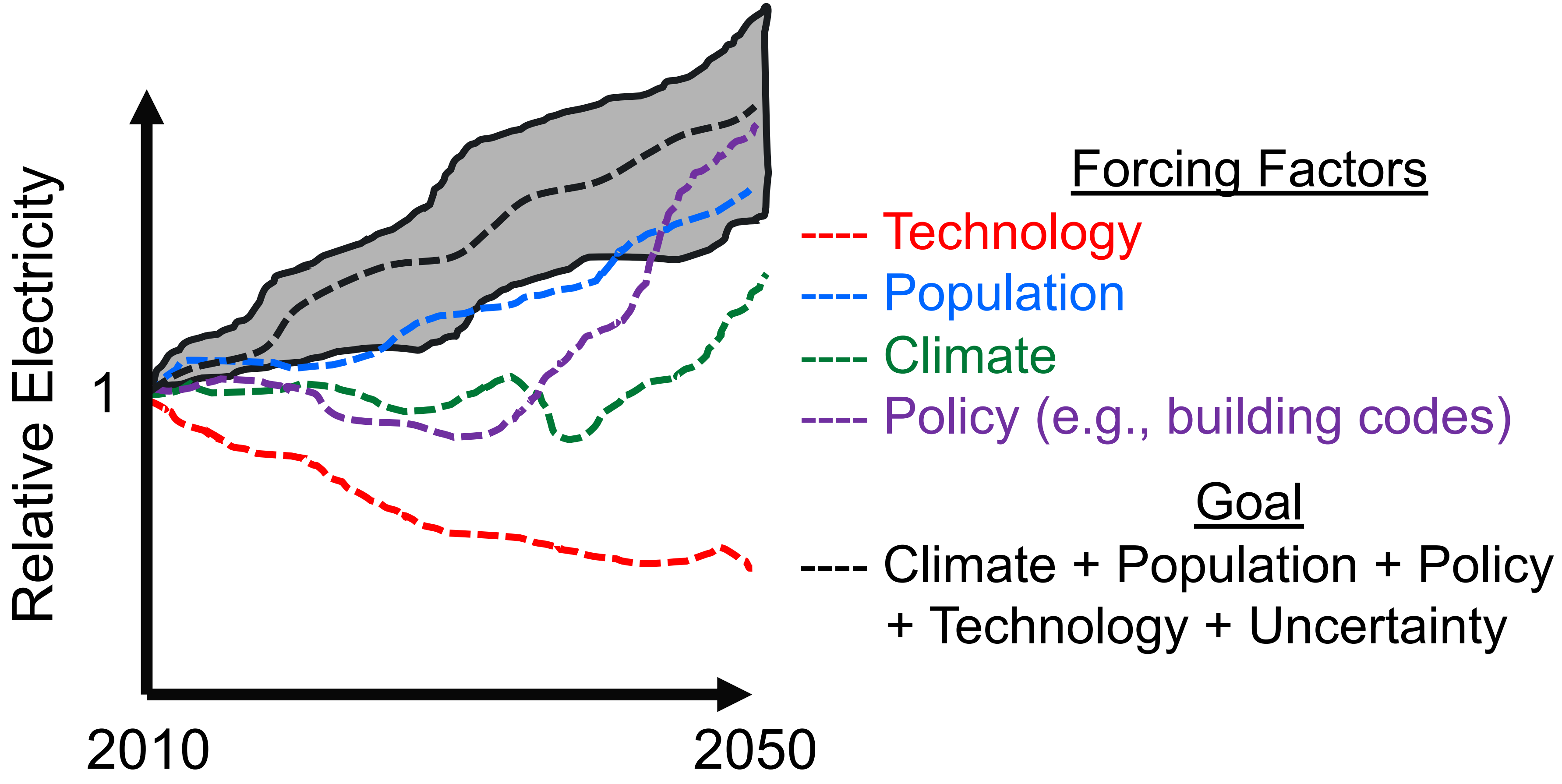

REXCELLENT!

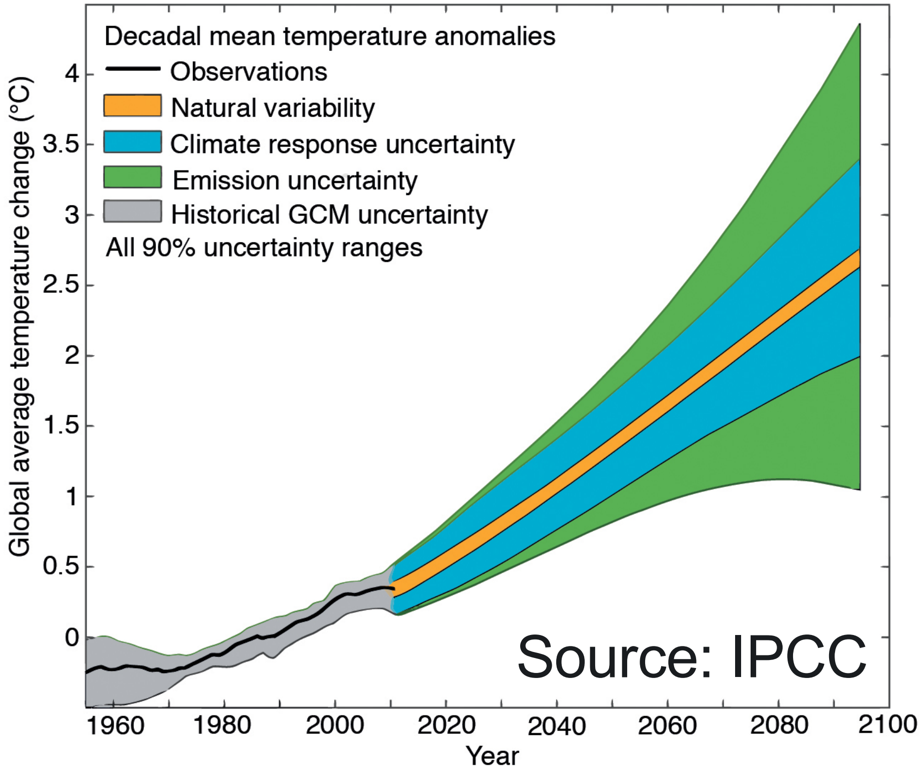
Credit: Todd Kirkland/Getty Images

Credit: Travel + Leisure

Building Electricity Demand Responds to Multiple Stressors

Challenge: Researchers from multiple communities are interested in understanding and projecting changes in building electricity demand due to changes in weather/climate, population, policy, and technology.





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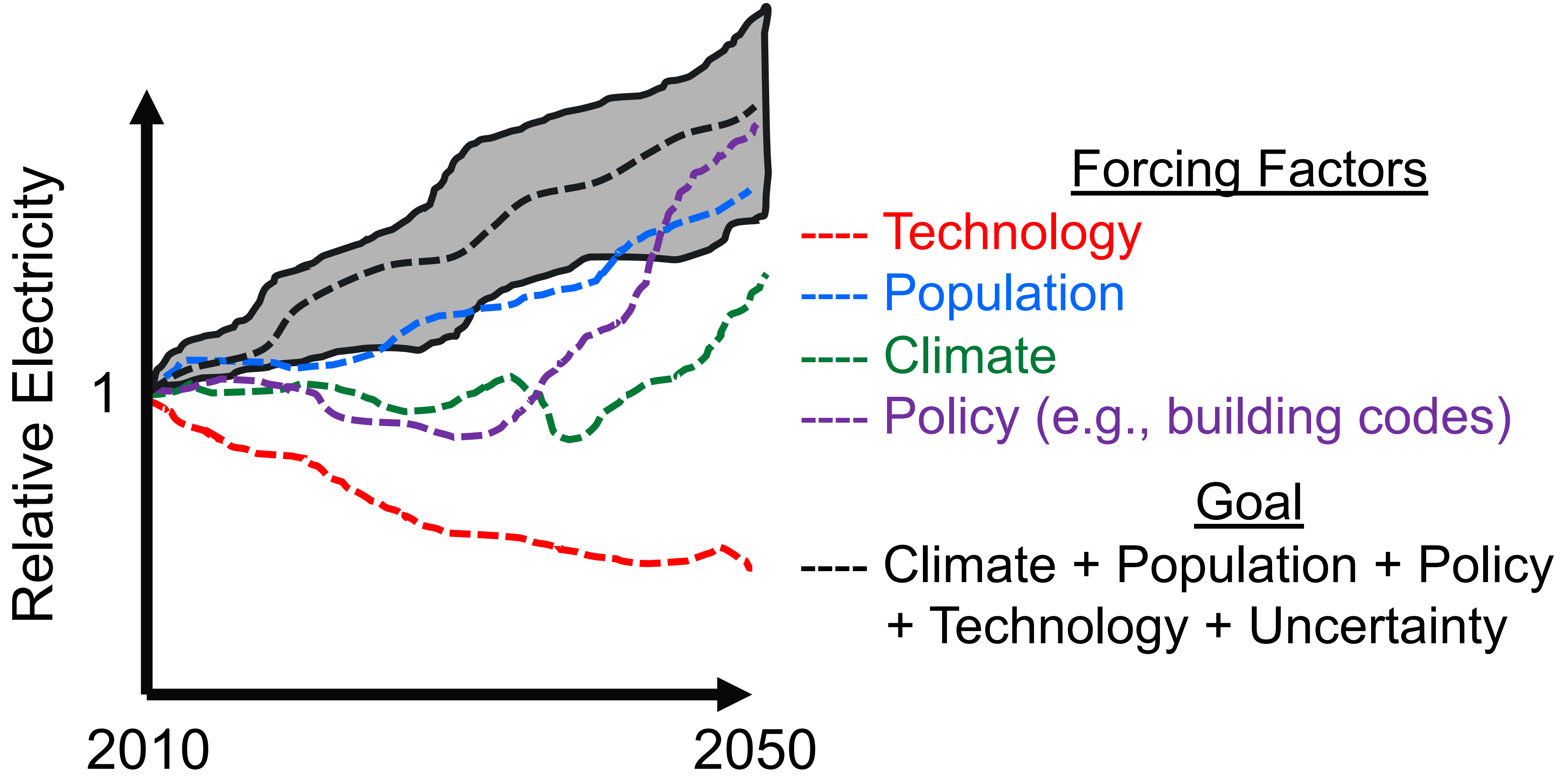
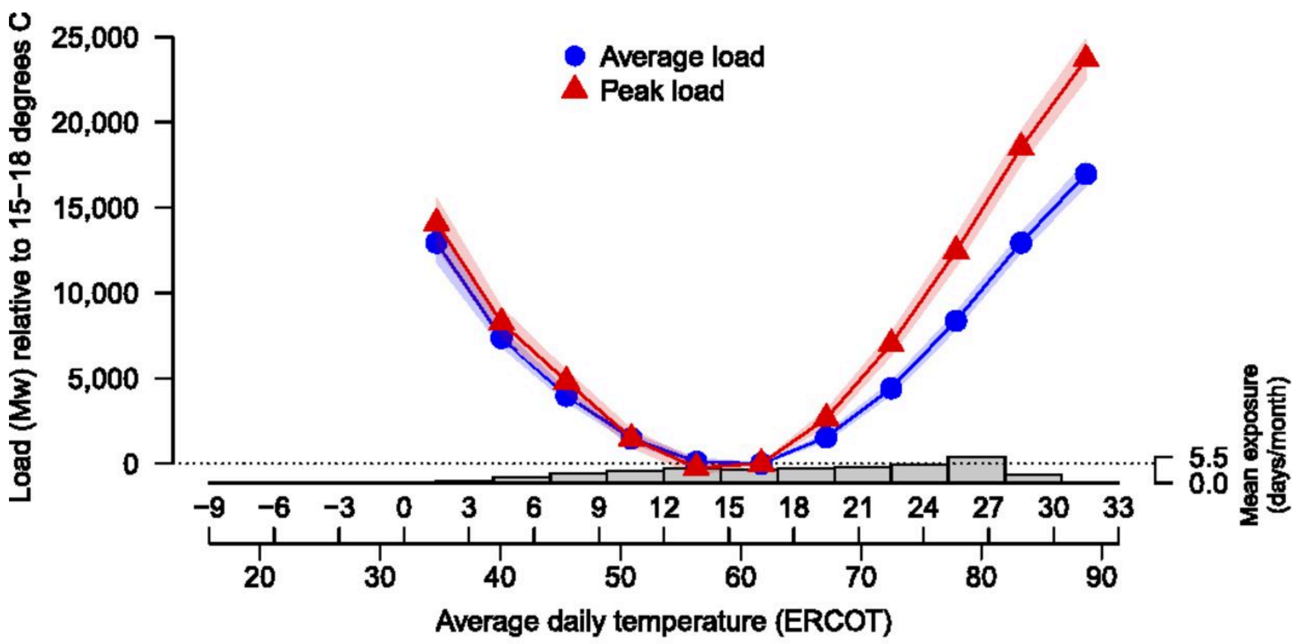


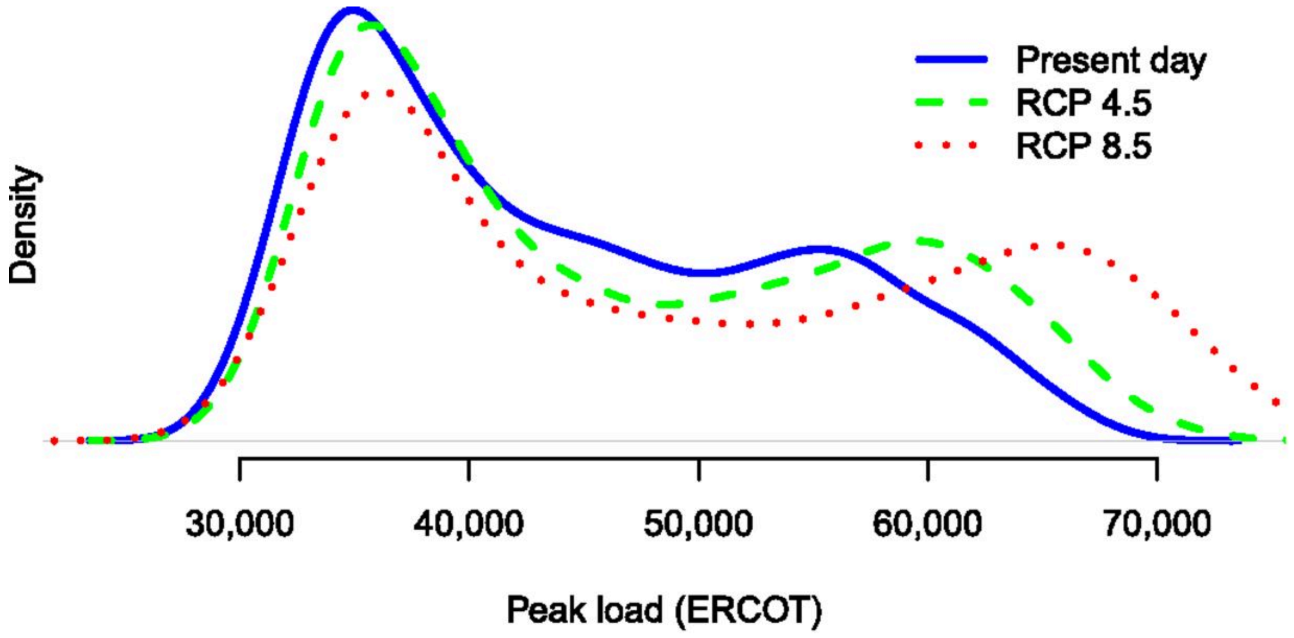
Example Applications

- Planning electricity infrastructure expansion
- Understanding future grid stress during extreme weather events

Empirical Modeling Approaches

Given enough data, you could formulate a statistical model relating the current state of the forcing factors to current electricity demand.



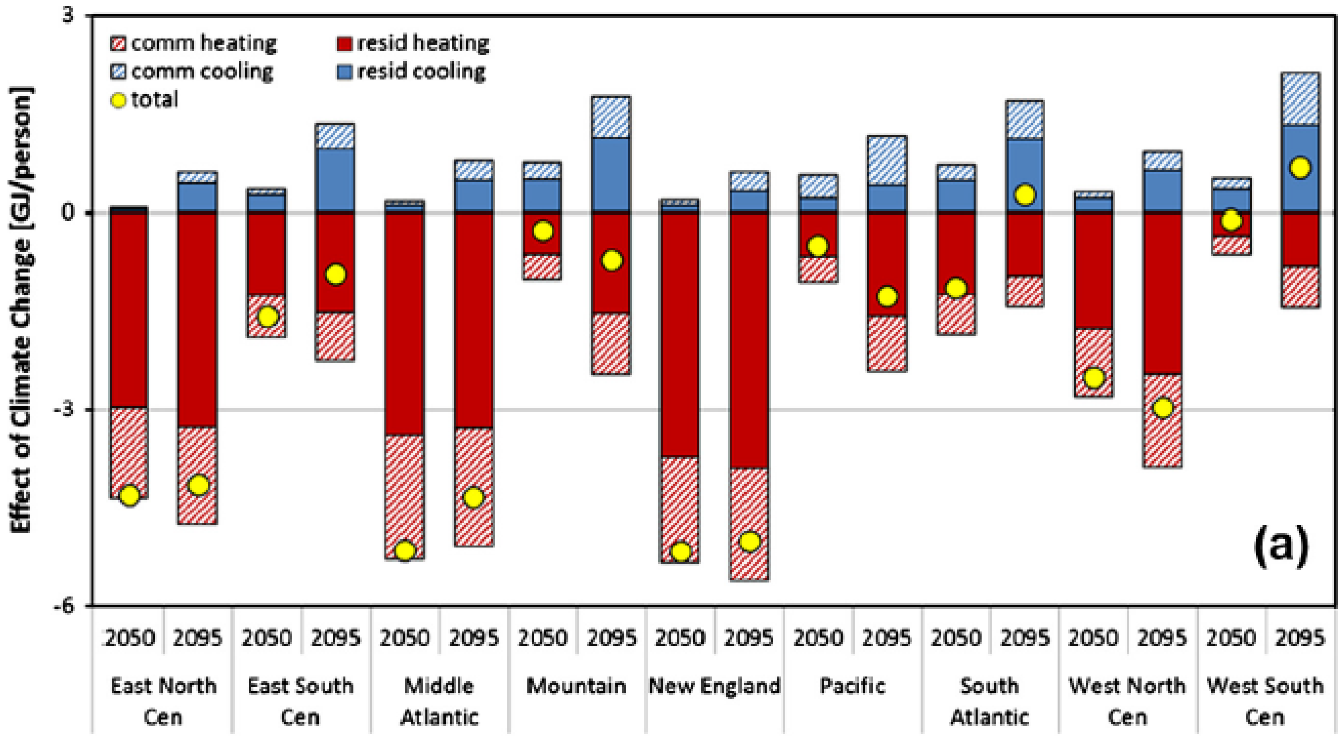


Auffhammer et al. 2017 – PNAS (Figs. 1 and 2)

Economic Modeling Approaches

Building electricity demand in GCAM-USA is determined for each state, year, sector (residential and commercial), and service (e.g., heating, cooling, and others), based on population, income, technology, energy prices, and average annual climate.

$$
\begin{cases}
Q^i_{heating} = k^i_{heating}(HDD^i \cdot Eff \cdot SR - G^i)\left[1 - \exp\left(-\frac{\ln 2}{\mu_j} \cdot \frac{Y^i}{P_j}\right)\right] \\
Q^i_{cooling} = k^i_{cooling}(CDD^i \cdot Eff \cdot SR + G^i)\left[1 - \exp\left(-\frac{\ln 2}{\mu_j} \cdot \frac{Y^i}{P_j}\right)\right] \\
Q^i_{others} = k^i_{others} q^i_{others}\left[1 - \exp\left(-\frac{\ln 2}{\mu_j} \cdot \frac{Y^i}{P_j}\right)\right]
\end{cases}
$$



Zhou et al. 2014 – Applied Energy (Eq. 2 and Fig. 6a)

Physical Modeling Approaches

Alternatively, you could simulate the electricity demand of specific buildings using a process-based model (e.g., EnergyPlus [*E*+]) and then force that process-based model with projections of future conditions.

E+ Parameters
HVAC type, wall type, roof type, insulation, windows, schedule, etc.

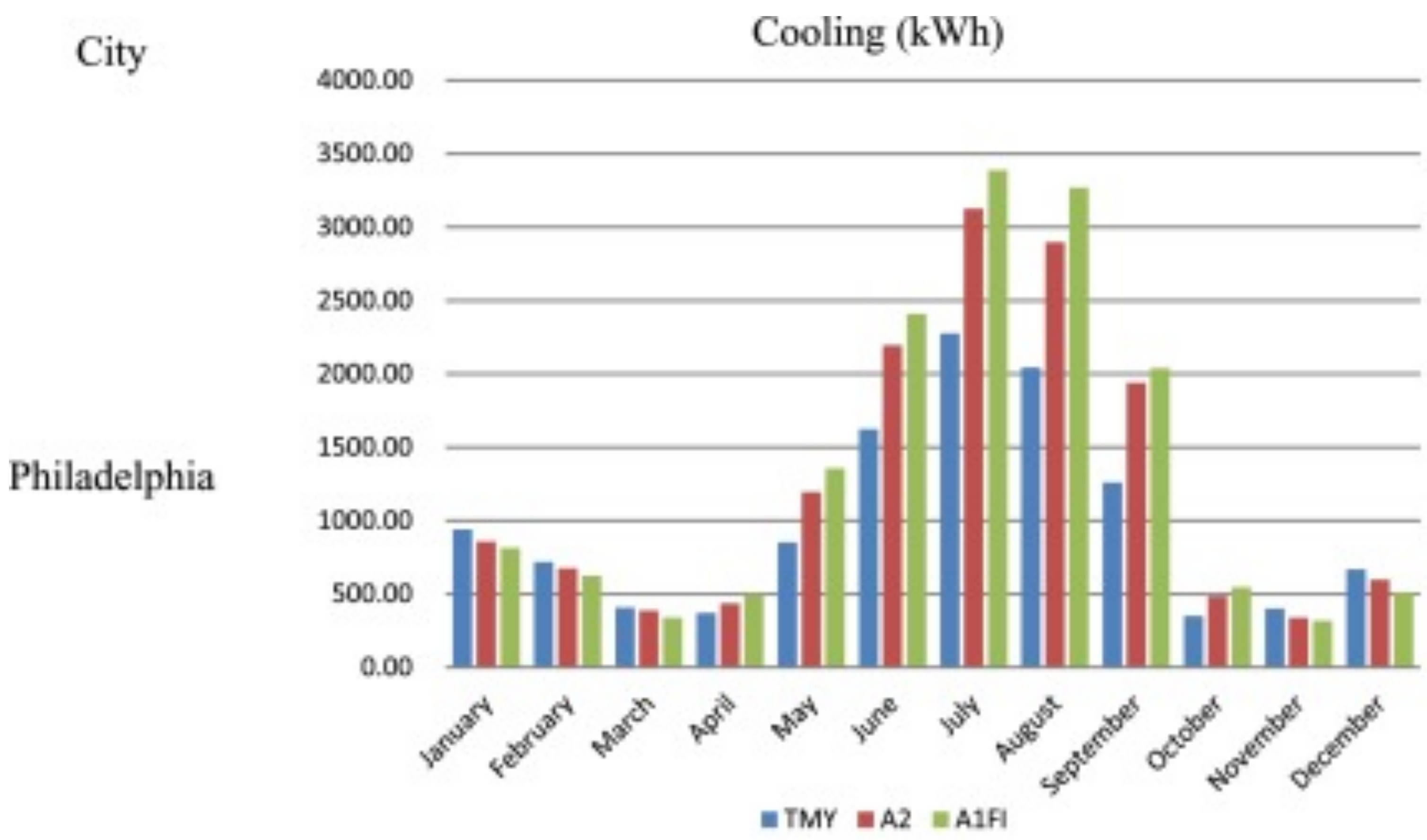
+

Weather data

Hourly electricity demand for 1 year

Physical Modeling Approaches

Shen (2017) simulated future heating and cooling energy consumption for 1 residential and 1 commercial building in 4 regions for 2 climate scenarios.



Shen 2017 – *Energy and Buildings* (Fig. 5)

Challenges

1) Diversity in the building stock is underrepresented.
2) Spatial variance in current and future climate is not captured by a single location or a small subset of locations.

