Master Thesis Defense
Department of Earth and Ocean Sciences
Duke UNIVERSITY

Changes in U.S. Residential Monthly Energy Use per Capita: 1990-2017

Xiaoxuan Yang

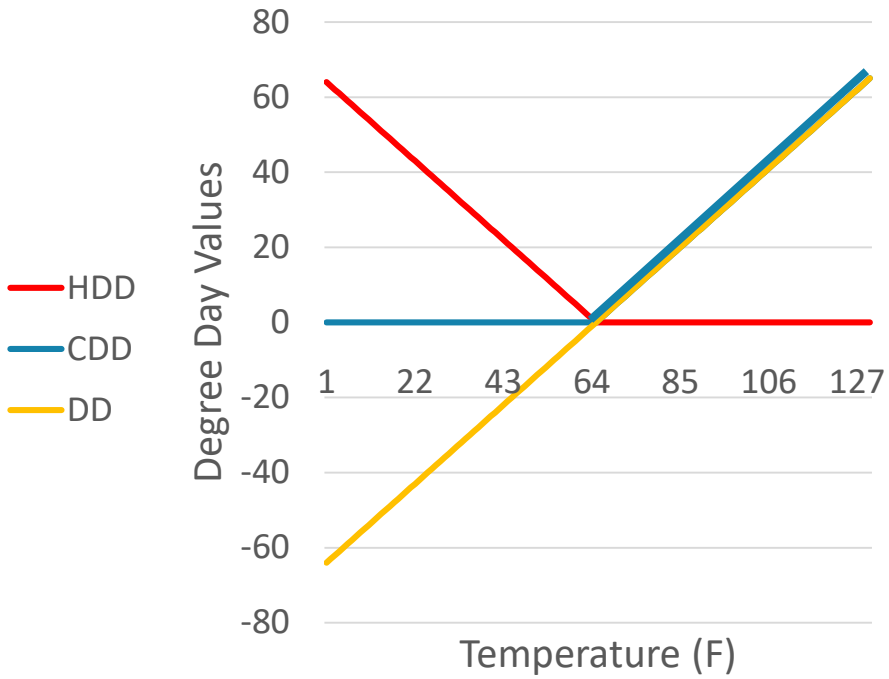
Degree Day Variables

Degree days are the differences between the daily temperature mean $\bar{T}$ and base temperature T_b (conventionally at 65°F).

$$CDD = \sum_{d=1}^{N_d} \gamma_d (T - T_b)$$

$$HDD = \sum_{d=1}^{N_d} (1 - \gamma_d)(T_b - \bar{T})$$

$$DD = CDD - HDD$$



Background

Degree day methodology – examine the impact of climate change on residential energy use

End-uses by Fuel – Space heating: natural gas, electricity, fuel oil, etc.

Space cooling: electricity

Climate Change Impact – expect higher cooling demand, which would lead to increased electricity consumption; Fewer cold winter days result in decreased heating demand

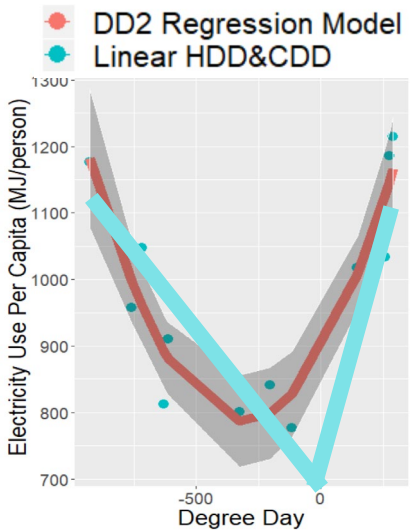
Research Question

How has the relationship between degree days and residential energy use been changing temporally and spatially?

Degree Day Literature

Linear symmetric models: energy demand responds the same to a marginal change in temperature (Eskeland et al., 2010)

Non-linear models*: allow more variation in the slope, reflecting constraints associated with capacity of space conditioning equipment.