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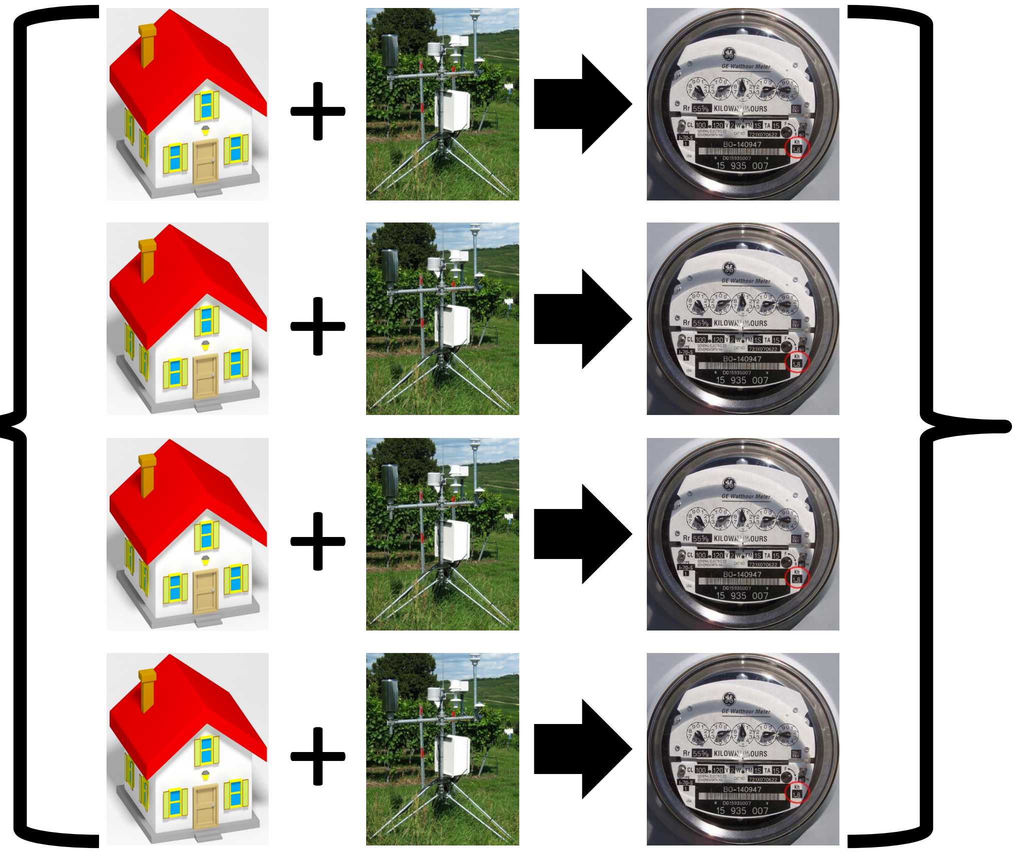
PNNL's Building ENergy Demand (BEND) Model

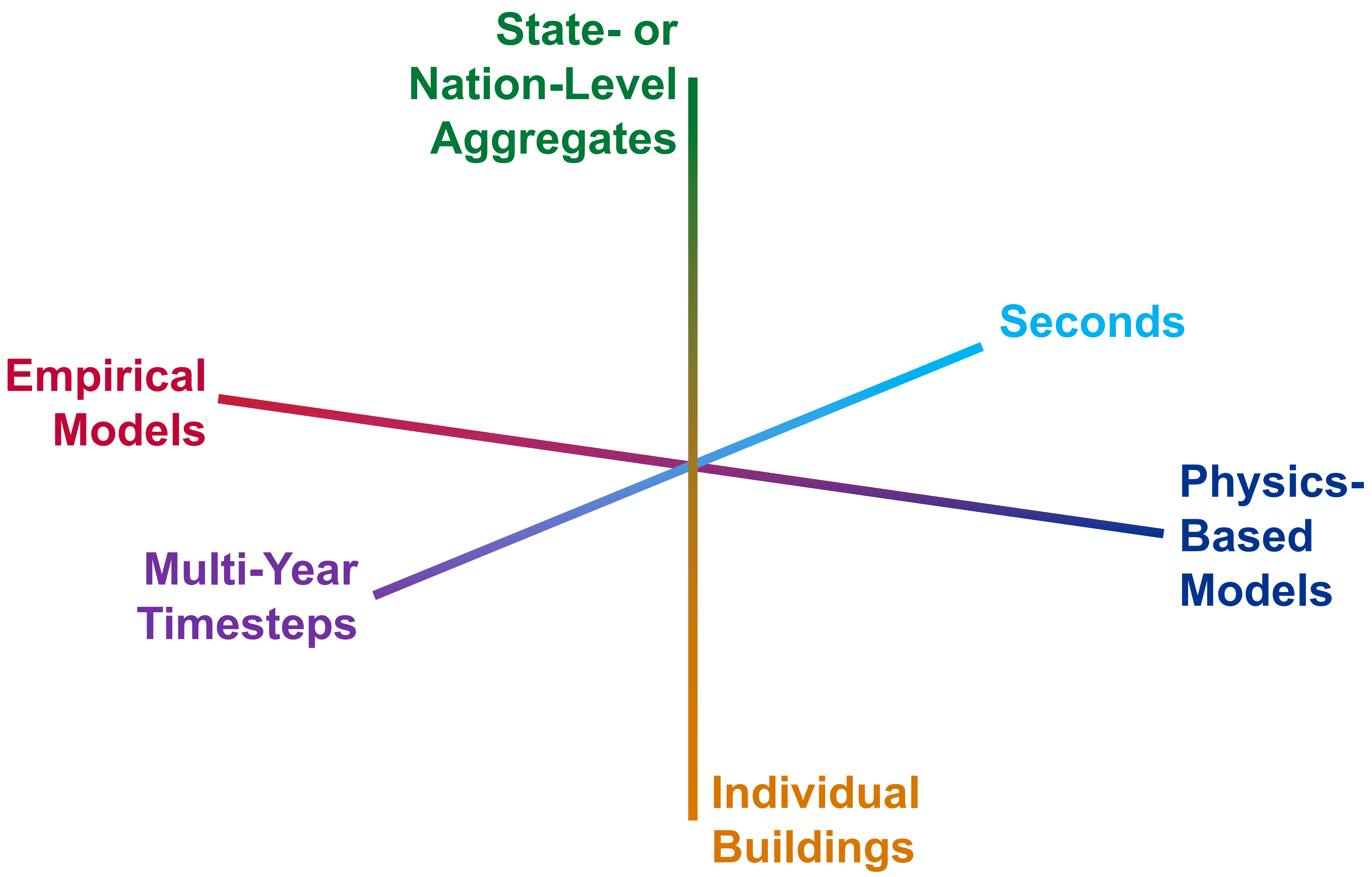
Novelty: Rather than simulating a single building in a single location and then extrapolating from the results, simulate a (very) large representative sample of *N* residential and commercial buildings over a distributed area.

Building Electricity Demand = Sum

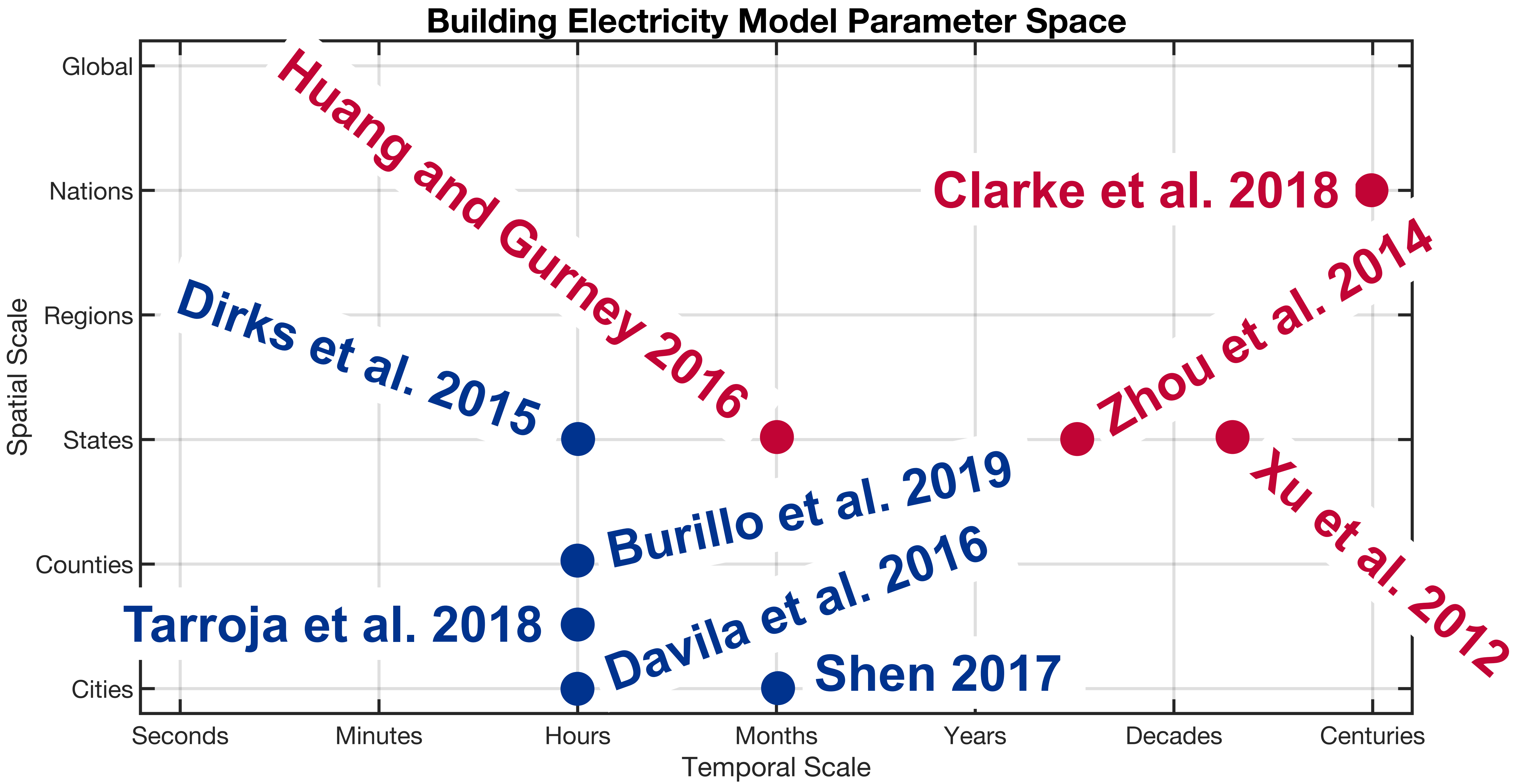


N = *1:100,000+*

Approaches to Building Electricity Modeling

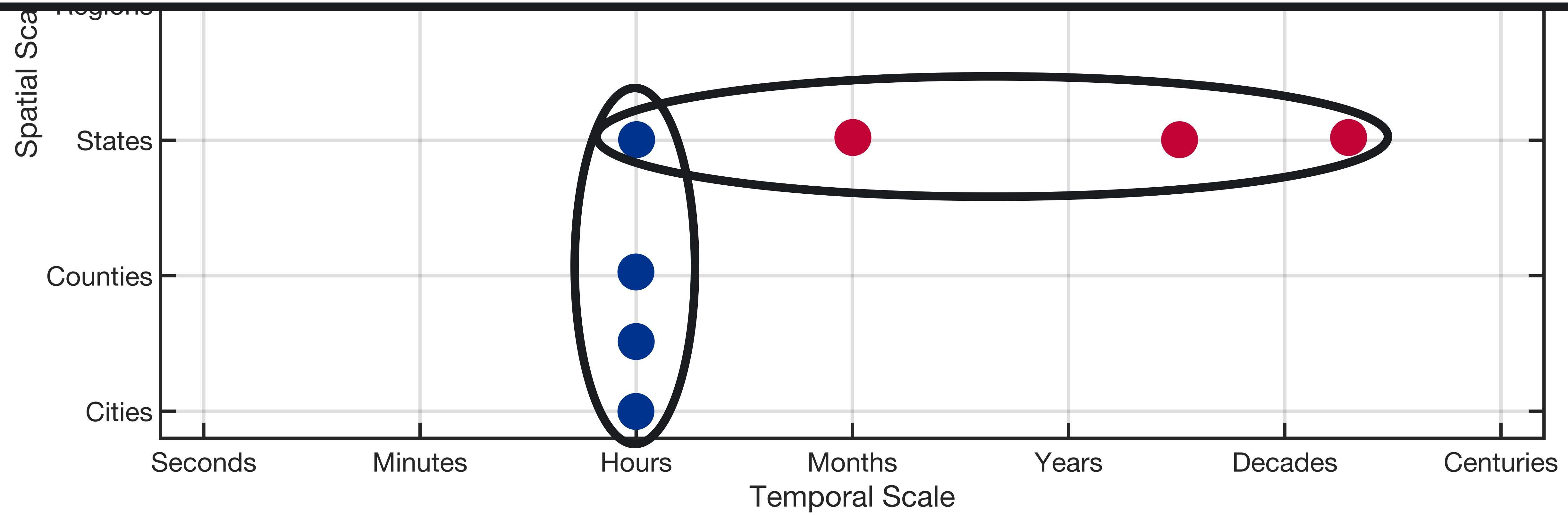


Approaches to Building Electricity Modeling



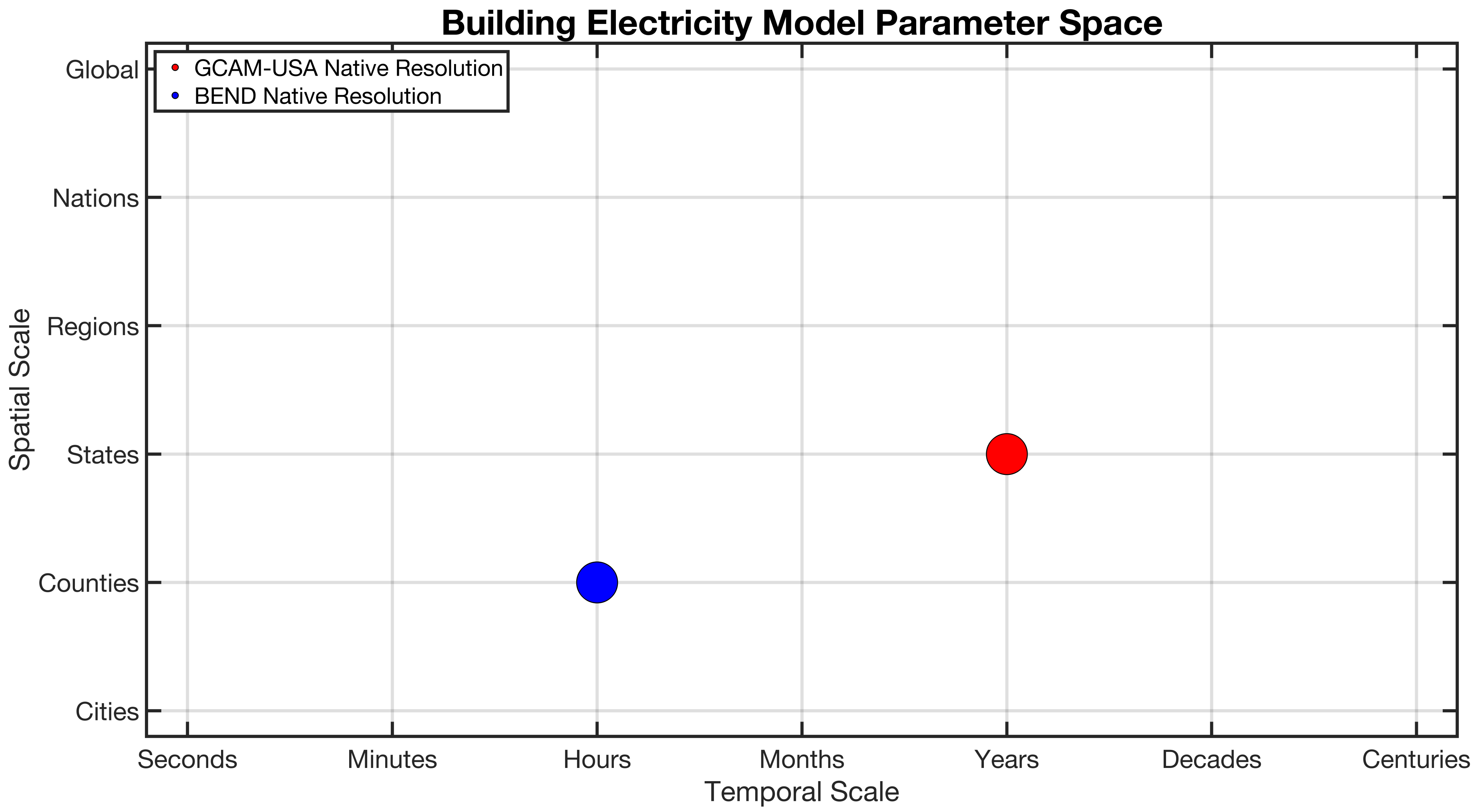
Reconciling Studies Across Scales

Challenges:
- Different climate and/or population scenarios
- Different climate models
- Different cities, counties, states, etc.
- Different time horizons
- Different methods for processing the input datasets



Climate and Population Impacts on Building Electricity Demand

Science Question: How does the impact of climate and population changes vary between models of building electricity consumption operating at different places across the methodological, spatial, and temporal spectra?



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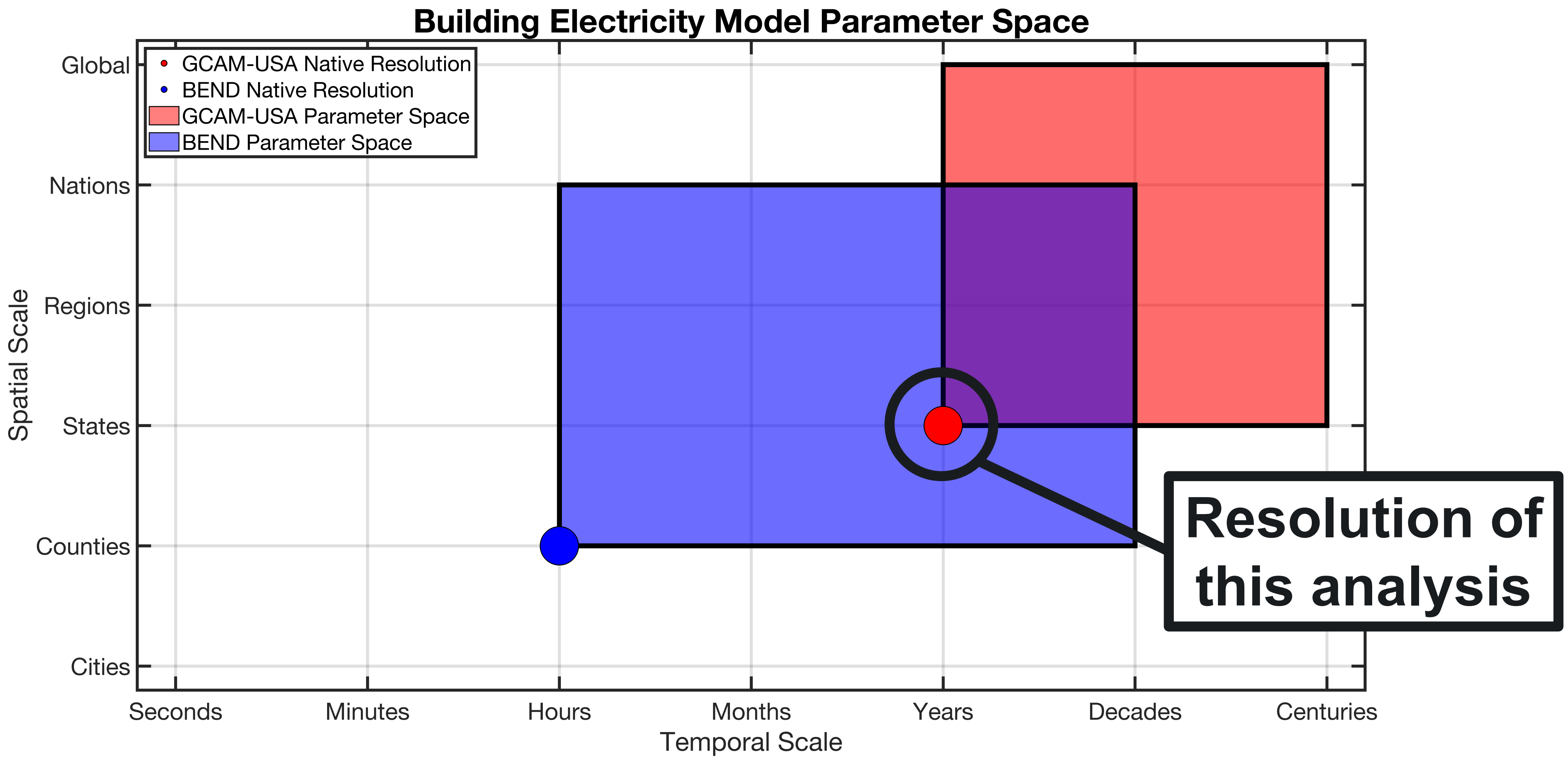

Formulation of the BEND Model

We used the Commercial Building Energy Consumption Survey (CBECS) and Residential Energy Consumption Survey (RECS) building surveys to construct a representative population of building models in the western U.S.

Group →

Bulk Characteristics

Size [N = 6]
Vintage [N = 7]
Type [N = 16]
Location [N = 15]
+
Each building is given a weight that reflects how many other buildings it represents

Infer →

E+ Parameters

HVAC type
Wall type
Roof type
Insulation
Windows
Schedule
…

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Type [N = 16], Size [N = 6], Vintage [N = 7], Location [N = 15]

Commercial Buildings [N = 11]

Building Type			
1	Public Assembly	7	Retail
2	School	8	Office
3	Food Sales	9	Public Safety
4	Food Service	10	Warehouse
5	Health Care	11	Other
6	Lodging		

Residential Buildings [N = 5]

	Building Type
1	Mobile Home
2	Single Family Home (Detached)
3	Single Family Home (Attached)
4	Apartment (2-4 Units)
5	Apartment (5+ Units)

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Type [N = 16], Size [N = 6], Vintage [N = 7], Location [N = 15]

	All Commercial Buildings	Mobile Home	Single Family Home (Detached)	Single Family Home (Attached)	Apartment (2-4 Units)	Apartment (5+ Units)
1	< 5,000	< 700	< 1,350	< 1,200	< 2,100	< 5,570
2	5,000-10,000	700-850	1,350-1,800	1,200-1,600	2,100-2,700	5,570-8,050
3	10,000-25,000	850-1,000	1,800-2,300	1,600-2,000	2,700-3,300	8,050-11,900
4	25,000-50,000	1,000-1,200	2,300-2,800	2,000-2,600	3,300-4,500	11,900-21,400
5	50,000-100,000	1,200-1,450	2,800-3,650	2,600-3,600	4,500-6,900	21,400-53,400
6	> 100,000	> 1,450	> 3,650	> 3,600	> 6,900	> 53,400

Range of sizes (in ft^2) in each size bin

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Type [N = 16], Size [N = 6], Vintage [N = 7], Location [N = 15]

	Vintages
1	< 1946
2	1946-1960
3	1961-1973
4	1974-1979
5	1980-1986
6	1987-1996
7	> 1997

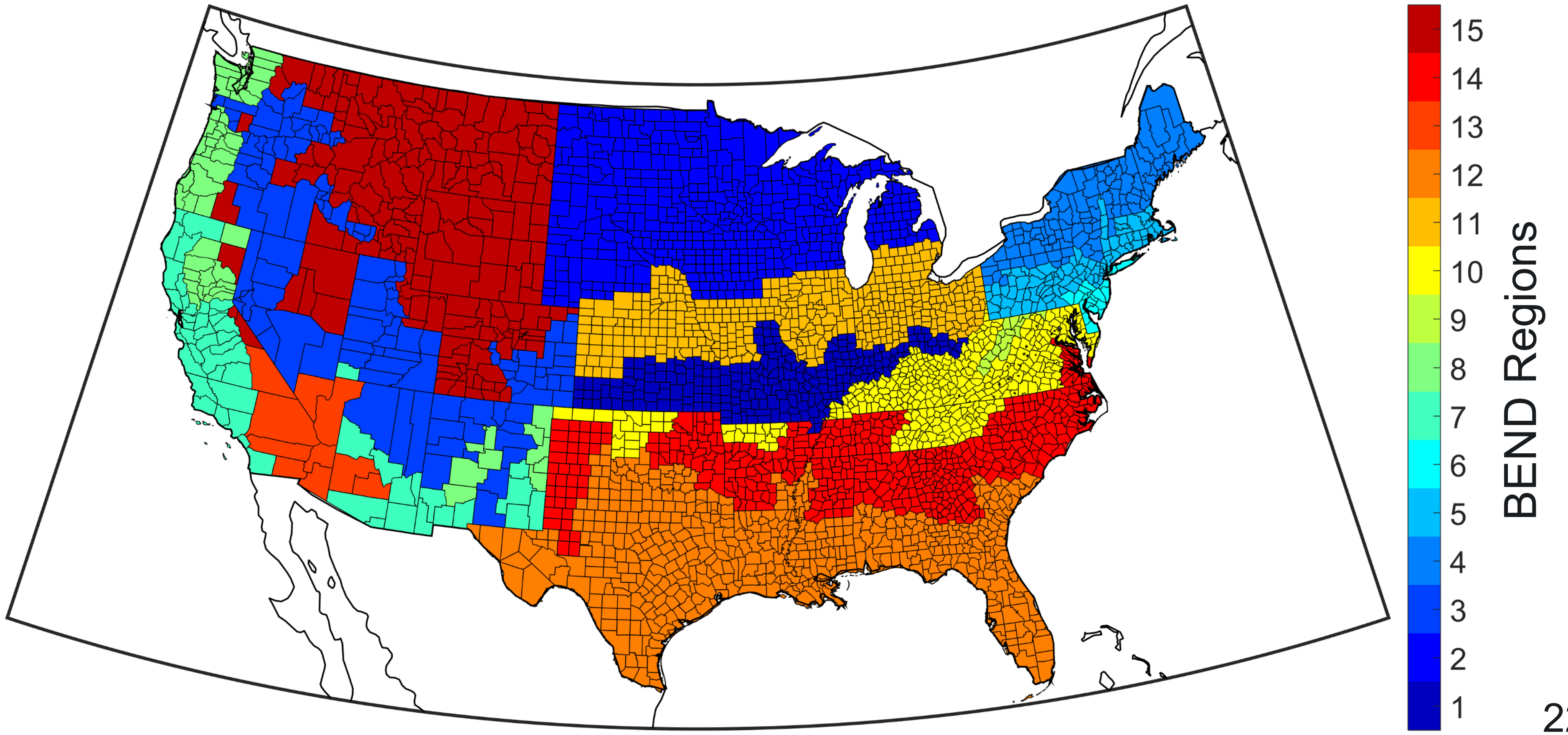
Range of year built in each vintage bin

Formulation of the BEND Model

We used the Commercial Building Energy Consumption Survey (CBECS) and Residential Energy Consumption Survey (RECS) building surveys to construct a representative population of building models in the western U.S.

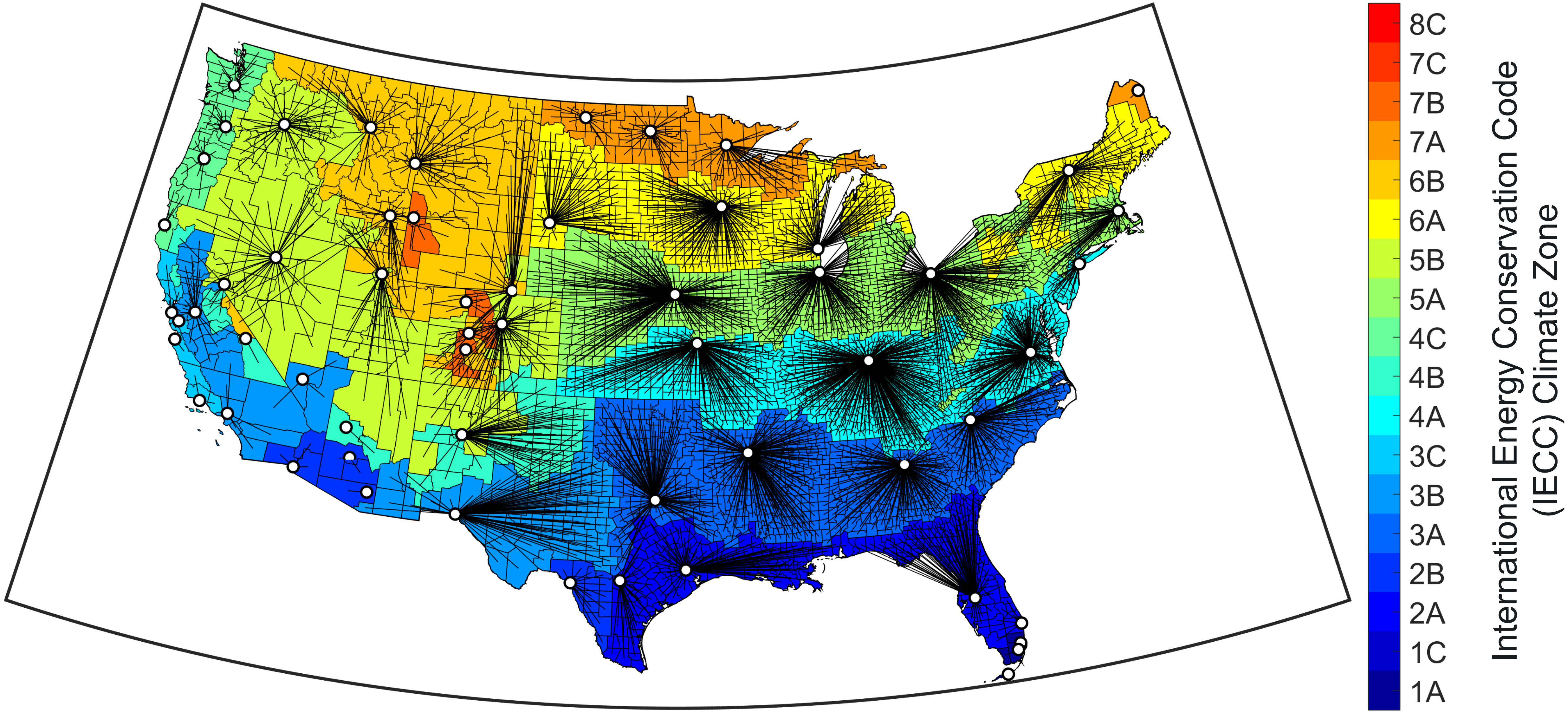
Type [N = 16], Size [N = 6], Vintage [N = 7], Location [N = 15]

There are 15 unique combinations of regional groupings in the building surveys. These 15 regions are the base spatial scale for the representative building population in BEND.



Formulation of the BEND Model

Hourly meteorology from weather stations drives the hour-to-hour variability of the EnergyPlus runs for each representative building in BEND.



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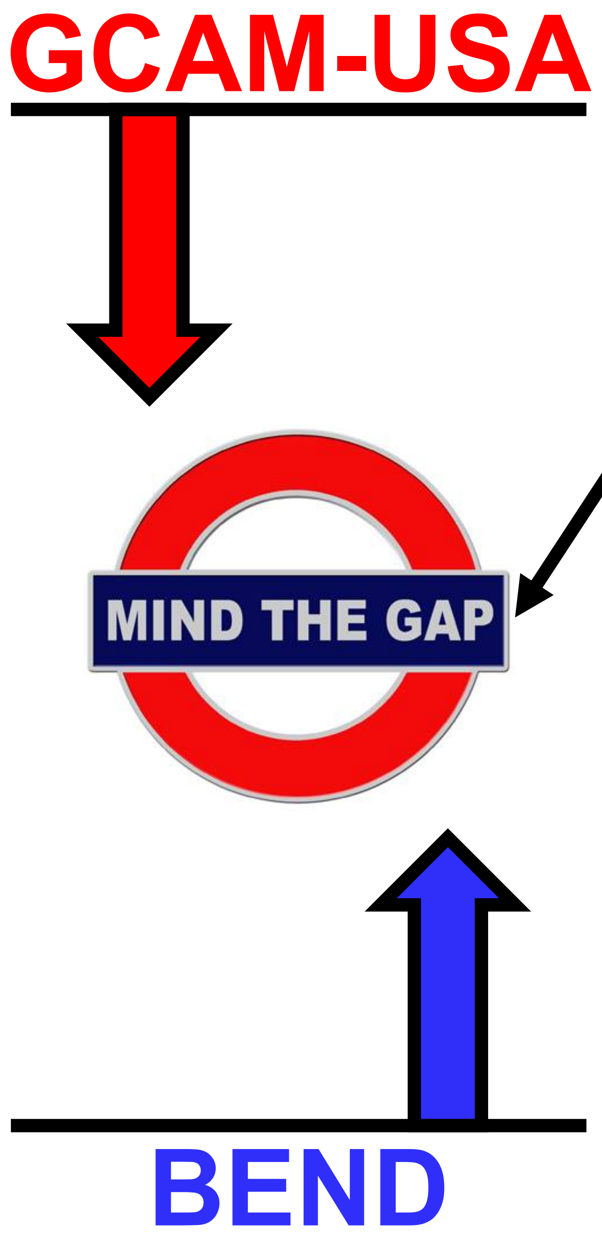
Model Formulation and Structure



GCAM-USA	BEND
Economic Model	Process-Based Model
Cross-Sectoral Impacts	Single Sector
Multiple Spatial Scale (States+)	Multiple Spatial Scales (Counties+)
Annual Time-Step	Hourly Time-Step
Endogenous and/or Exogenous Evolution of Technology	Endogenous and/or Exogenous Evolution of Technology
Sensitive to Climate	Sensitive to Climate via Weather
Sensitive to Population	Sensitive to Population via Floor Space

The overall strategy of the experiment is to reconcile as many variables as possible in order to understand how the model's different structures contribute to differences in their projections.

Experimental Design

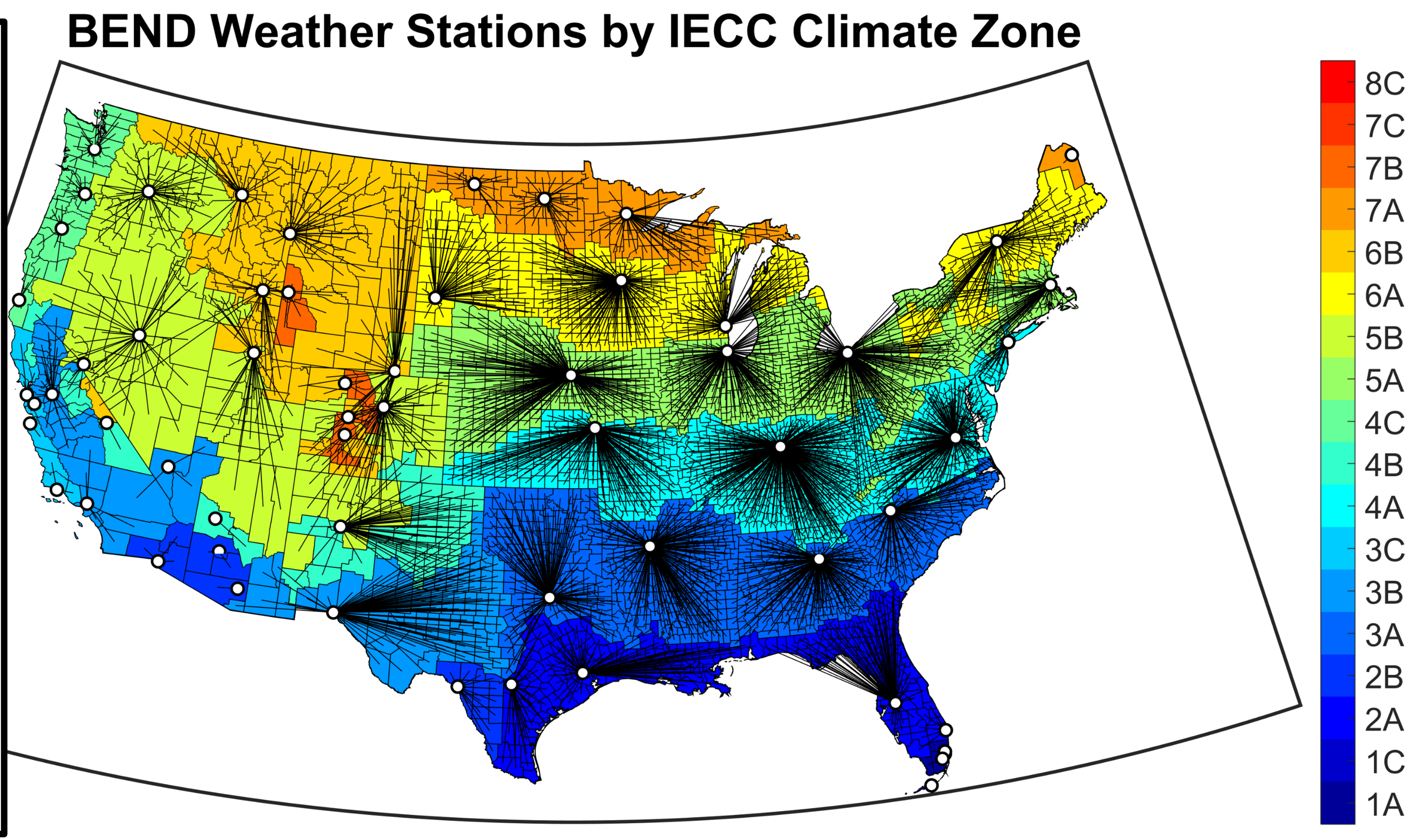
We ran 4 experiments using different combinations of climate/radiative forcing scenarios (RCP 4.5 and RCP 8.5) and population scenarios (SSP 3 and SSP 5) over the western U.S.

	SSP3	SSP5	Label
RCP 4.5	X		LowRF-LowPop
RCP 4.5		X	LowRF-HighPop
RCP 8.5		X	HighRF-HighPop
No Climate Change Impacts		X	NoCCI-HighPop

Homogenizing Climate Projections

To minimize the differences in climate, we adapted the weather forcing of BEND into the standard HDD/CDD approach for GCAM-USA.

1. BEND uses 4 weather stations per IECC climate zone.



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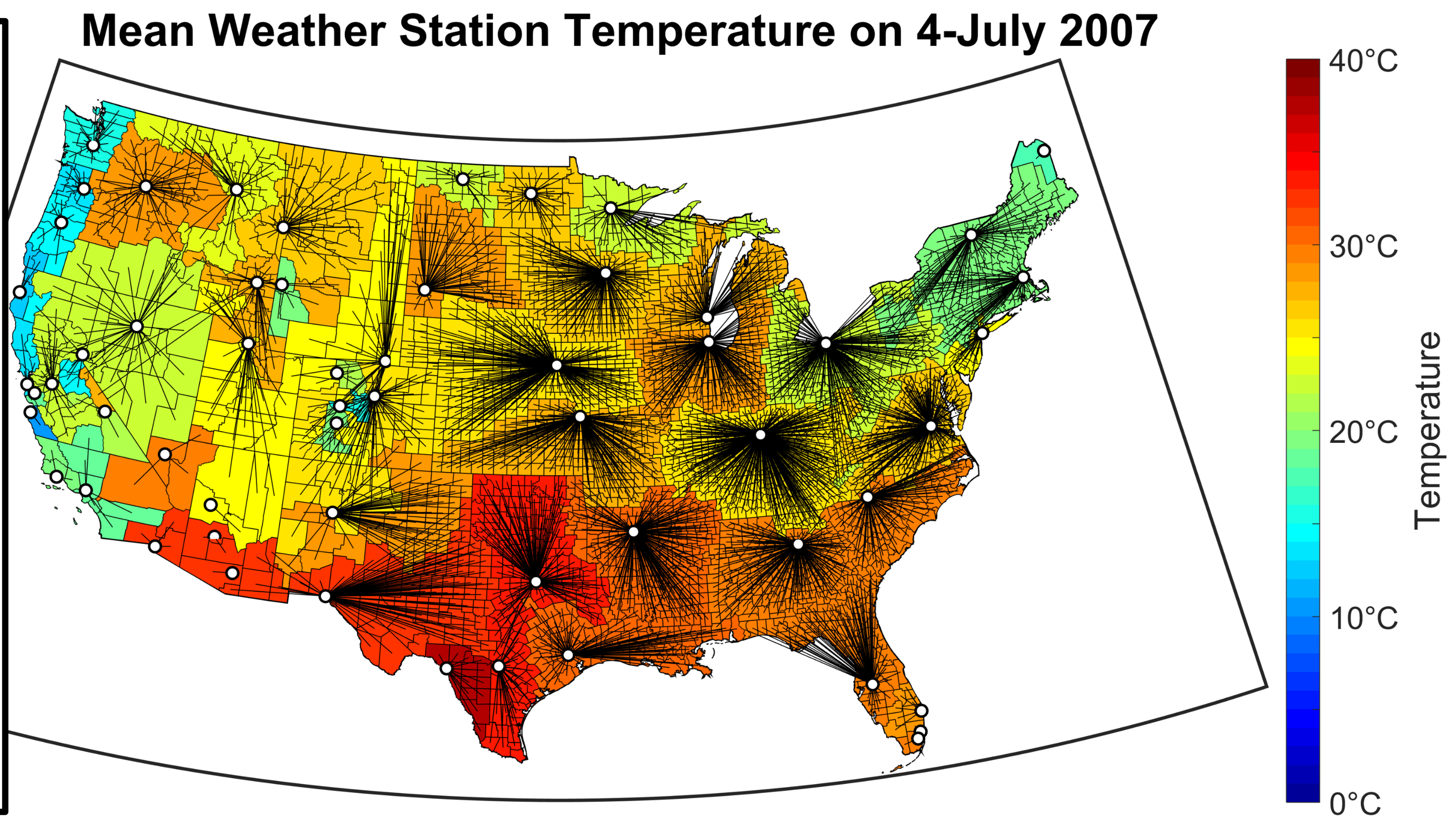

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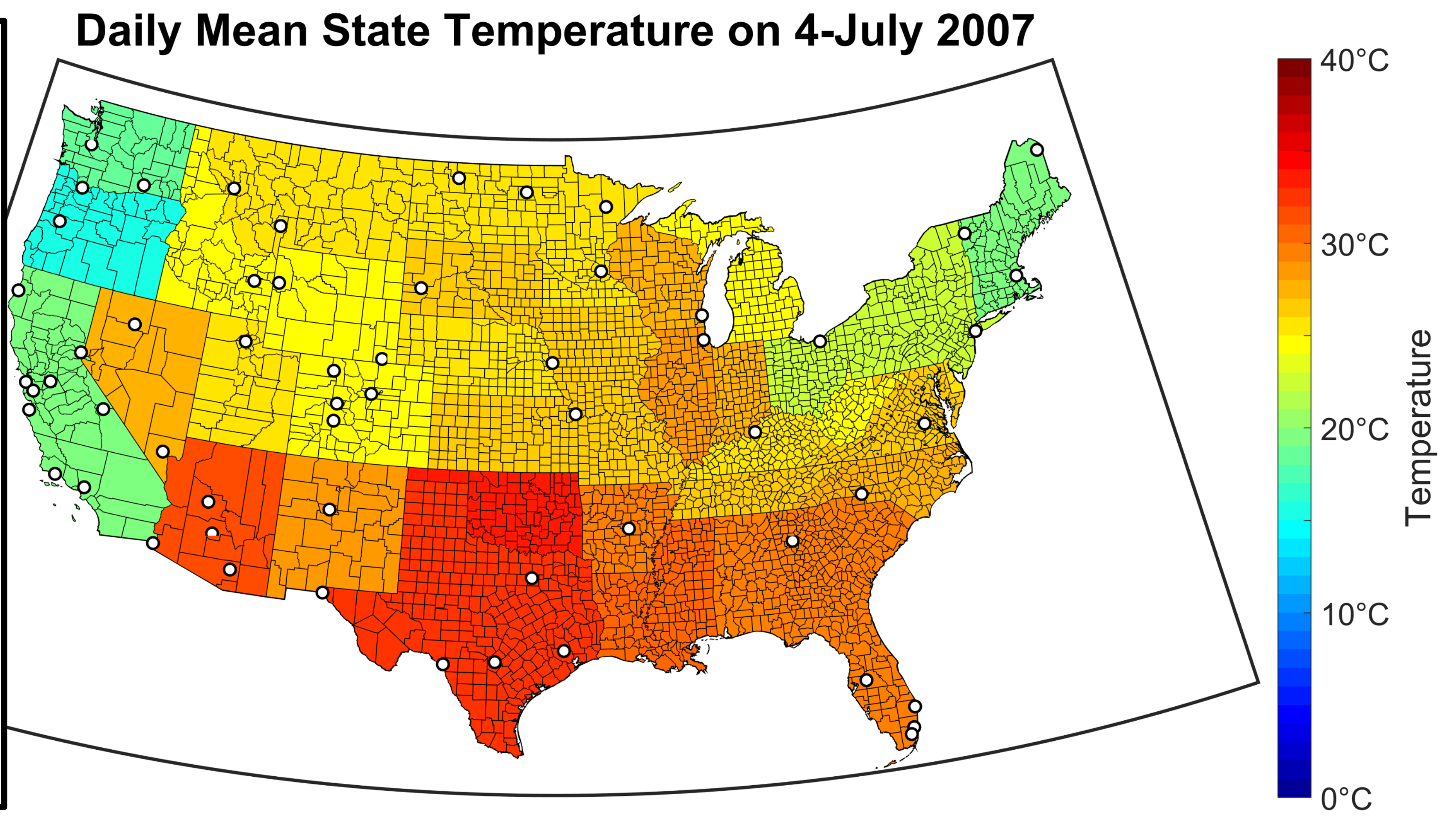
3. We population-weight those means into daily mean state temperatures.



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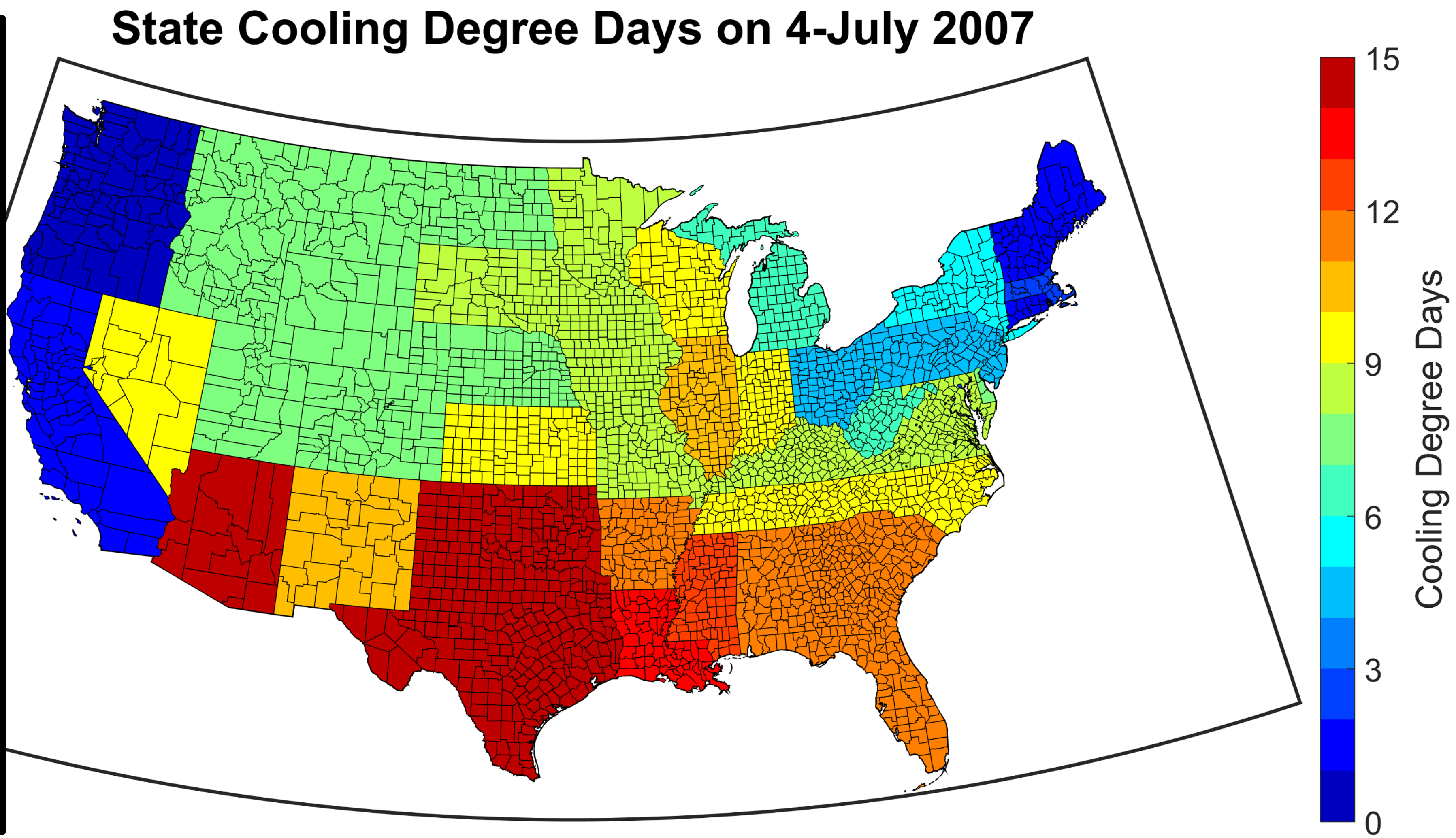
2. We take a daily mean temperature for each weather station.
3. We population-weight those means into daily mean state temperatures.
4. We use the state temperatures to compute HDD/CDD.