Other variables: two major categories:

- socio-economic (GDP, fuel prices, household income)
- climatological (humidity, precipitation)

Non-linear OLS Regression Models

Combination of independent variables (including their first and second order if appropriate):

1. Spatial and Temporal Fixed Effects:

$$C_e = \beta_1 \cdot DD + \beta_2 \cdot DD^2 + \beta_3 \cdot GDP + \alpha_t + \alpha_s + \varepsilon_{st}$$
$$C_g = \beta_1 \cdot DD + \beta_2 \cdot DD^2 + \beta_3 \cdot GDP + \alpha_t + \alpha_s + \varepsilon_{st}$$

2. State-by-state, Year-by-year:

$$C_e = \beta_1 \cdot DD + \beta_2 \cdot DD^2 + \varepsilon_{st}$$
$$C_g = \beta_1 \cdot DD + \beta_2 \cdot DD^2 + \varepsilon_{st}$$

Variables

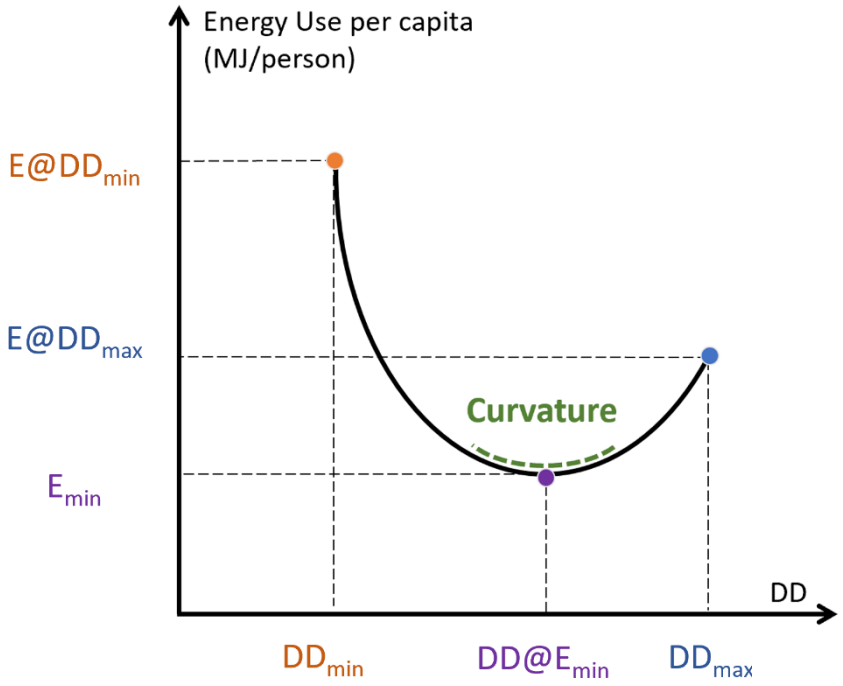
Dependent variables:

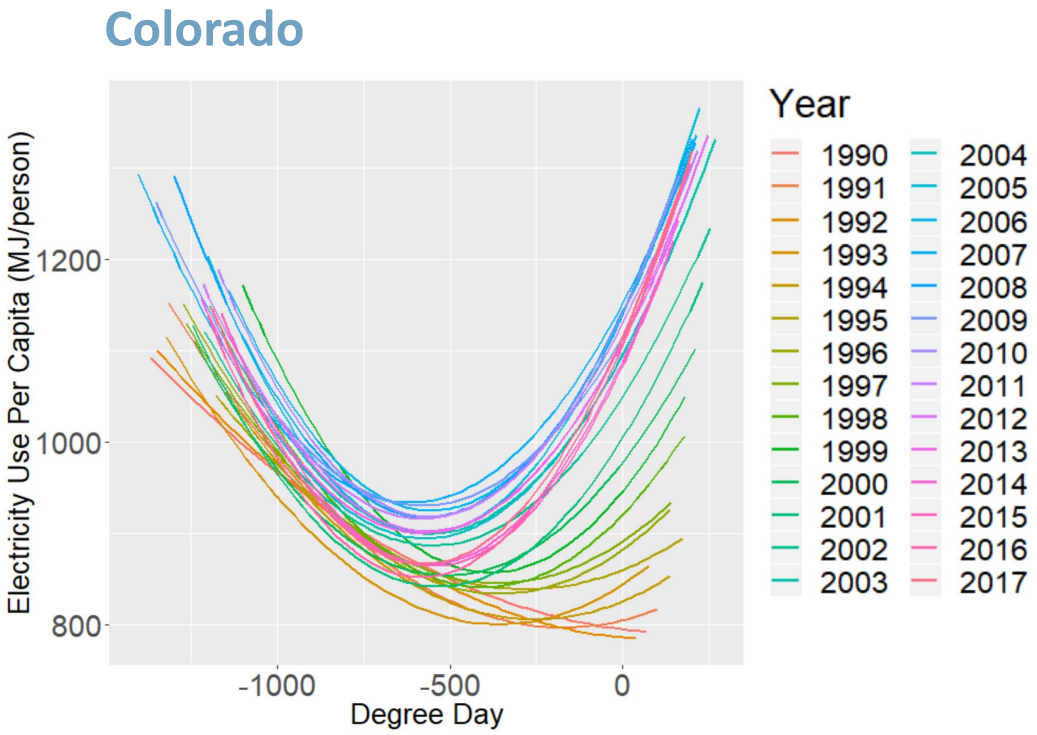
- Monthly electricity use (EIA-861M)
- Monthly natural gas use (EIA)