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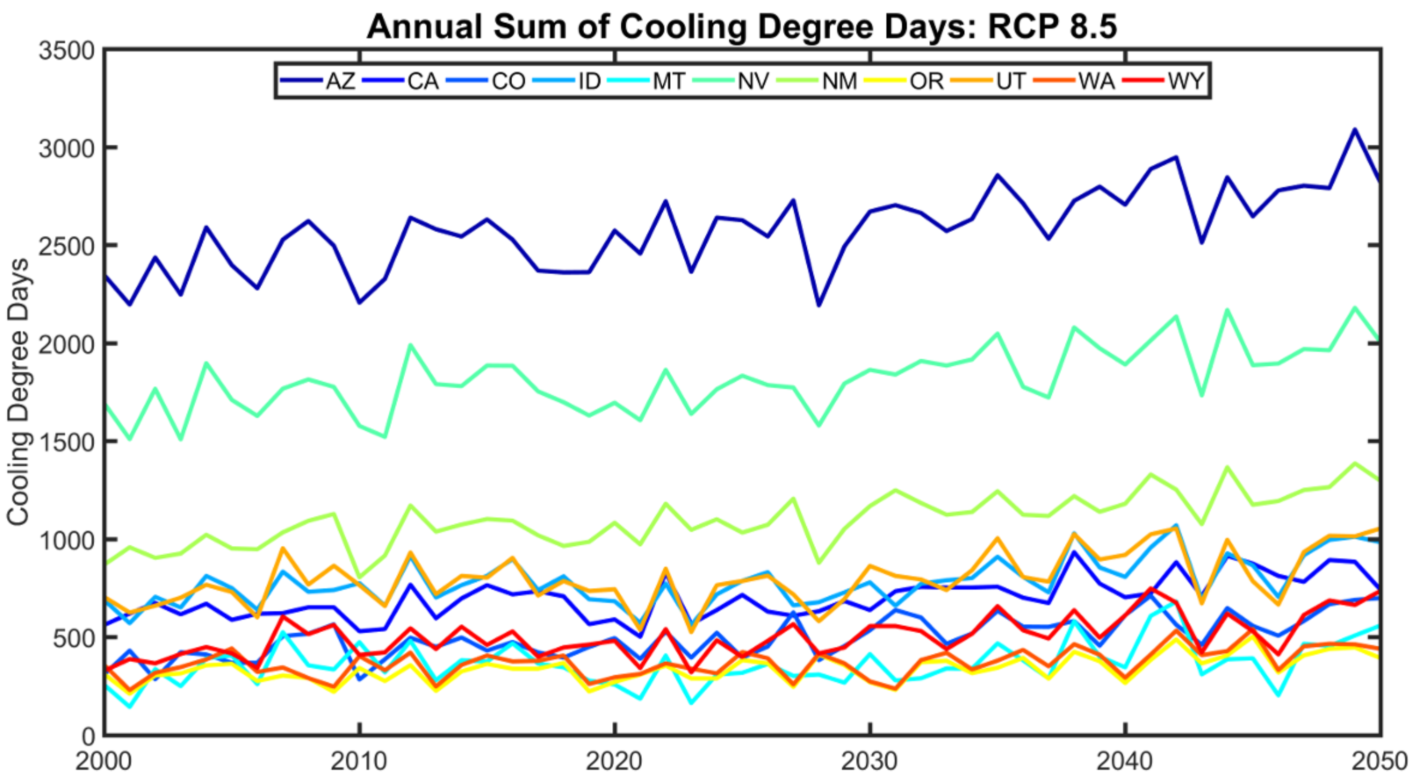
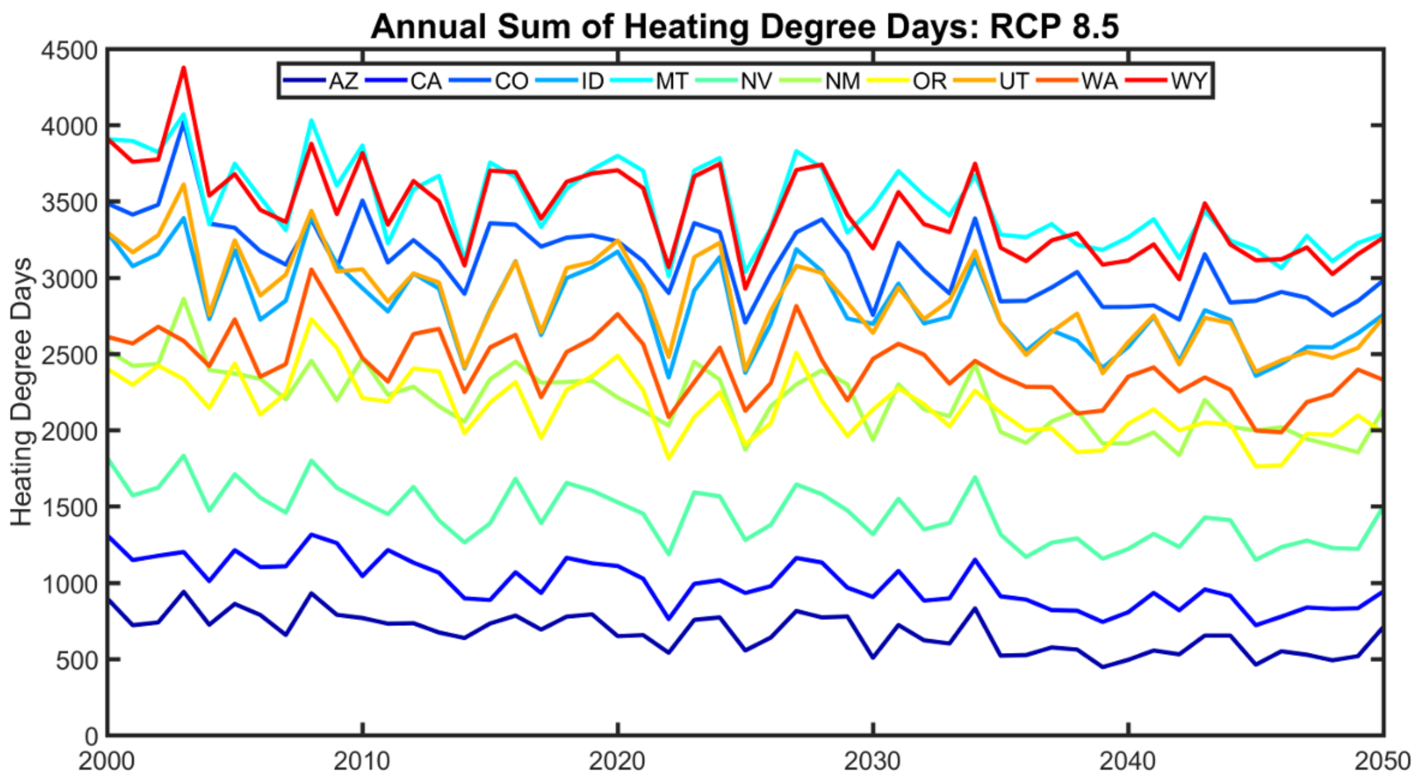
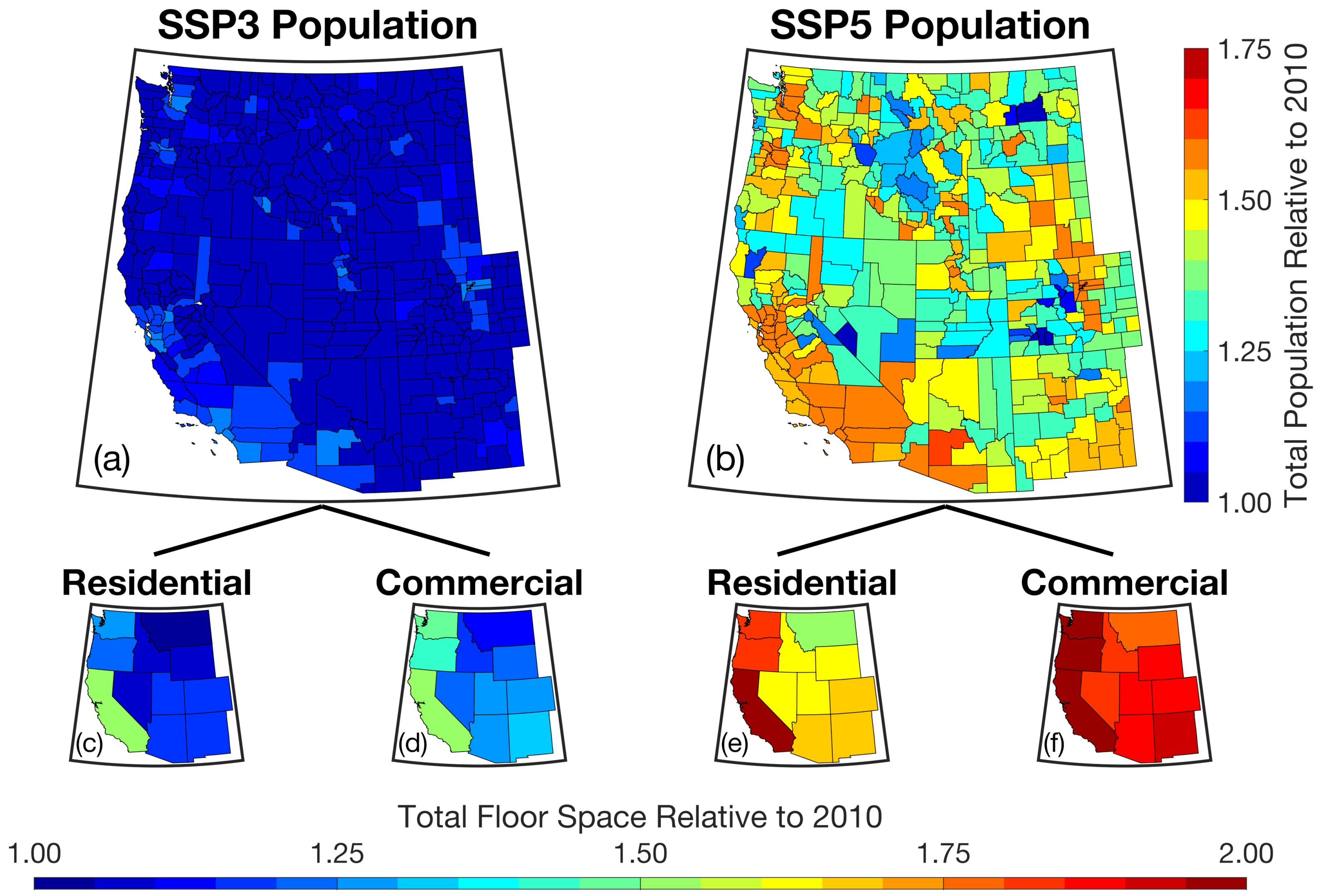


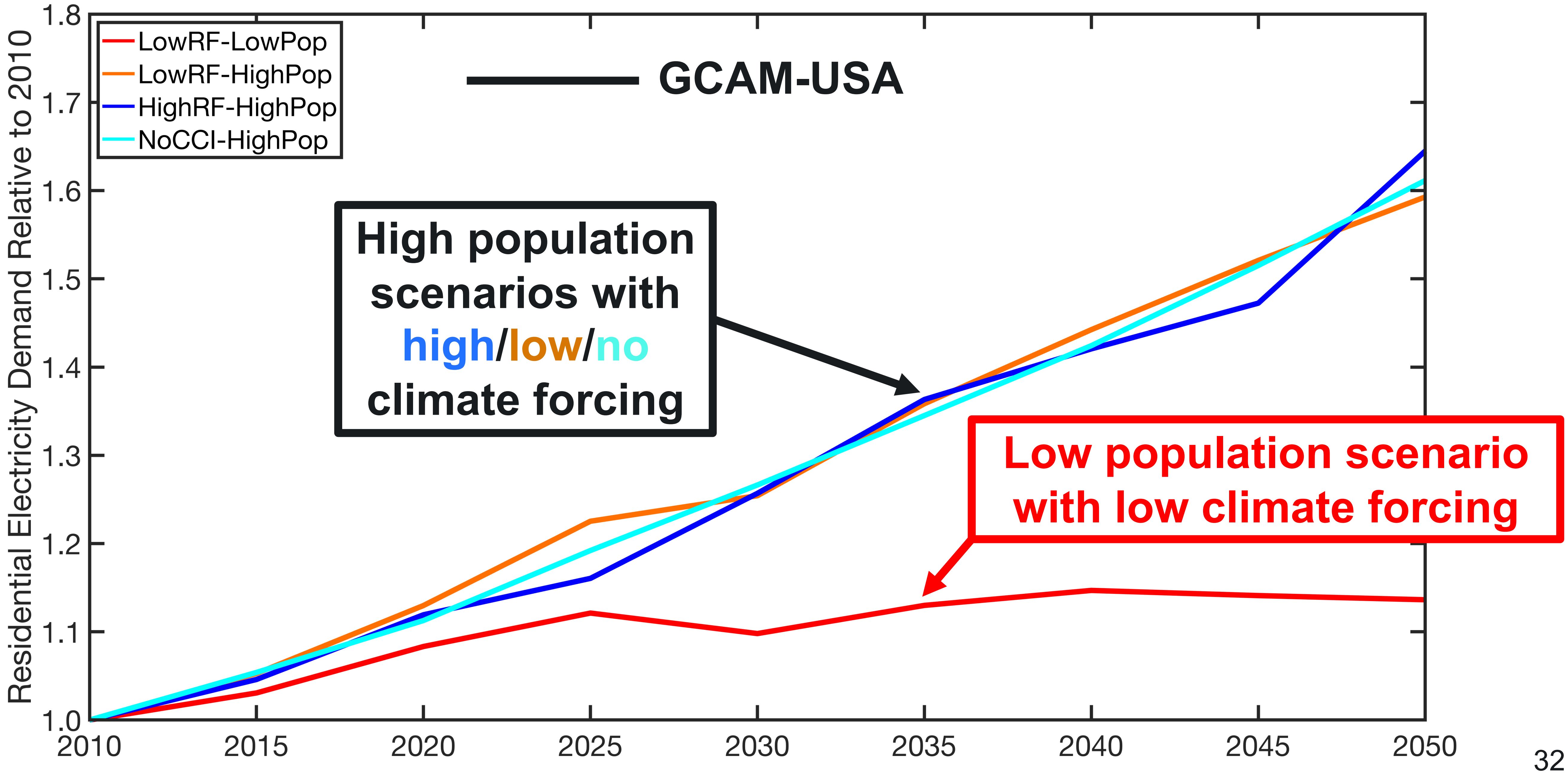


Homogenizing Population and Floor Space Projections

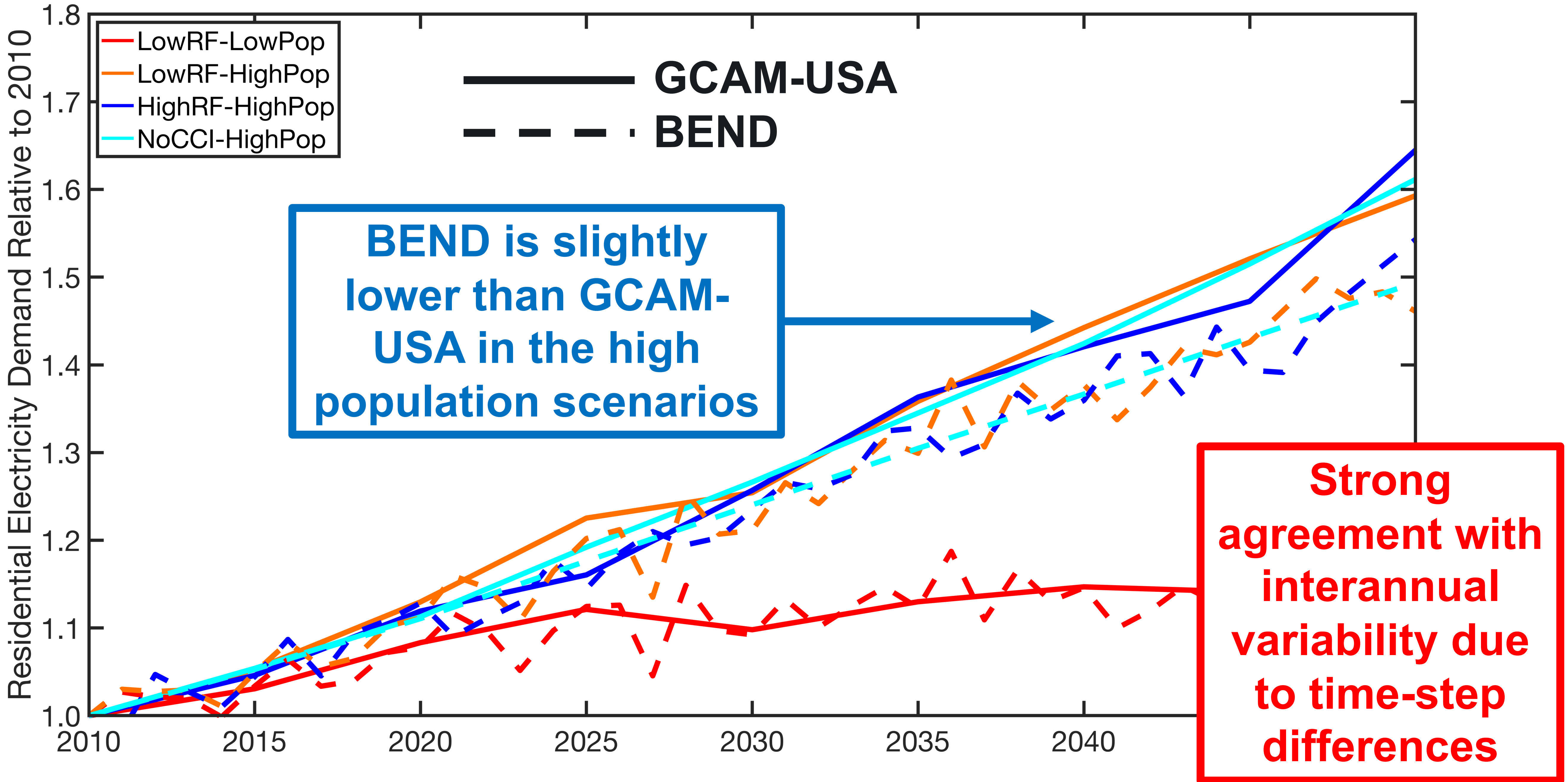
GCAM-USA calculates changes in residential and commercial floor space as a function of population and GDP.



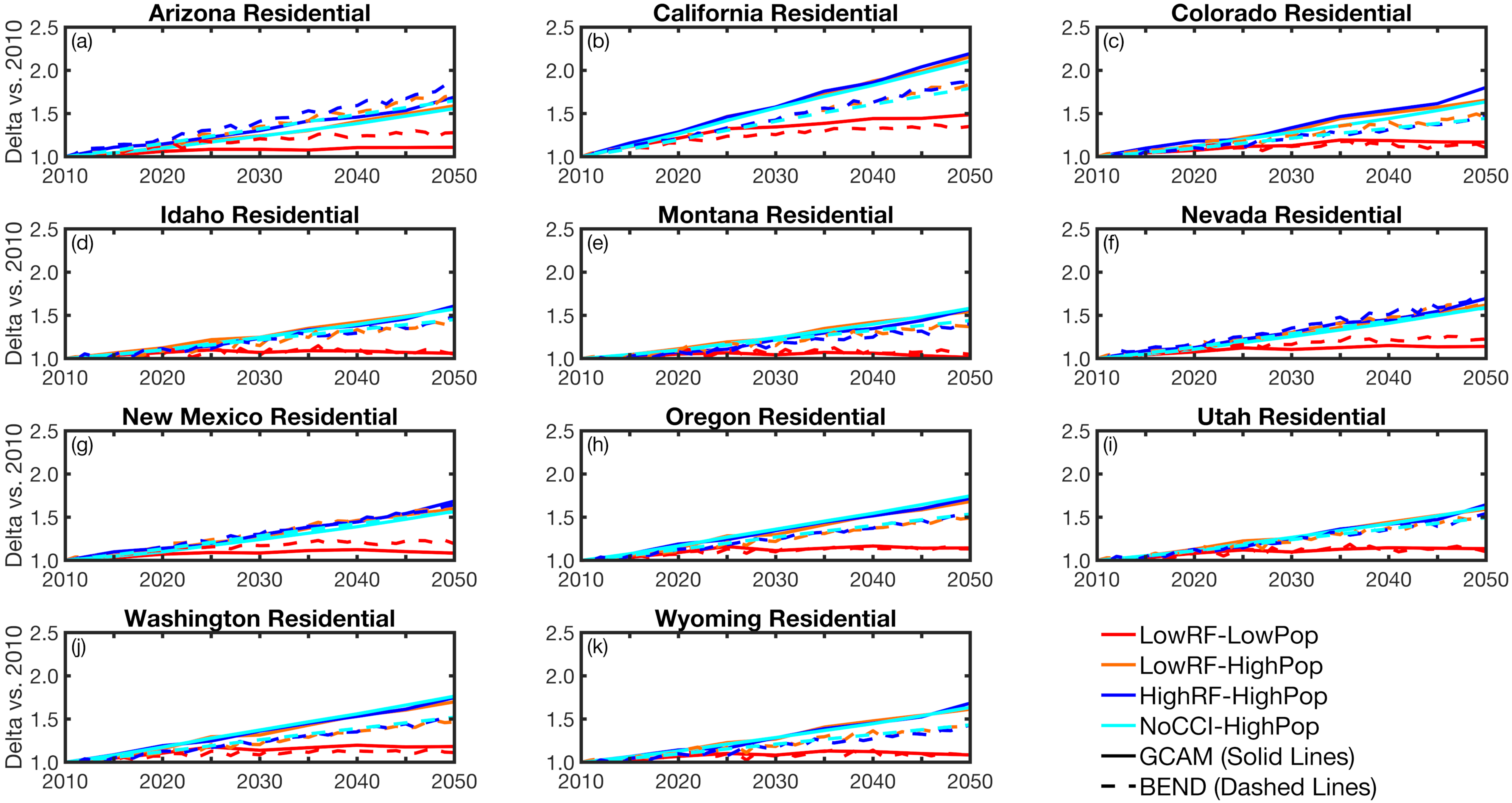
Projections of Residential Building Electricity Demand in Utah



Projections of Residential Building Electricity Demand in Utah



High vs. Low Population Growth States



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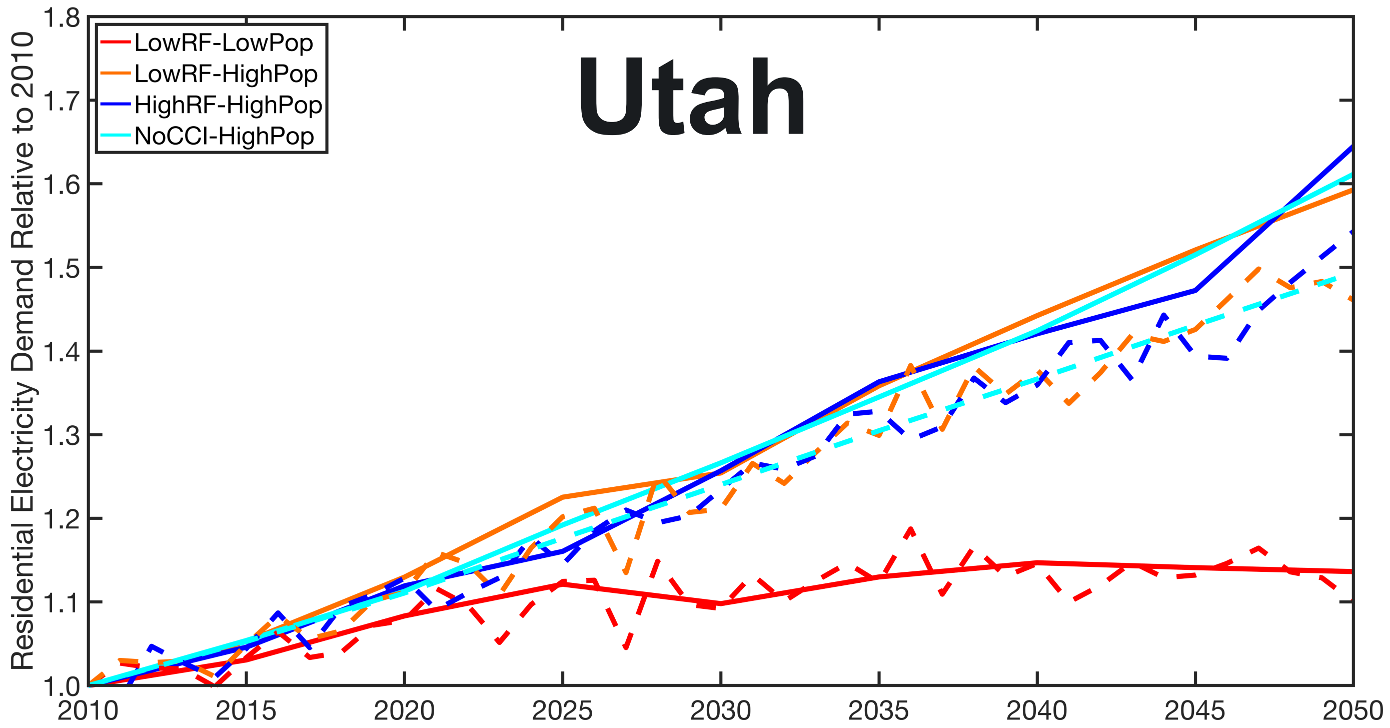
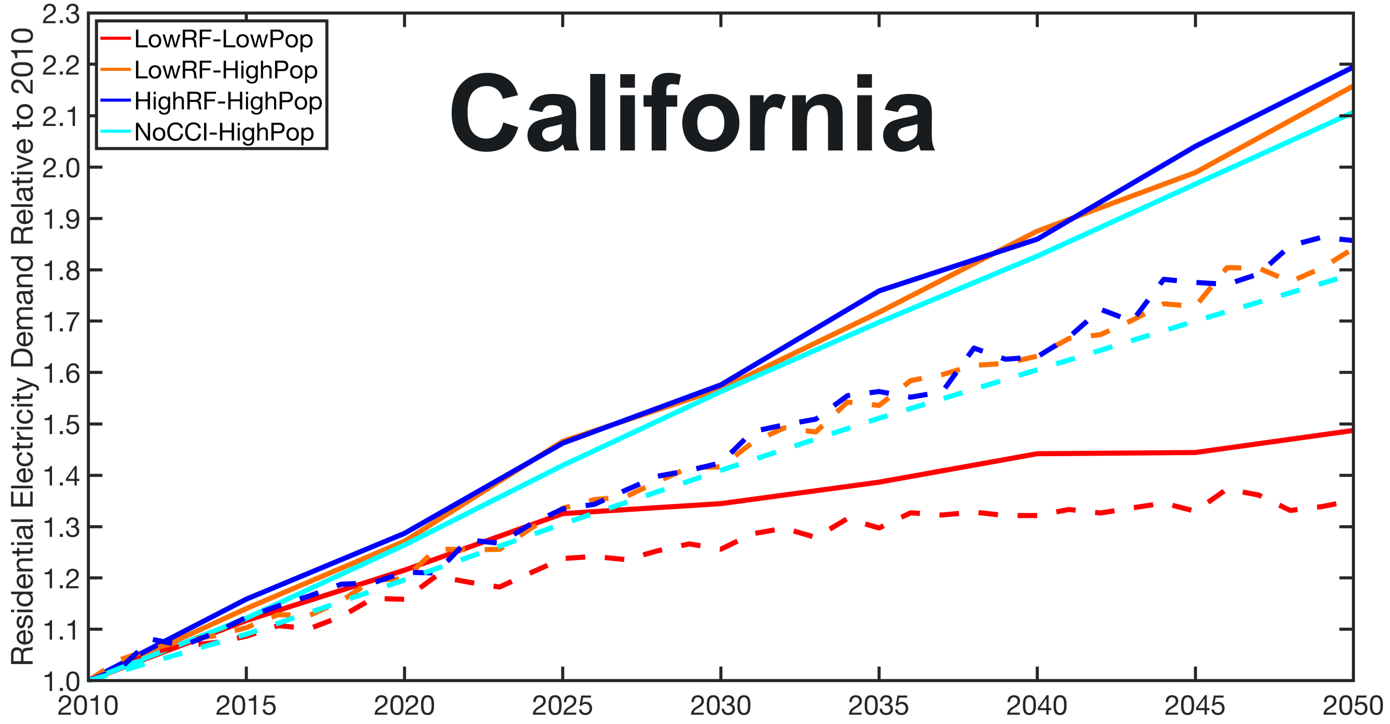
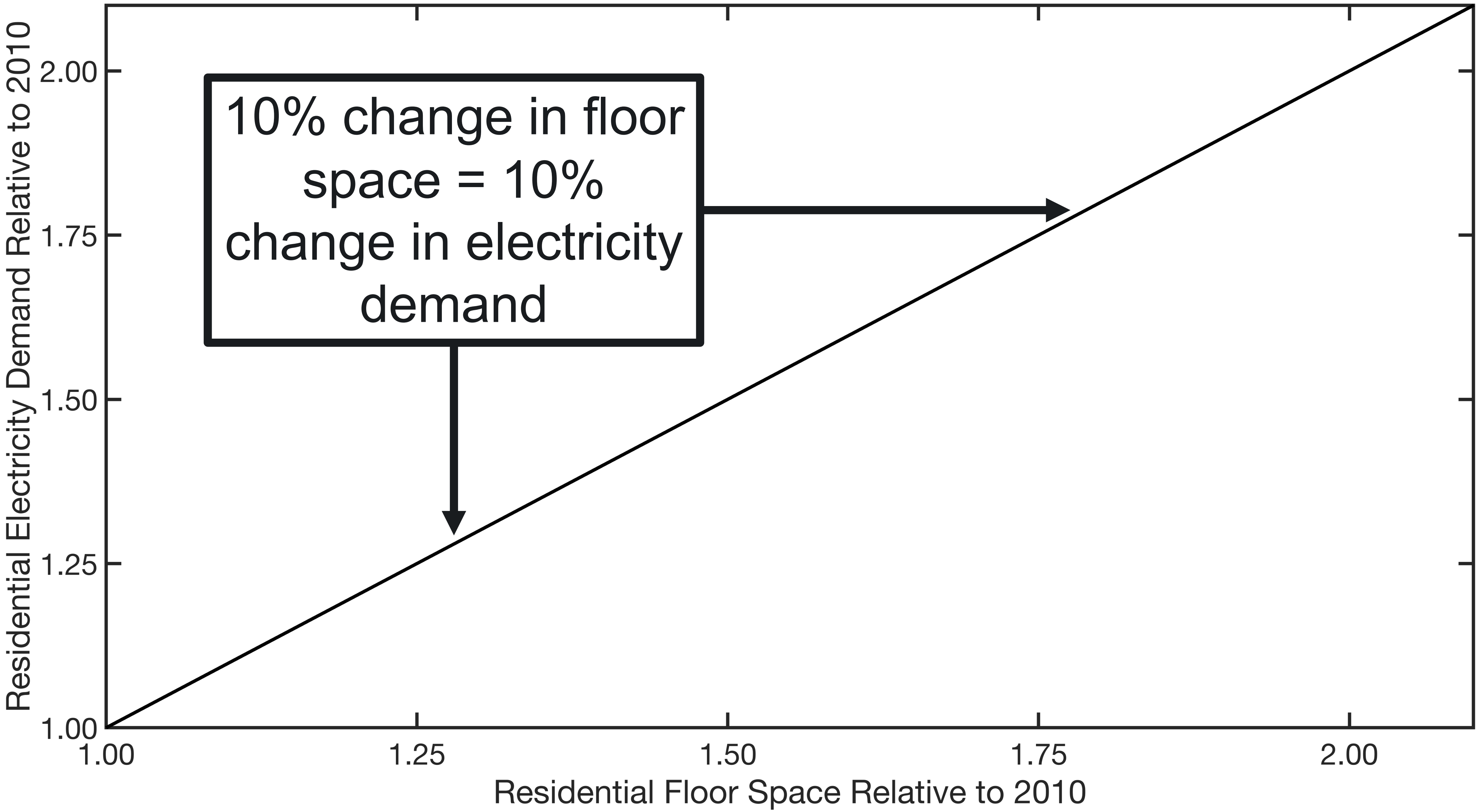


The agreement in projections of both residential and commercial building electricity demand was generally worse in states with higher population growth.

Note y-axis limit differences



Floor Space vs. Electricity Demand HighRF-HighPop Scenario



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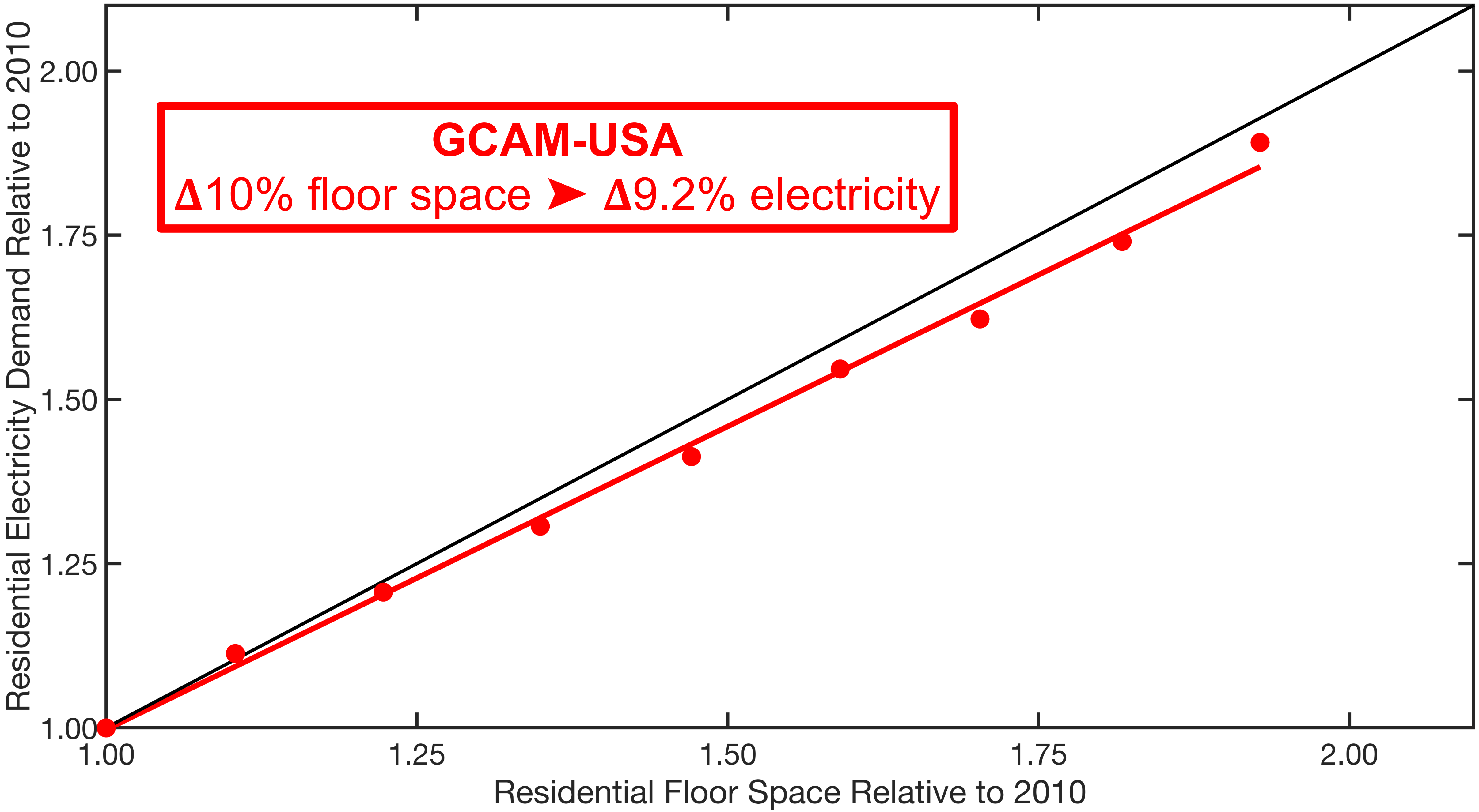

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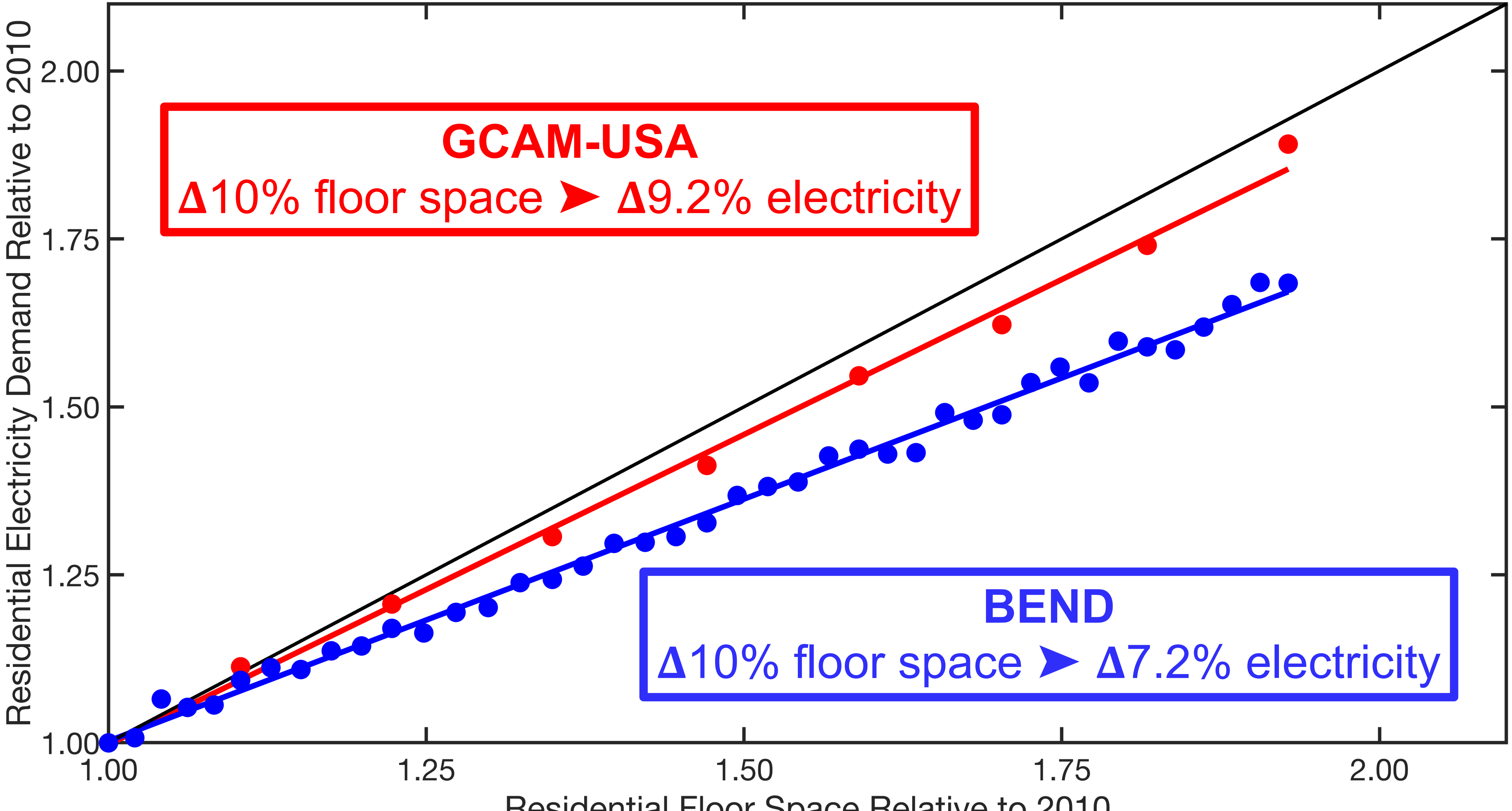

Evolution of Building Technology

$$Q^i_{heating} = k^i_{heating}(HDD^i \cdot Eff \cdot SR - G^i)\left[1 - \exp\left(-\frac{\ln 2}{\mu_j} \cdot \frac{Y^i}{P_j}\right)\right]$$

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	Vintages
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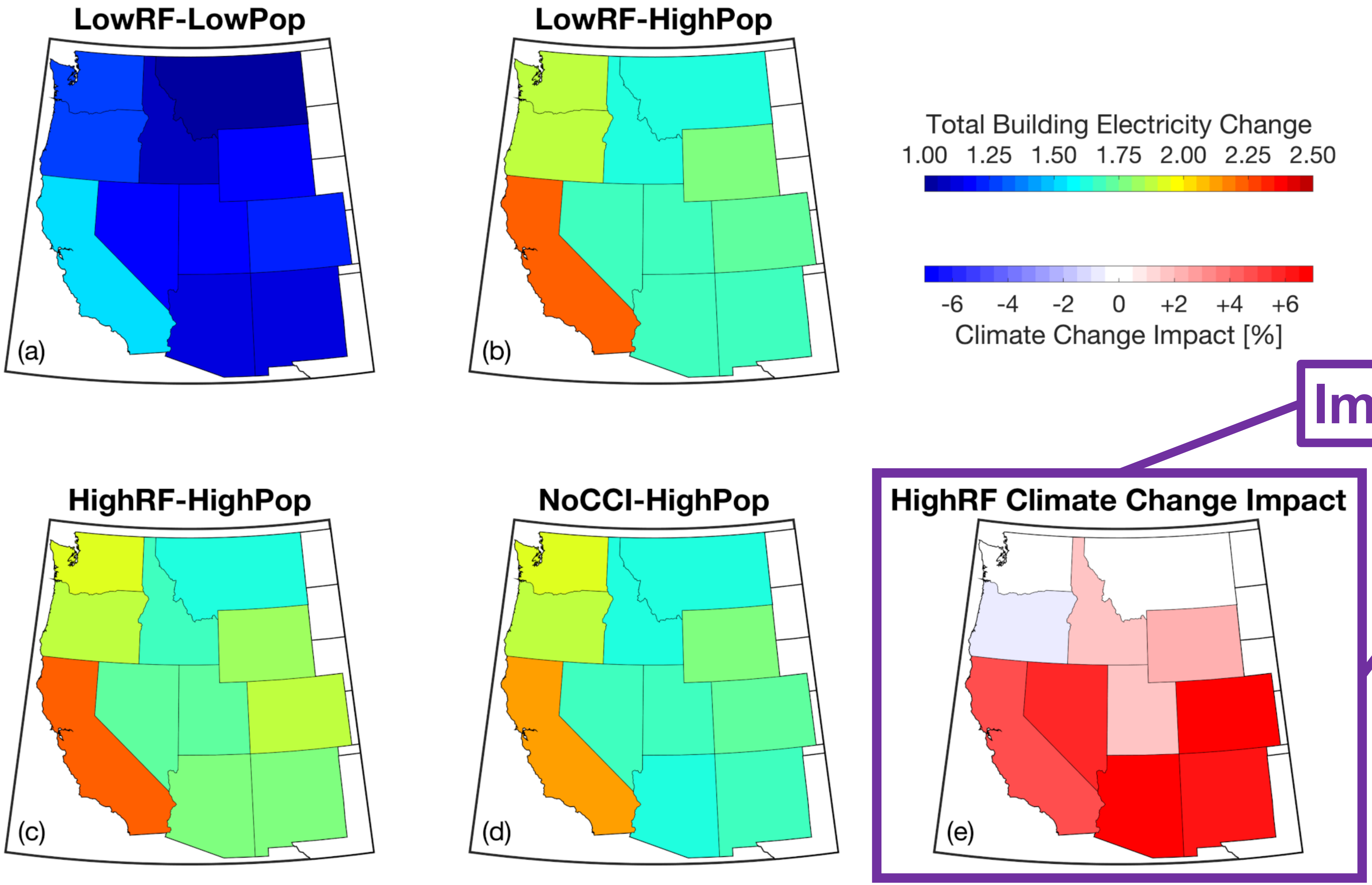
GCAM-USA exogenously prescribes a rate of change for building shell efficiencies that mimics building turnover.

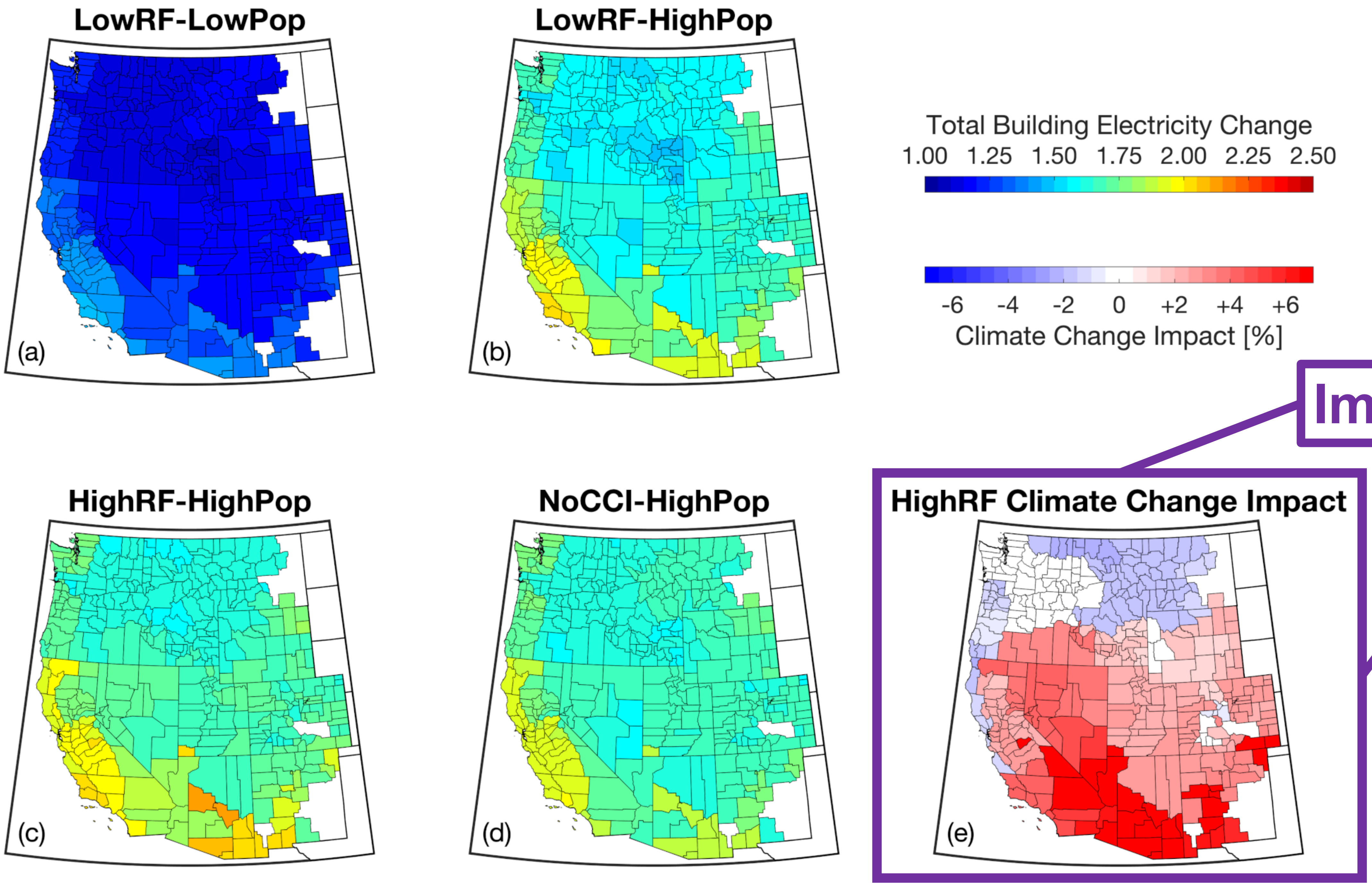
Floor space is expanded in BEND by "building" newer buildings in the model. This endogenously increases the aggregate efficiency of the total building stock.