Independent variables:

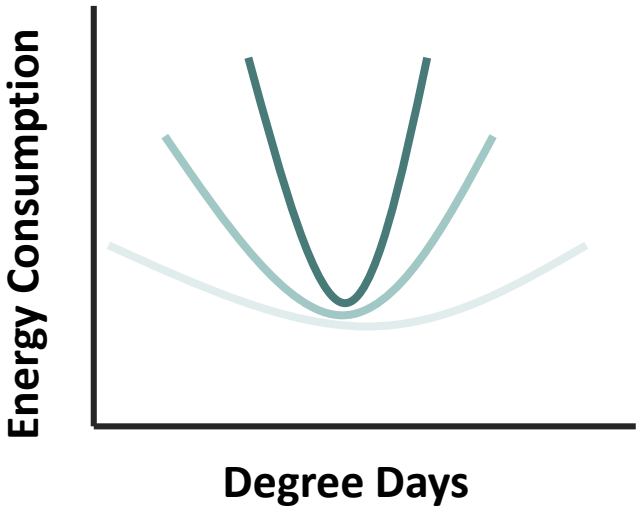
- Population-weighted monthly CDD, HDD (NOAA)
- Real GDP (applying quadratic-match average to annual GDP)
- Residential population (interpolating annual state population from Census Bureau)

Identify Seven Unique Curve Dimensions

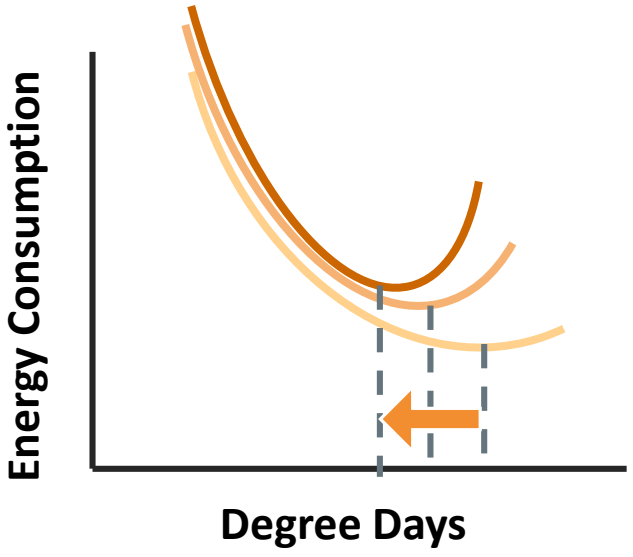




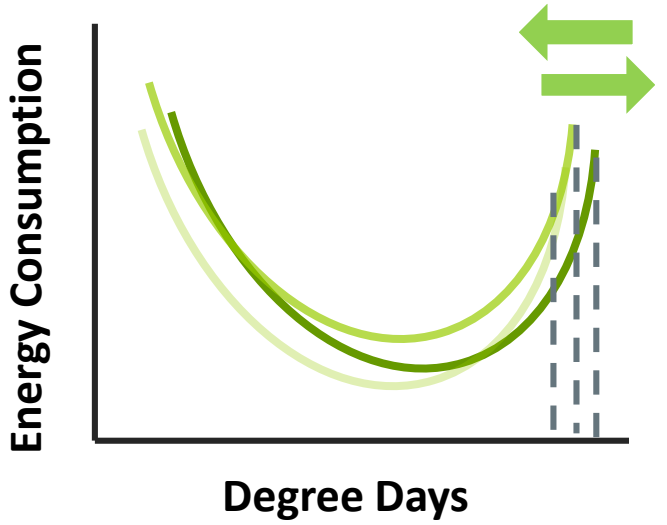
Curve Movements



Positive trend in curvature: +1



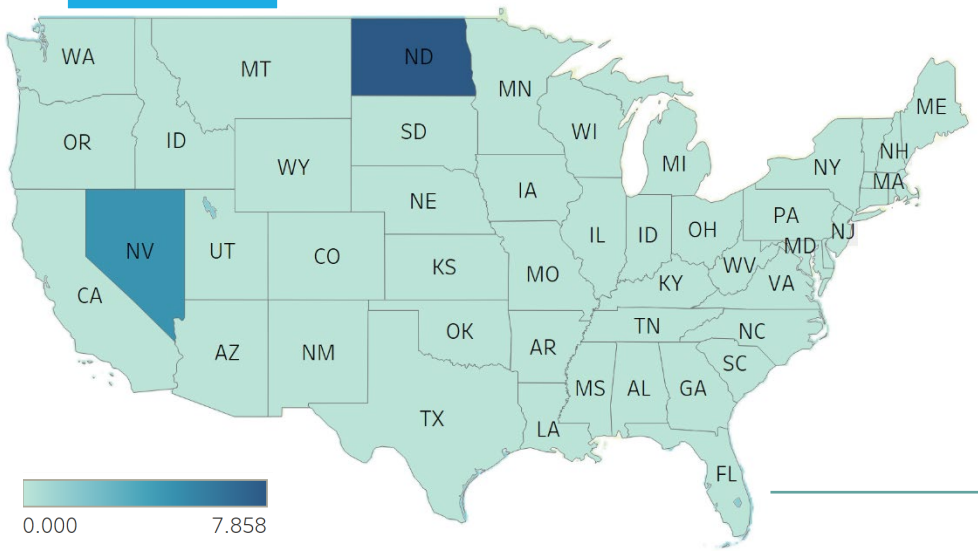
Negative trend in DD@E_{min} : -1