Climate Change Impact: GCAM-USA



Impact = (c-d) / d

Climate Change Impact: BEND



Impact = (c-d) / d

Climate and Population Impacts on Building Electricity Demand

Key Results

1) Residential building electricity demand in 2050 increases in both models by 1-49% under the SSP3 population scenario and by 37-119% under the SSP5 population scenario.

2) Climate should be considered a stress multiplier for electricity demand, not a major driver of change by itself (relative to population change). RCP 8.5 increases total building electricity demand by 4-6% in the southern states of the western U.S.

3) Disagreements between BEND and GCAM-USA are due to differences in how each model improves the efficiency of the building stock over time.

Publication

Burleyson et al., 2020: Closing the Scale Gap: Evaluating Western U.S. Building Electricity Consumption in Response to Climate and Population Drivers. *Energy*, **208**, 118312.

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Free Bonus Content: How Your Utility Knows You've Been Sleeping in During COVID-19

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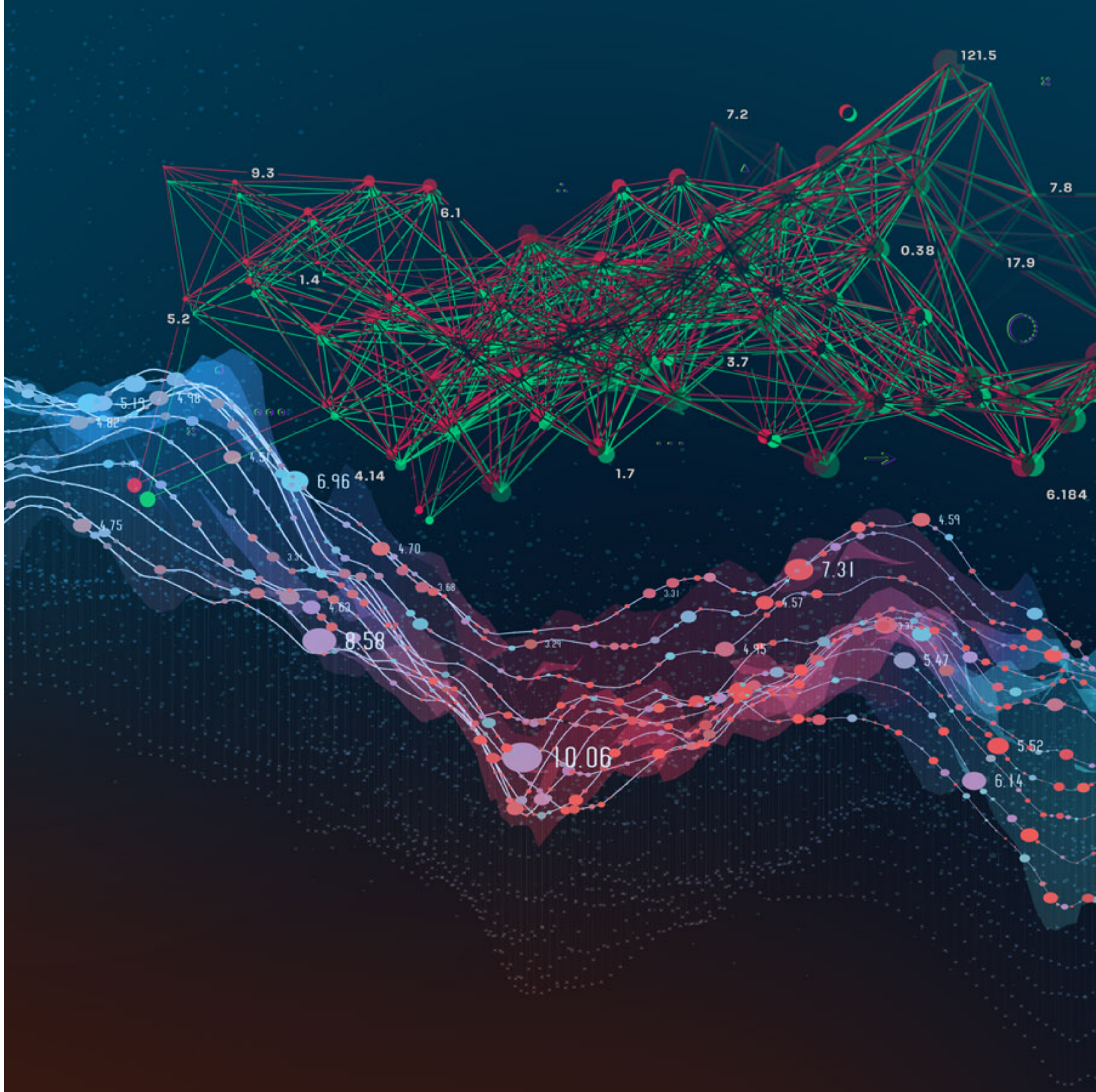
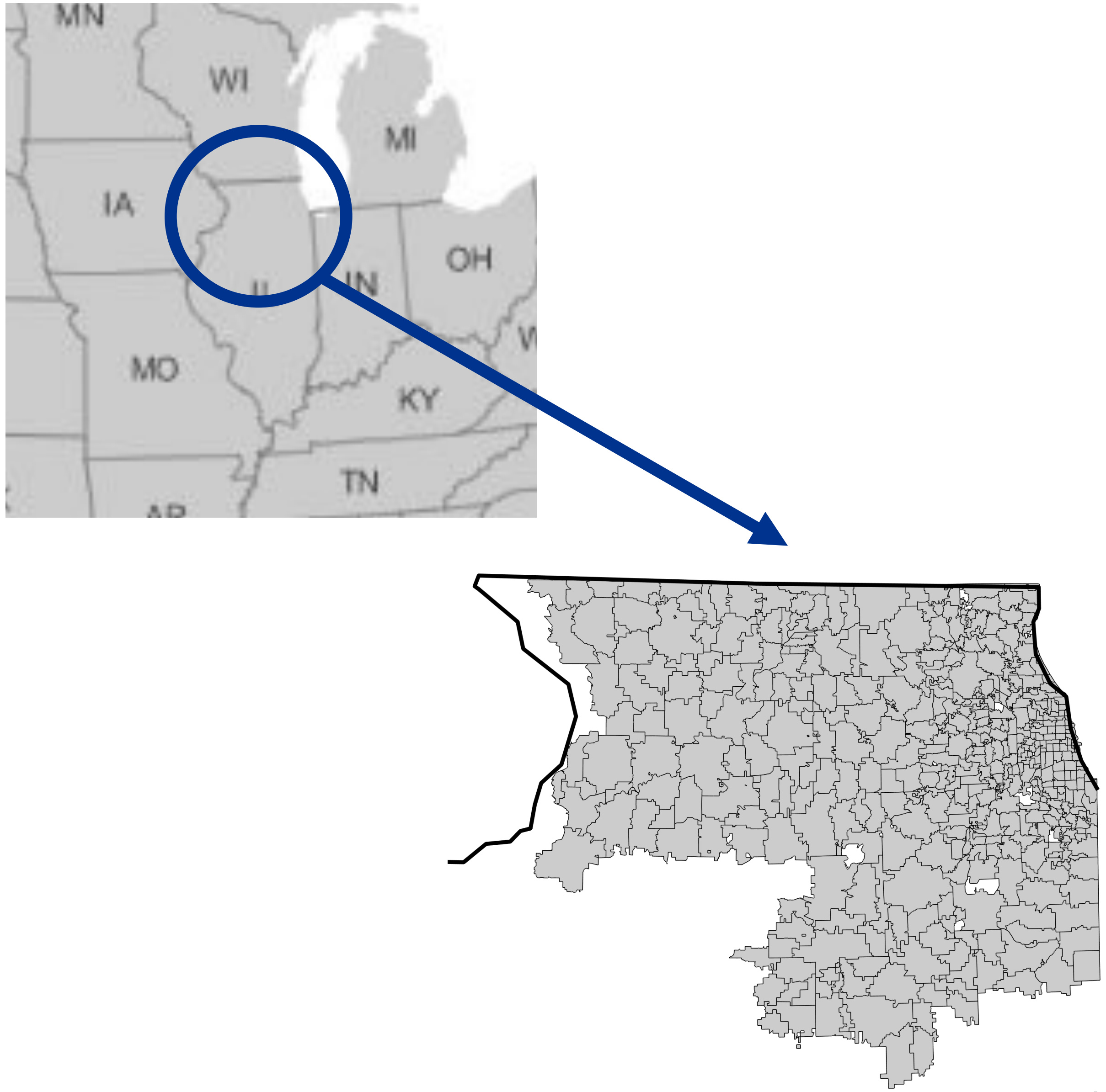


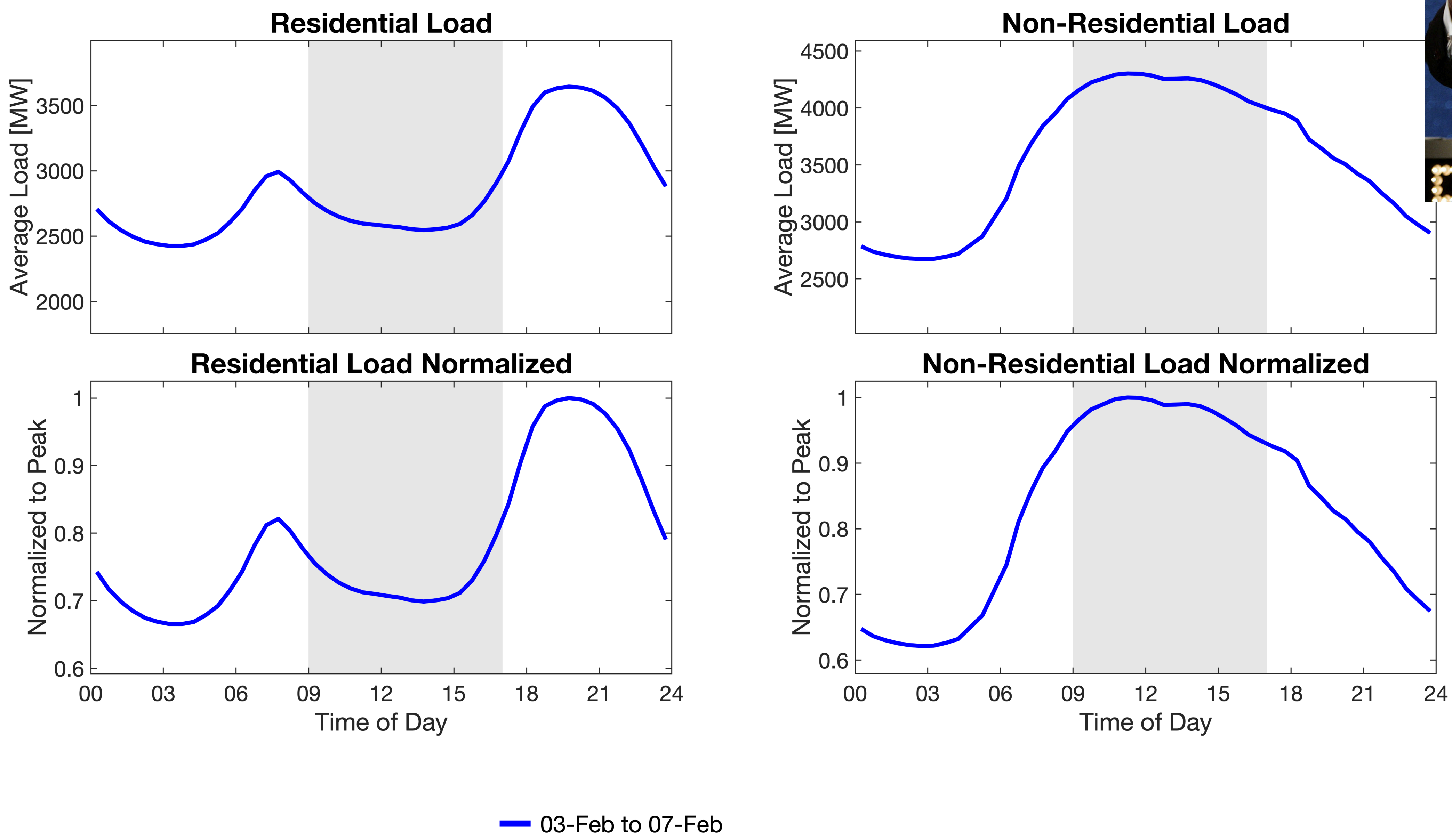
The Data is the Key: Anonymized End-Use Electricity Sales

Stats

1) 30-minute electricity usage from more than 2.2 million individual customers of the Commonwealth Edison utility.
2) Only geolocation is the zip code of the customer.
3) Data we have is from April 2018 through the end of April 2020.
4) 4 residential customer classes and 10 non-residential customer classes.
5) Data is proprietary and we had to purchase access.



Spot the Change!



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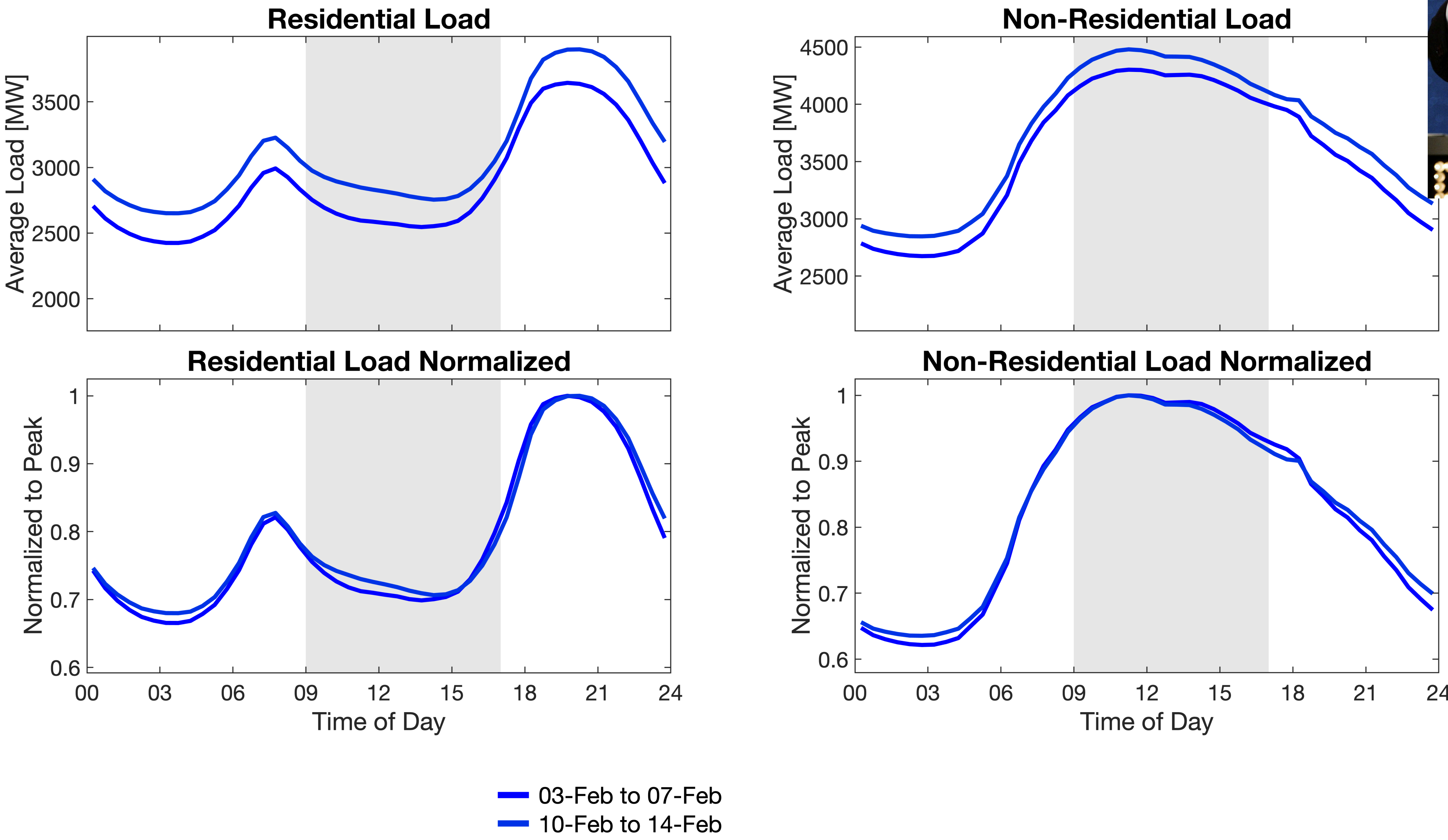

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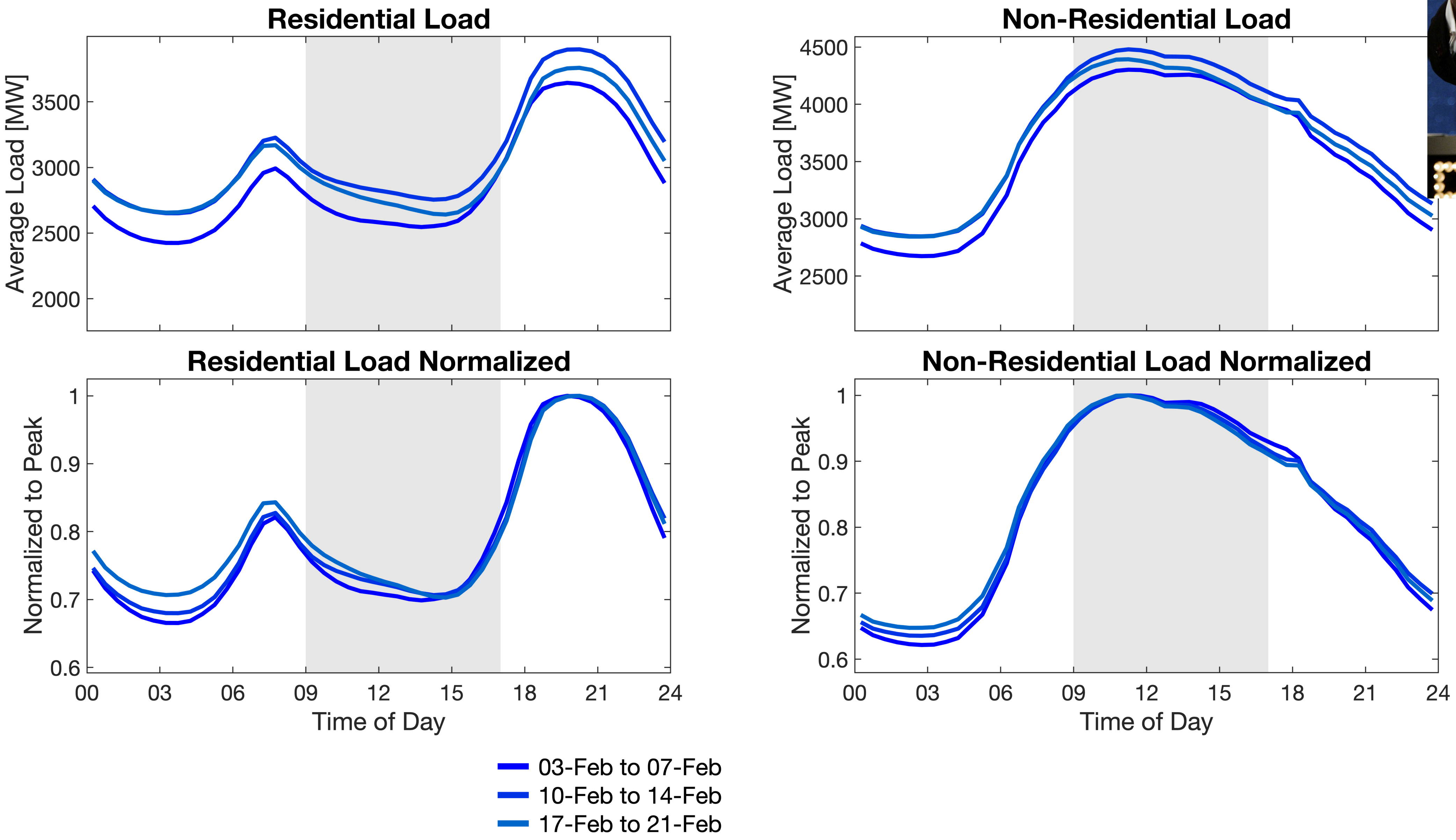

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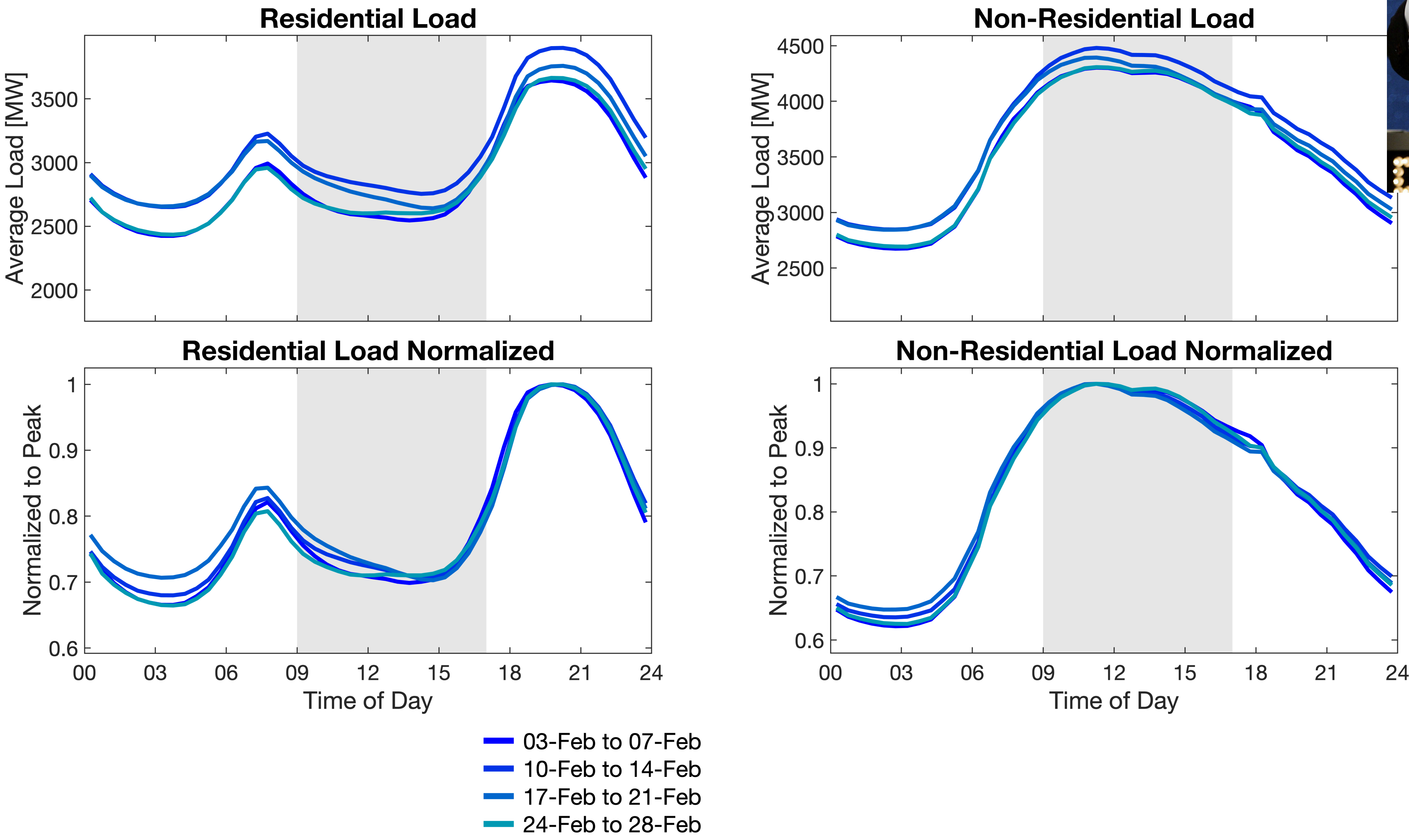

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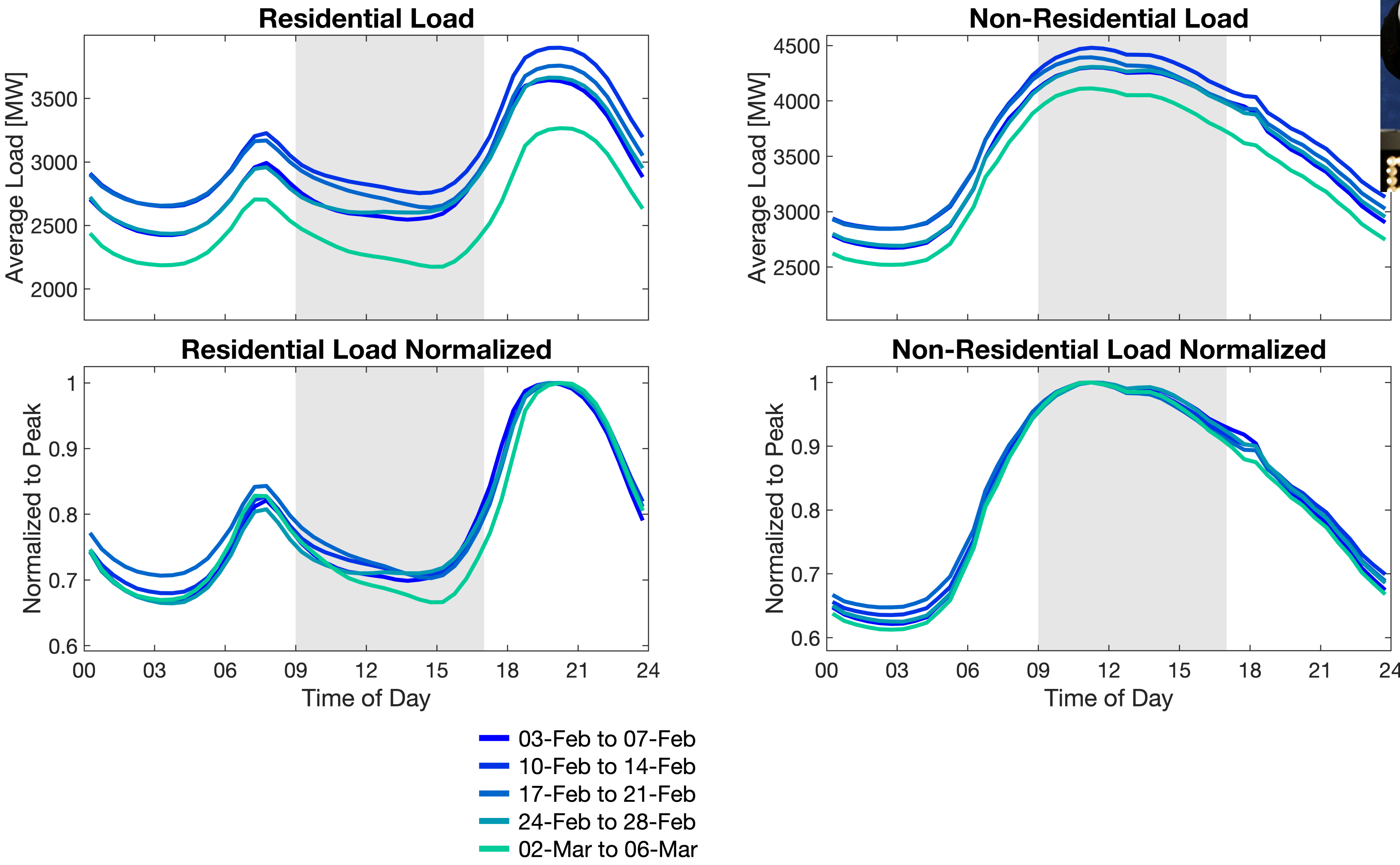
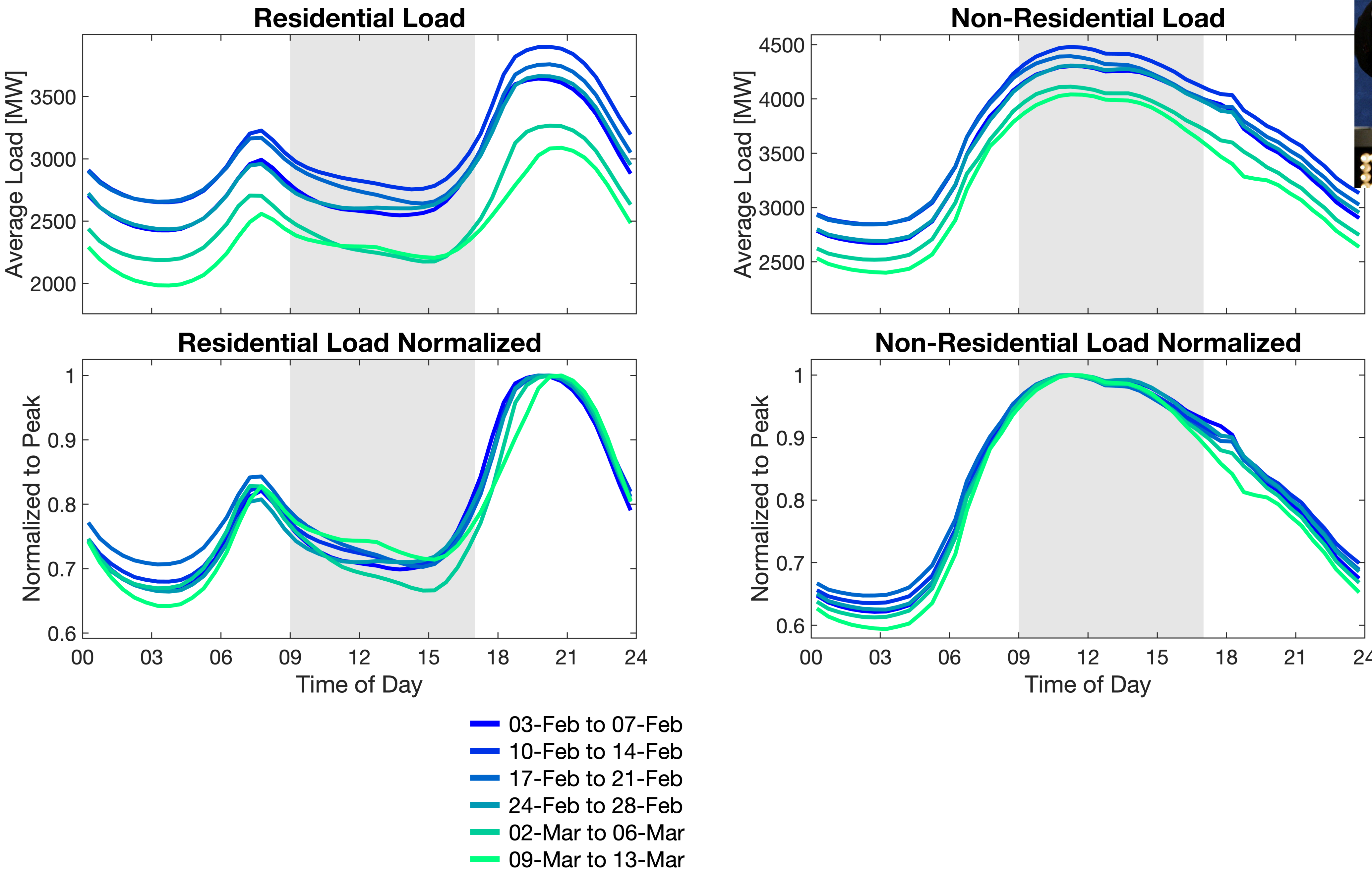


Spot the Change!



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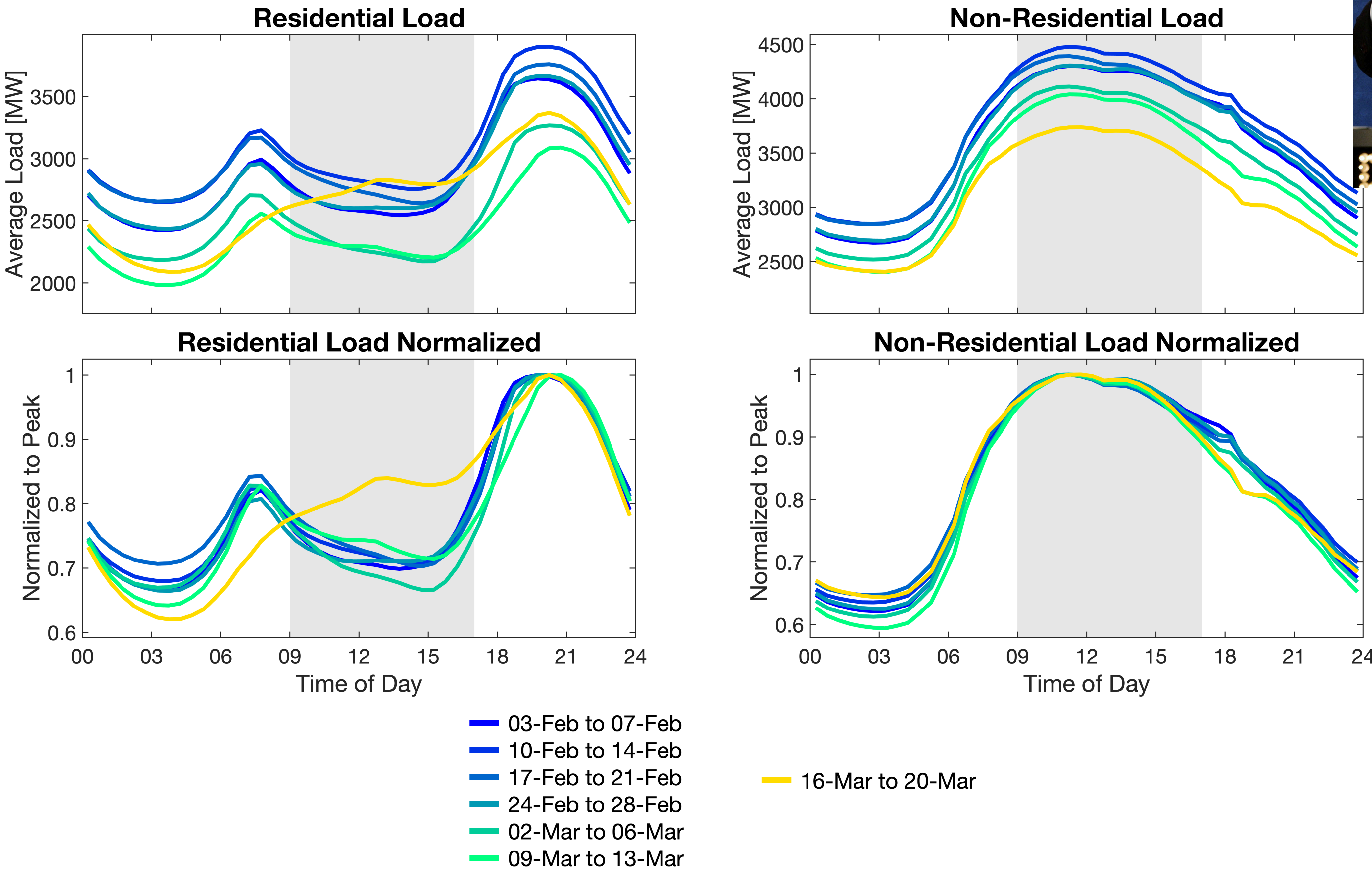

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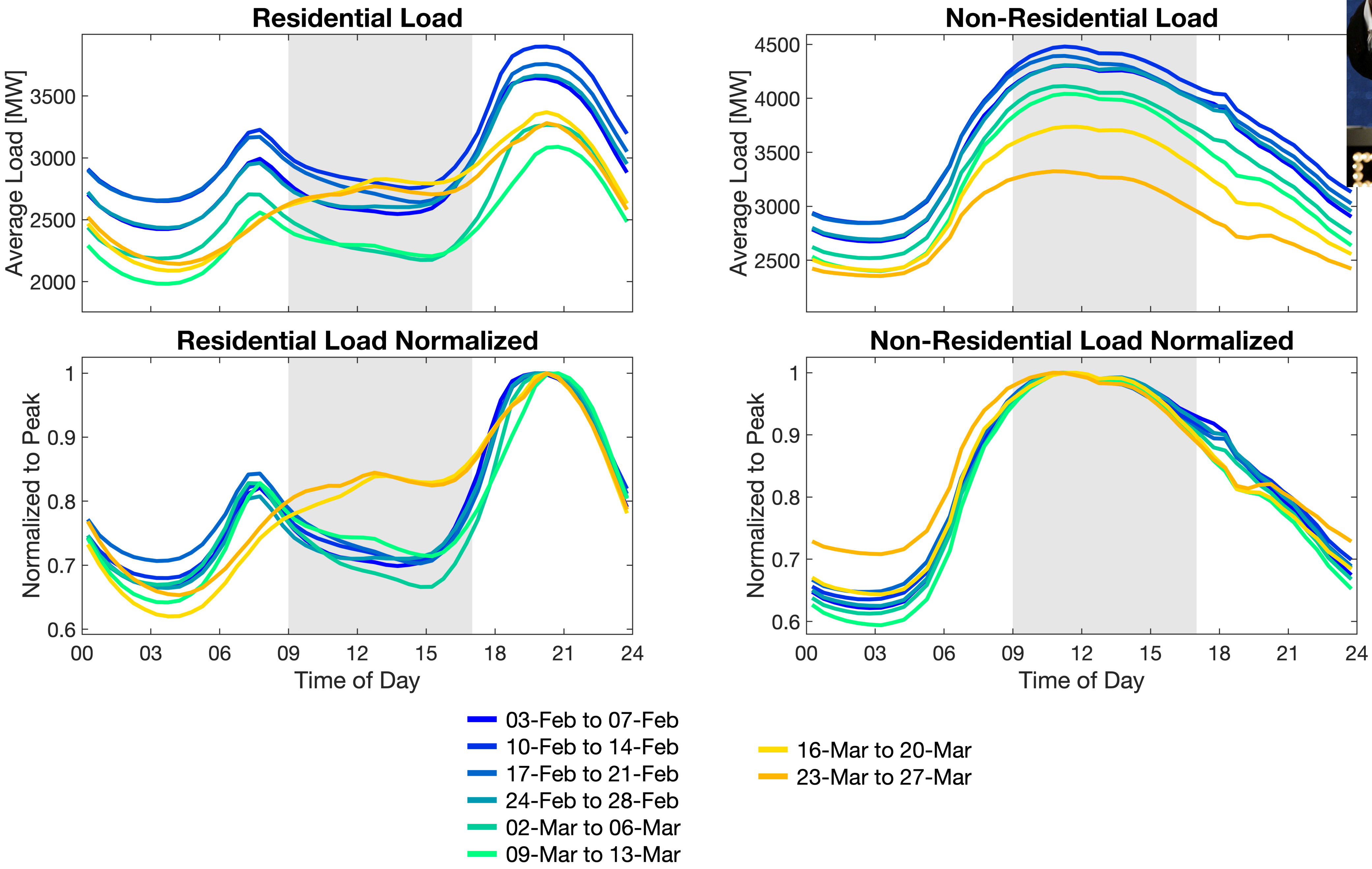
Spot the Change!



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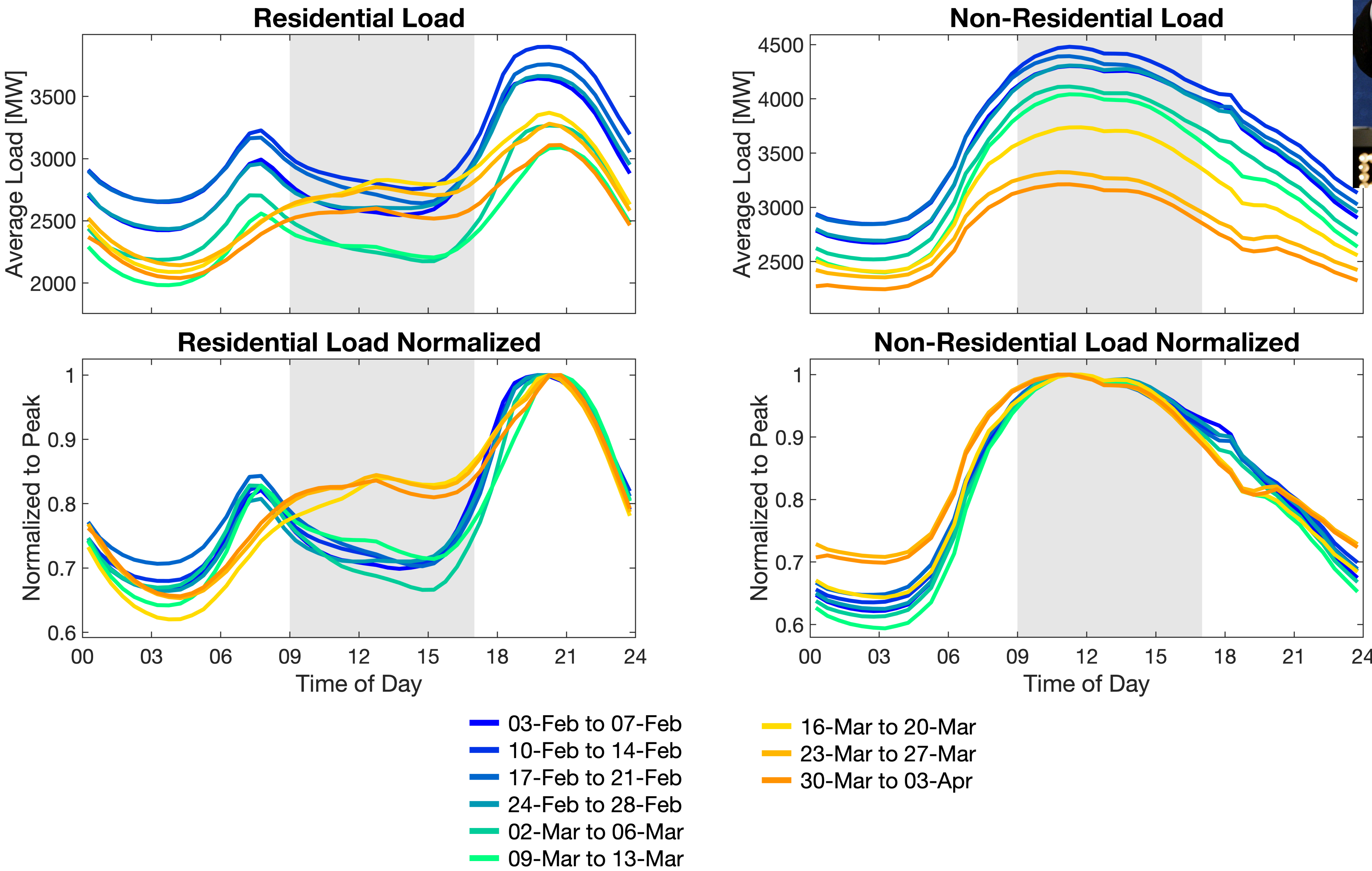

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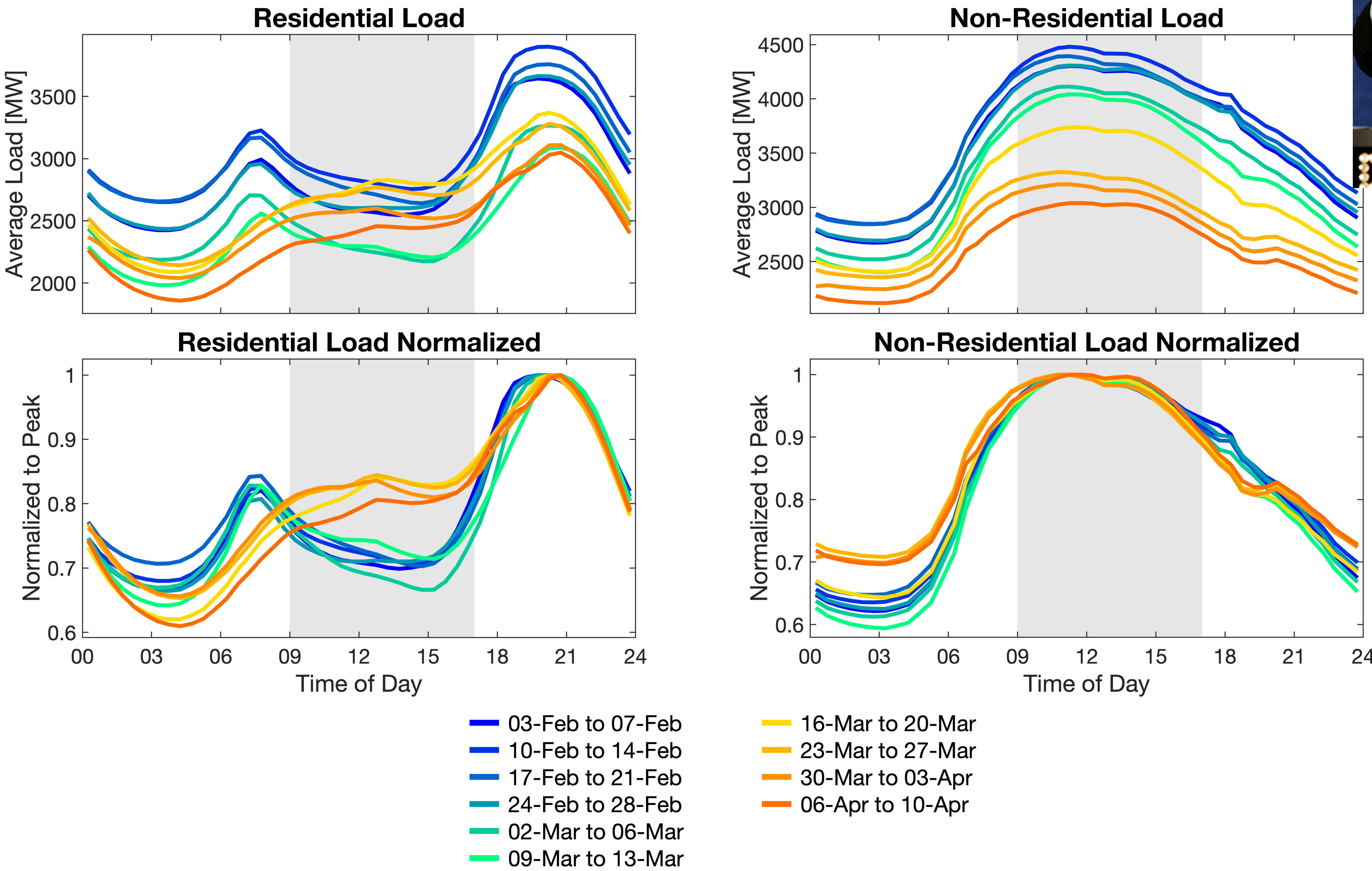