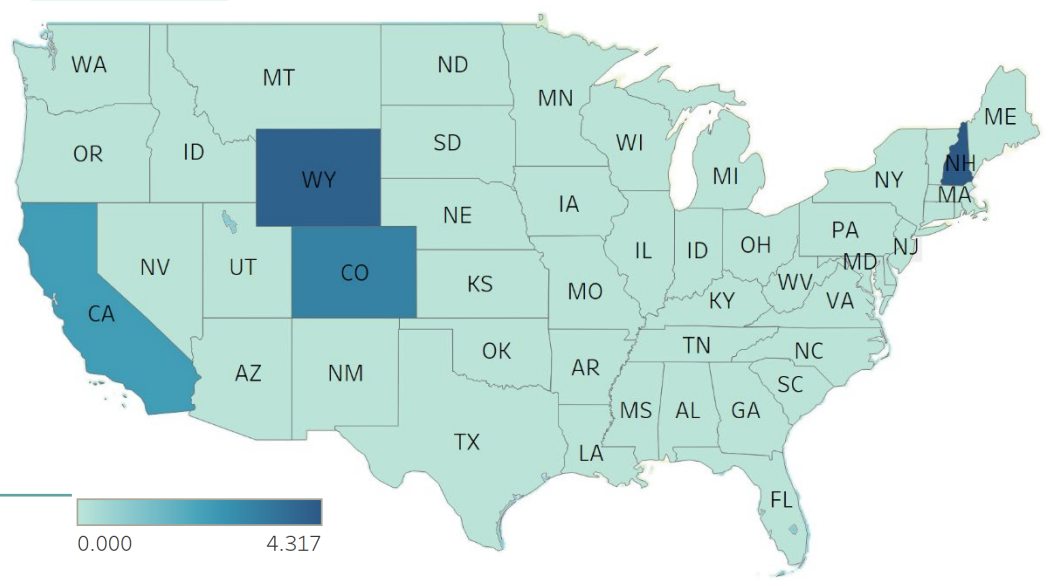
Insignificant change in climate: 0

Trends in Degree Day

DD_{min}



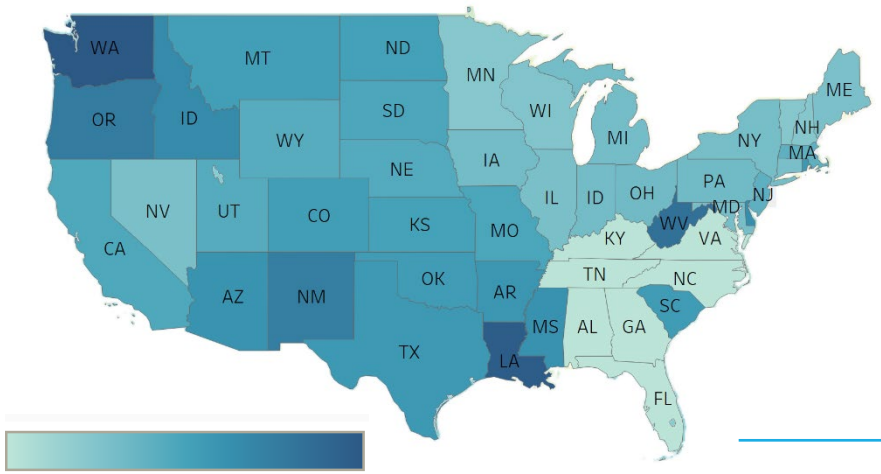
DD_{max}



	DD_{min}	DD_{max}
Insignificant (0)	96%	92%
Significant (+)	4%	8%
Significant (-)	0%	0%

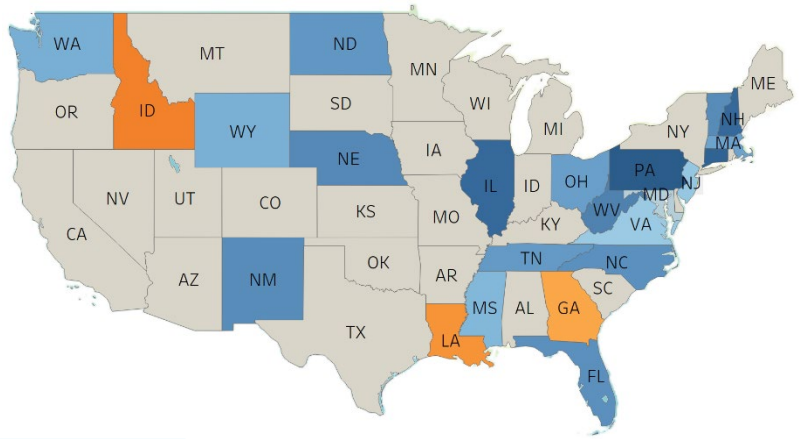
Trends in Curvature

Electricity



0.00000000 0.00007686

Natural Gas

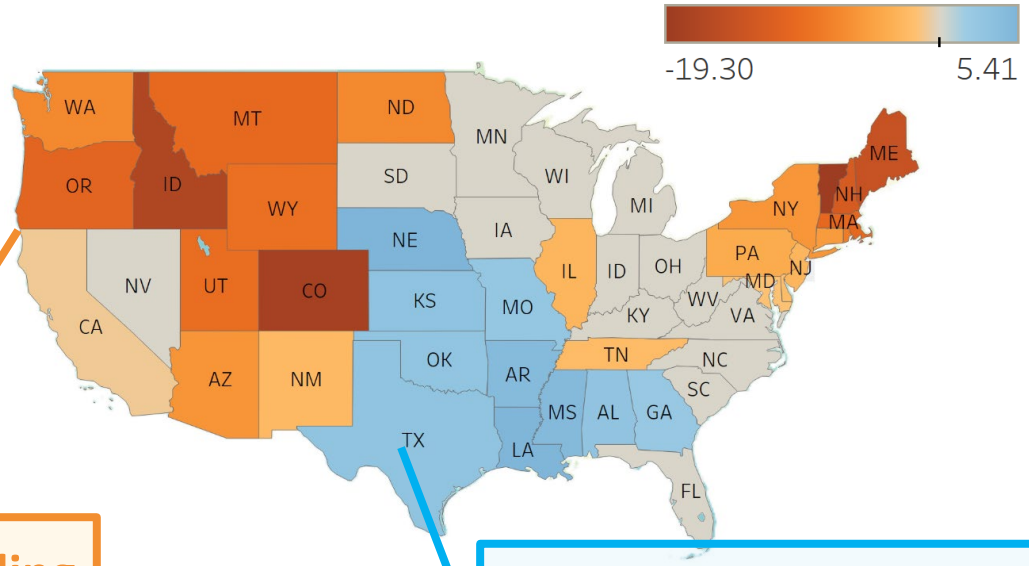


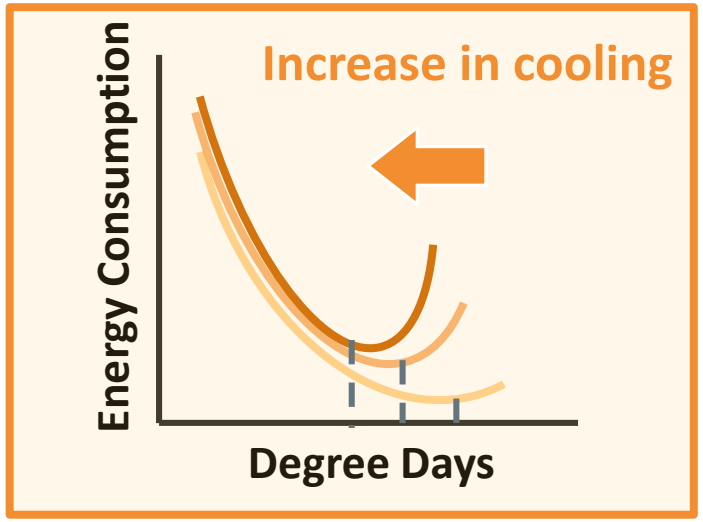
-0.0000396 0.0000985

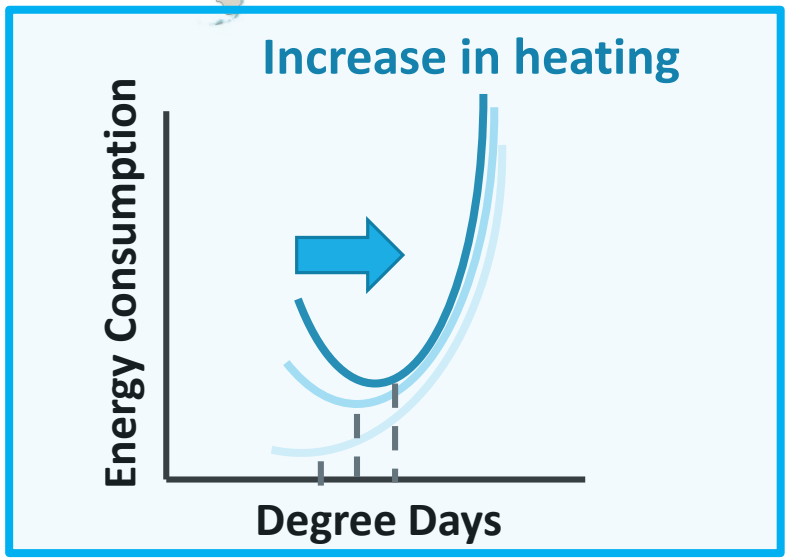
	Curvature (electricity)	Curvature (natural gas)
Insignificant	15%	52%
Significant (+)	81%	42%
Significant (-)	0%	6%

DD at Lowest Electricity Use

	DD at lowest Electricity
Insignificant	29%
Significant (+)	21%
Significant (-)	50%







Trends in Curve Dimensions

Electricity

	Curvature	DD at lowest Electricity	Electricity use at DD_{max}	Electricity use at DD_{min}	Lowest Electricity Use
Insignificant	15%	29%	6%	13%	17%
Significant (+)	81%	21%	94%	79%	81%
Significant (-)	0%	50%	0%	8%	2%