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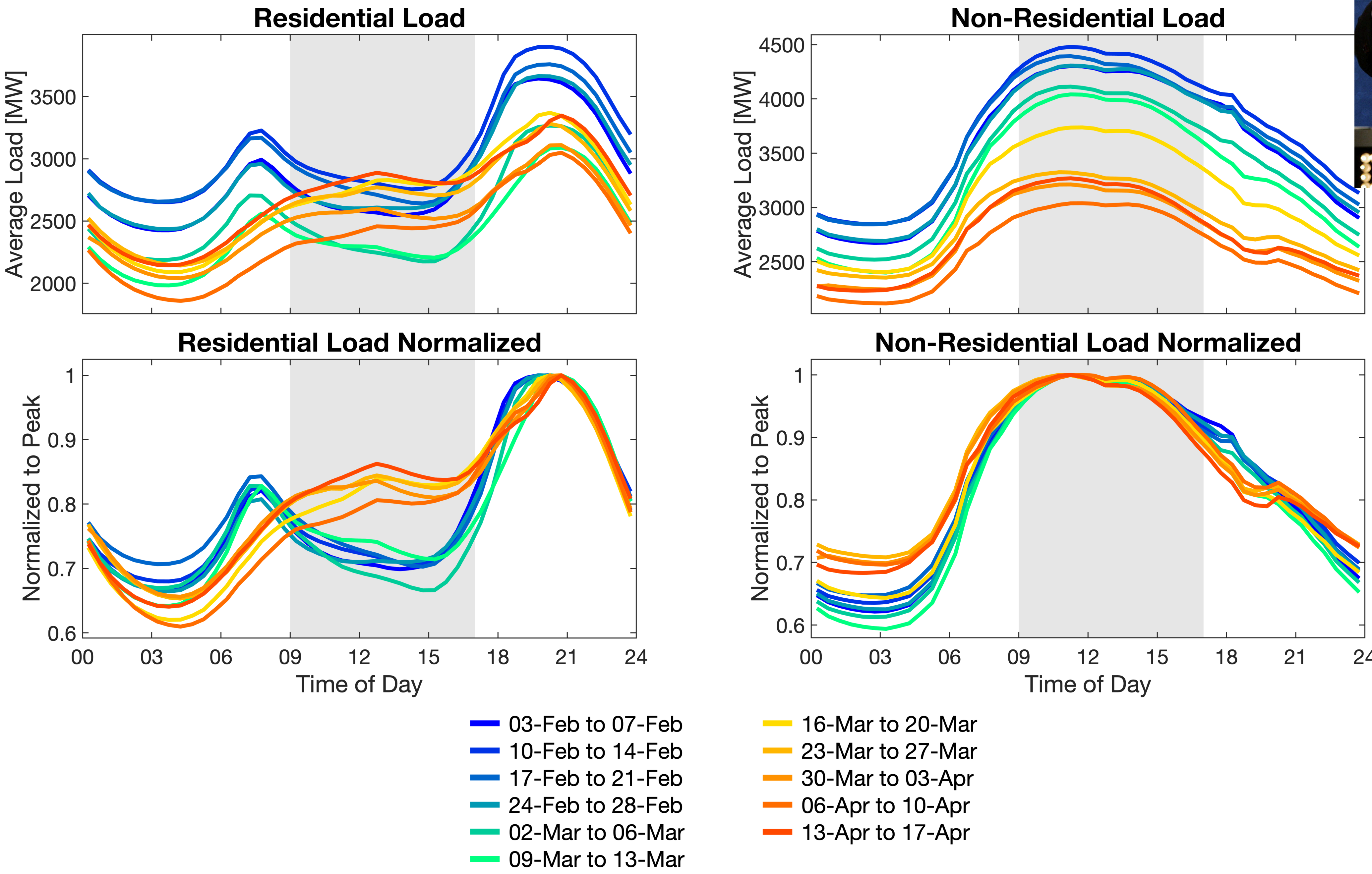

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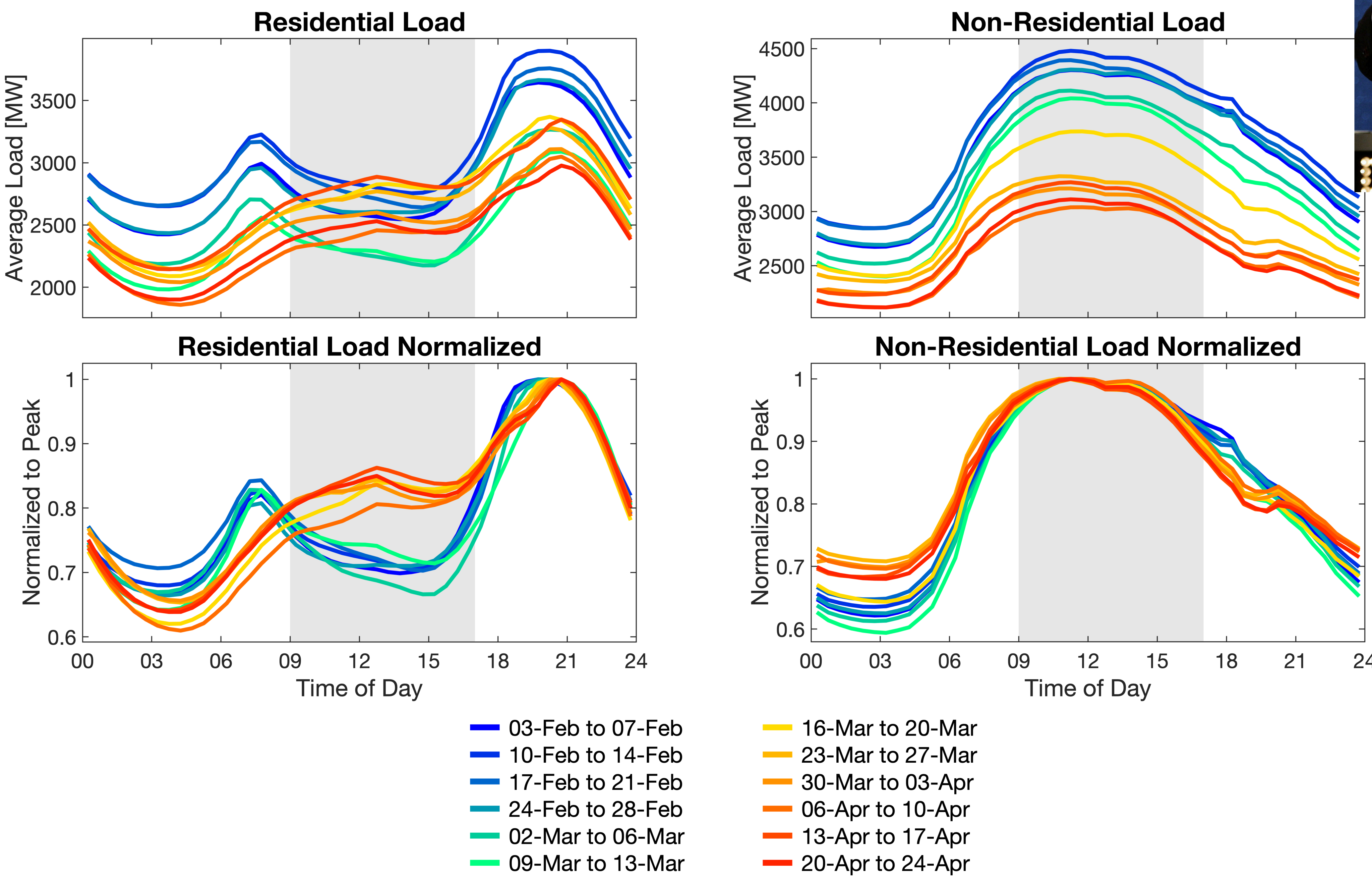

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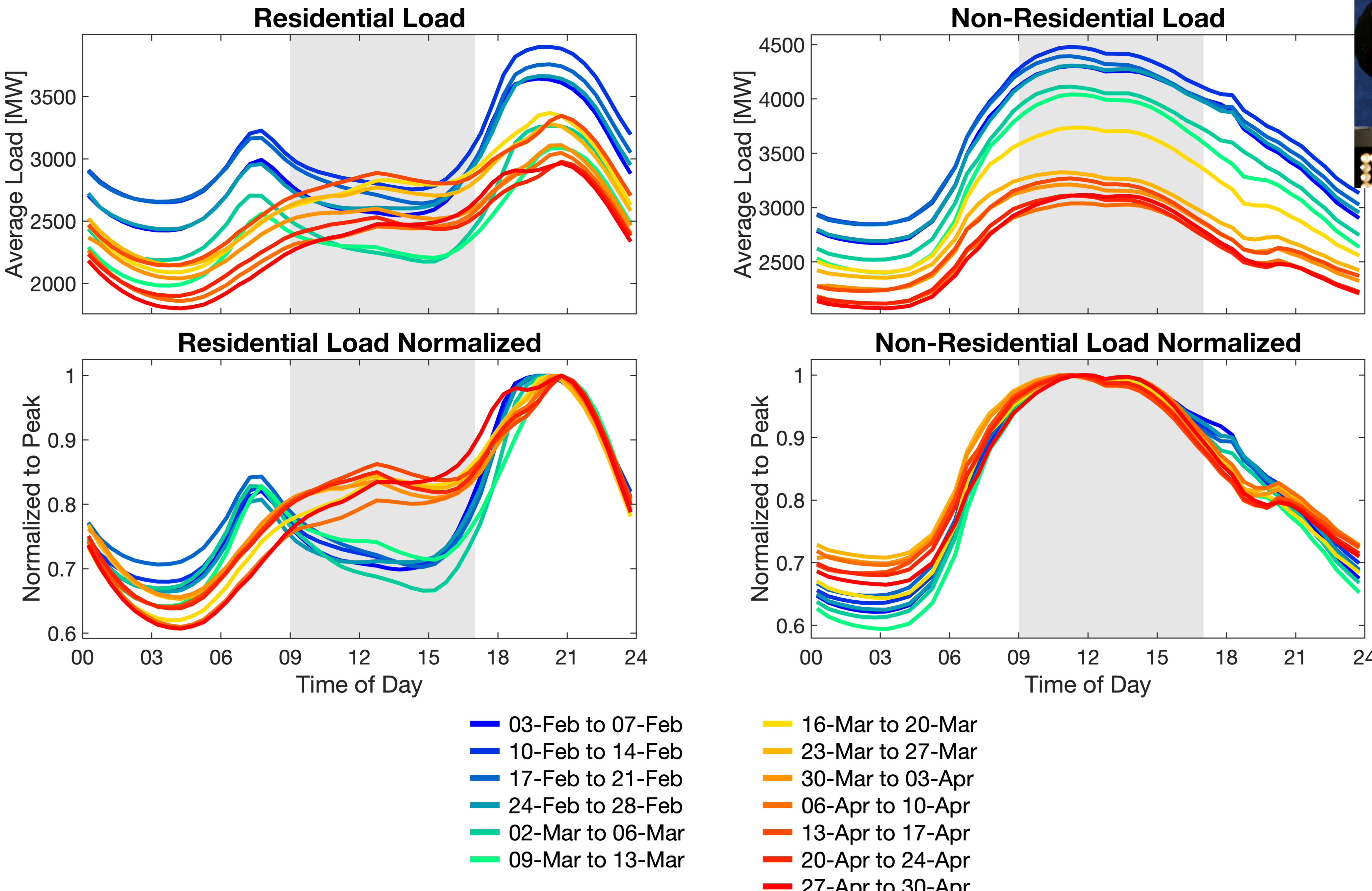
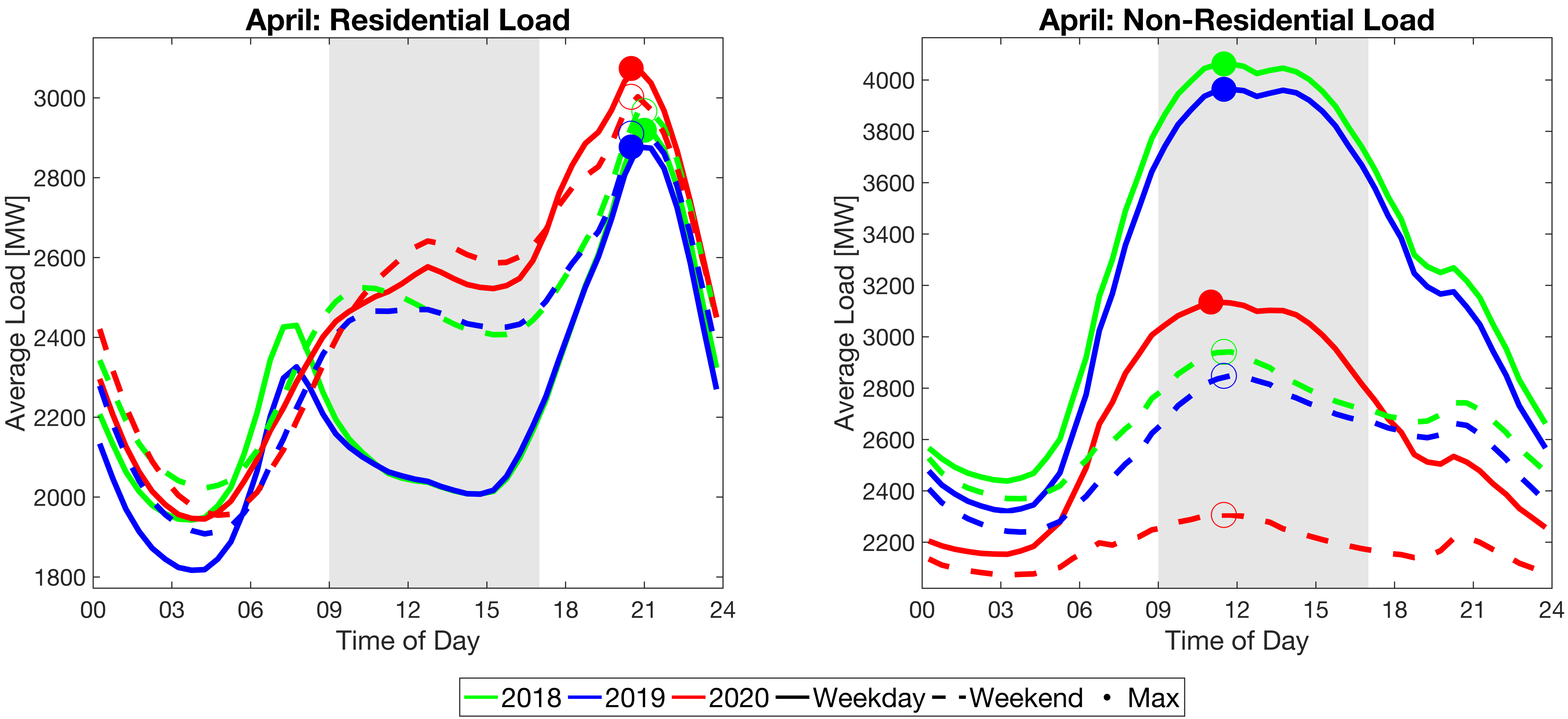


“Perpetual Weekends” Under COVID-19

Weekday residential load profiles from April 2020 looked like *weekend* profiles from previous years.



Eastside | Education | Education Lab | Health | Local News

Seattle, Bellevue, other King County schools announce intentions to go online-only come fall

July 22, 2020 at 8:04 pm | *Updated July 23, 2020 at 4:33 pm*

recode

Facebook is the latest major tech company to let people work from home forever

The social media giant is letting its employees request to permanently work from home.

By Shirin Ghaffary | May 21, 2020, 4:41pm EDT

TECH / CORONAVIRUS

Twitter Will Allow Employees To Work At Home Forever

Two months into working from home, Twitter makes it permanent for some.

Alex Kantrowitz
BuzzFeed News Reporter

Posted on May 12, 2020, at 12:08 p.m. ET

3 Signs You'd Be Happy Working From Home Forever

Kourtney Whitehead Senior Contributor
Careers
I write about uniting core values and relationships with work.

Richland school board votes to start school year online

by Christopher Poulsen | Tuesday, July 28th 2020

HOME > STRATEGY

A survey finds more than two-thirds of companies may be working from home forever

Juliana Kaplan Jun 20, 2020, 12:11 PM

BACK-2-SCHOOL

WSU decides to shift to online learning only for fall 2020

All undergraduate courses at WSU Pullman will be done remotely with extremely limited exceptions for in-person instruction.

UP FRONT

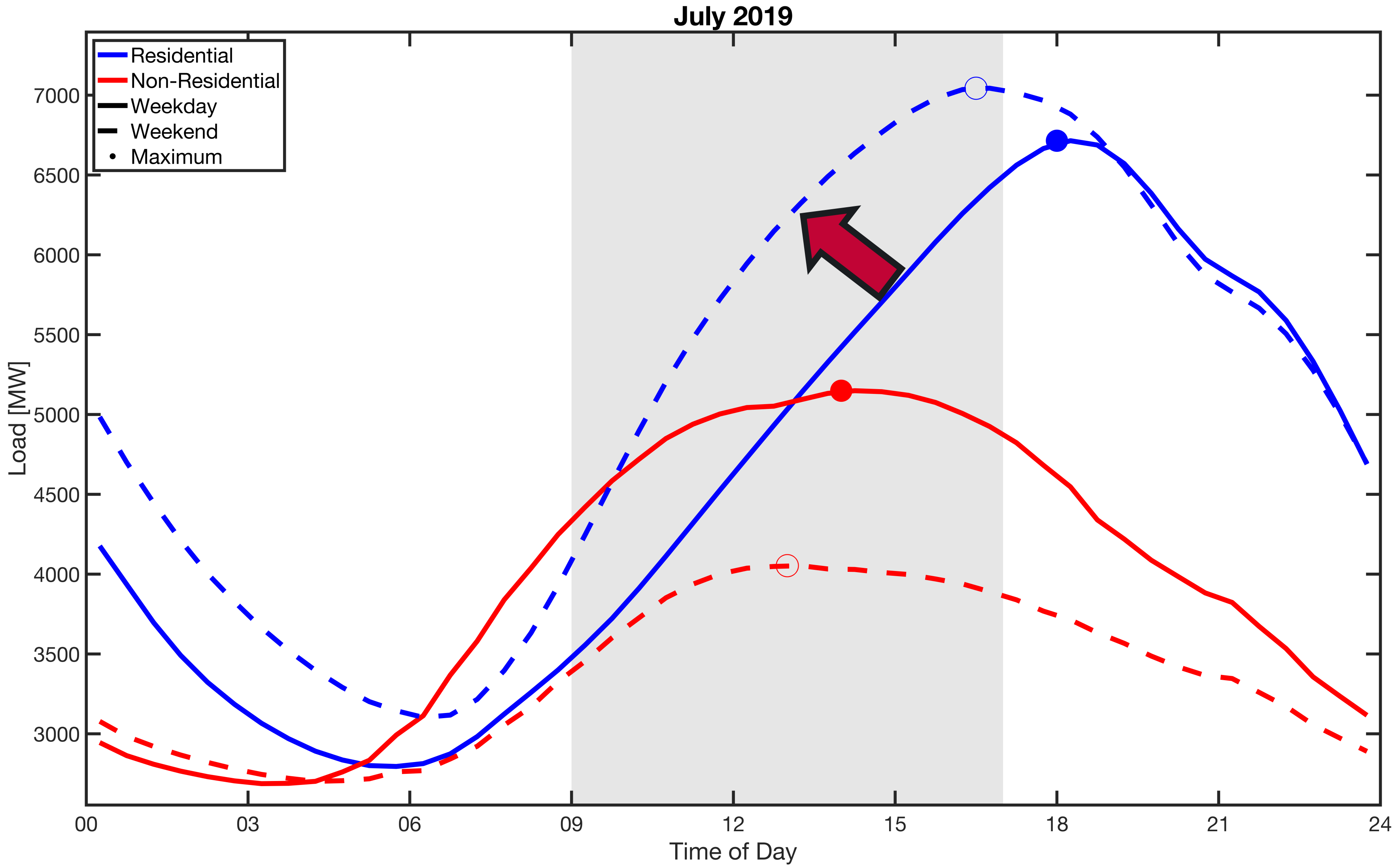
Telecommuting will likely continue long after the pandemic

Katherine Guyot and **Isabel V. Sawhill** · Monday, April 6, 2020

Pacific Northwest NATIONAL LABORATORY

Implications of “The New Normal”

Can we use historical load profiles to understand what might happen in the future if widespread teleworking and home-schooling continues?

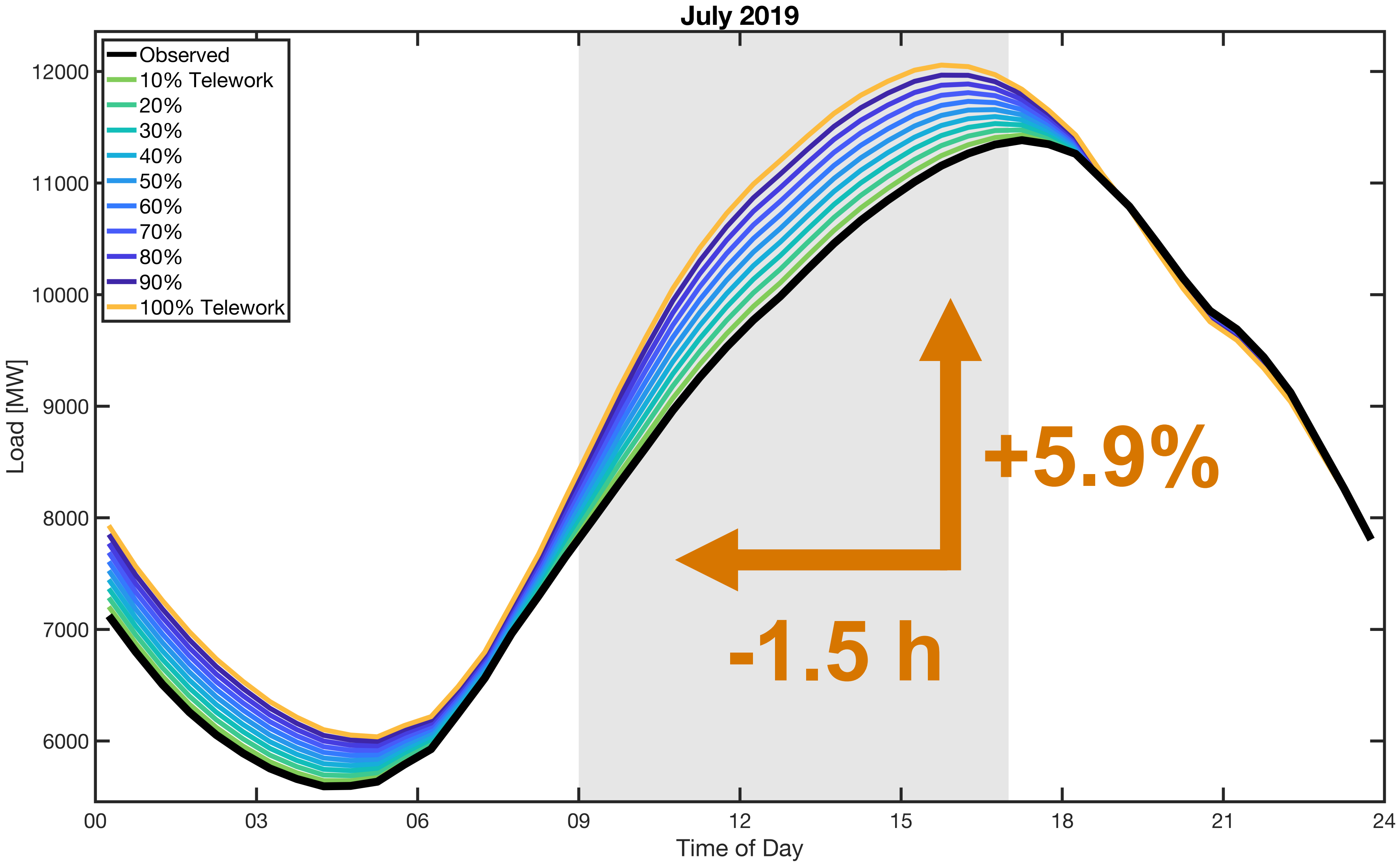


Method

To simulate a subset of the population teleworking, swap in incrementally larger fractions of the historical weekday residential load profiles with their corresponding weekend profiles.

Implications of “The New Normal”

Can we use historical load profiles to understand what might happen in the future if widespread teleworking and home-schooling continues?



Key Result

If lots of people were teleworking in the summer of 2019, the peak of the electricity load profile would have been ~6% higher and occur up to 1.5 hours earlier in the day!