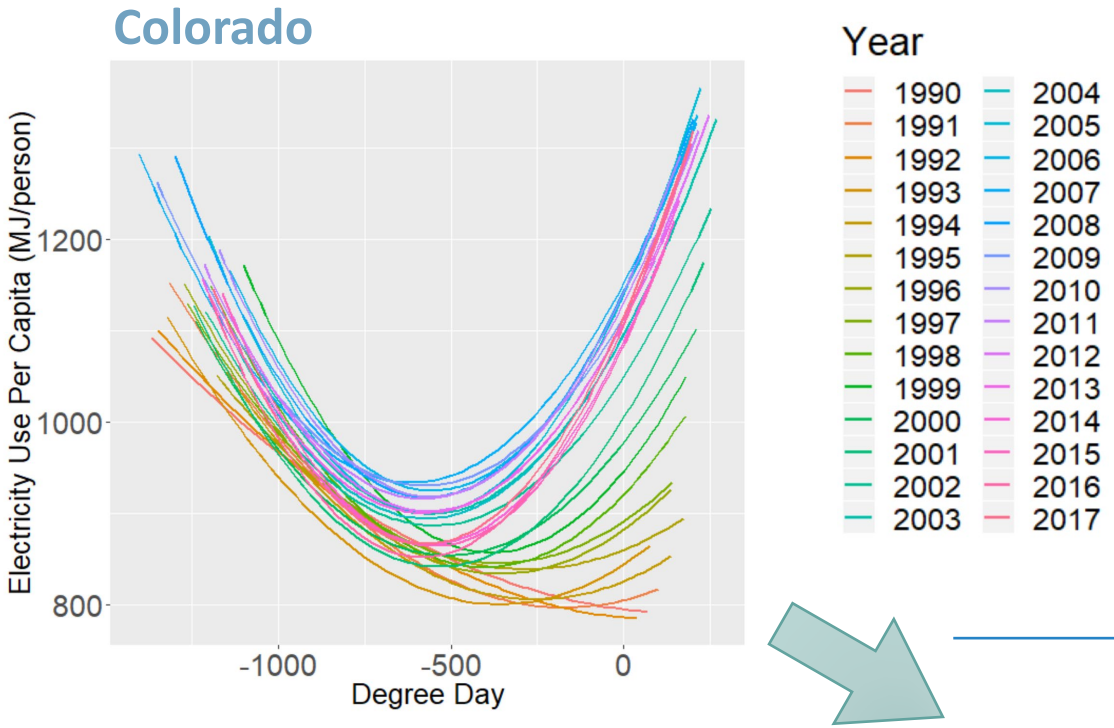
Natural gas

	Curvature	DD at lowest NG	NG use at DD_{max}	NG use at DD_{min}	Lowest NG Use
Insignificant	52%	73%	21%	40%	15%
Significant (+)	42%	6%	8%	23%	6%
Significant (-)	6%	21%	71%	38%	79%

- Sensitivity of energy use to temperature
- National trends of increasing or decreasing
- Change in cooling and heating

	DD_{min}	DD_{max}
Insignificant	96%	92%
Significant (+)	4%	8%
Significant (-)	0%	0%

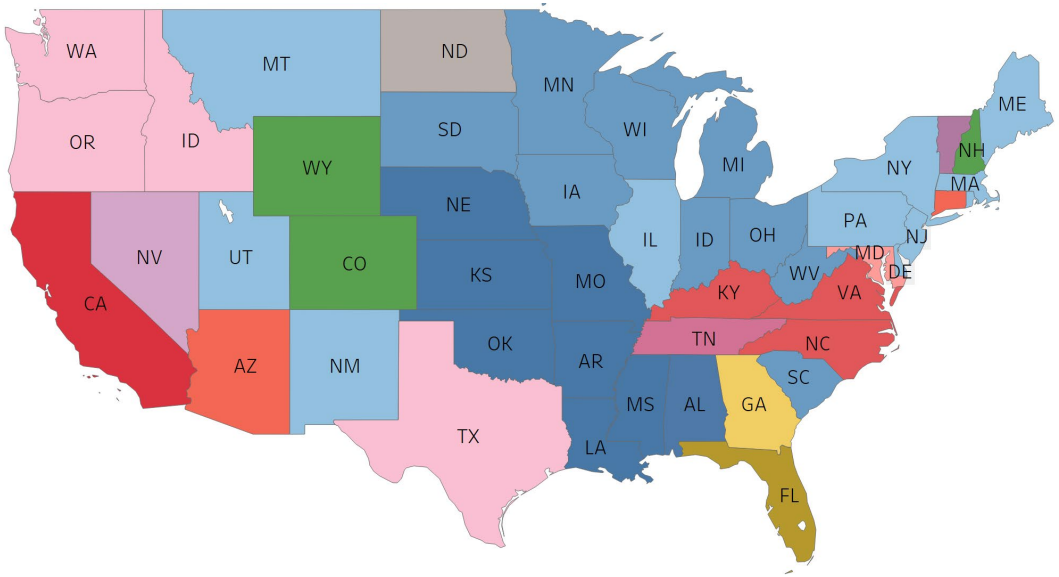
Identify Trends in Curve Dimensions



	Curvature	DD at E_{min}	DD_{max}	DD_{min}	E at DD_{max}	E at DD_{min}	E_{min}	Combination
Colorado	1	-1	1	0	1	1	1	1-110111

Classification of States

Electricity

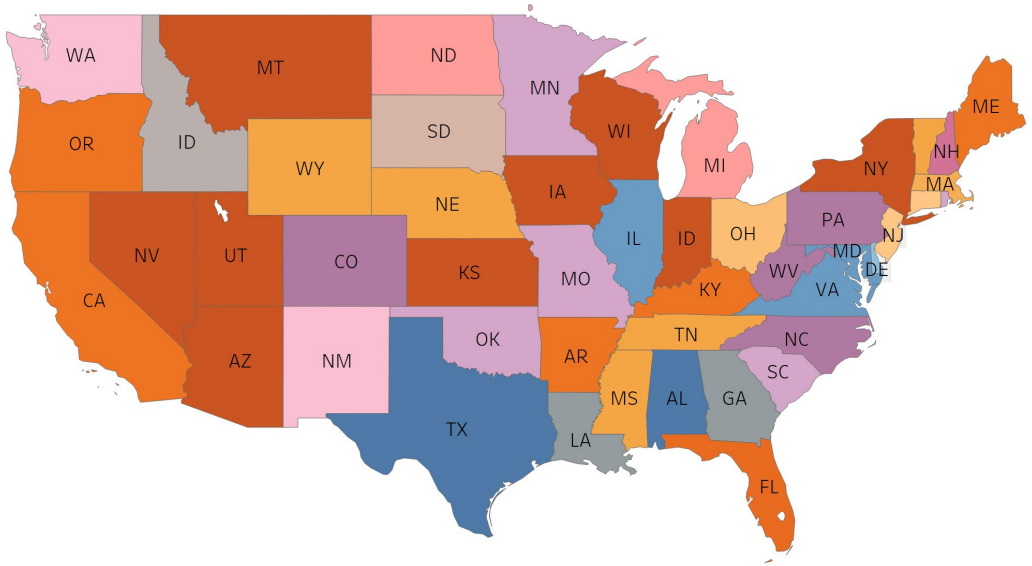


Blue – top 3 common class: upward movement of electricity use and increased sensitivity to changing temperatures

Pink – Mostly increased electricity use except at low temperature

Red – other

Natural gas

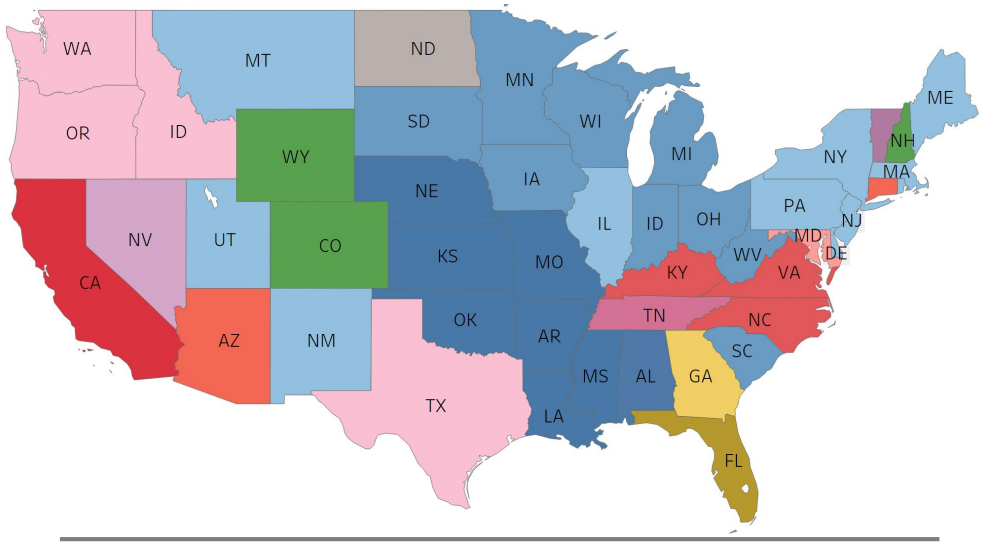


Orange – decreased natural gas use at all temperatures

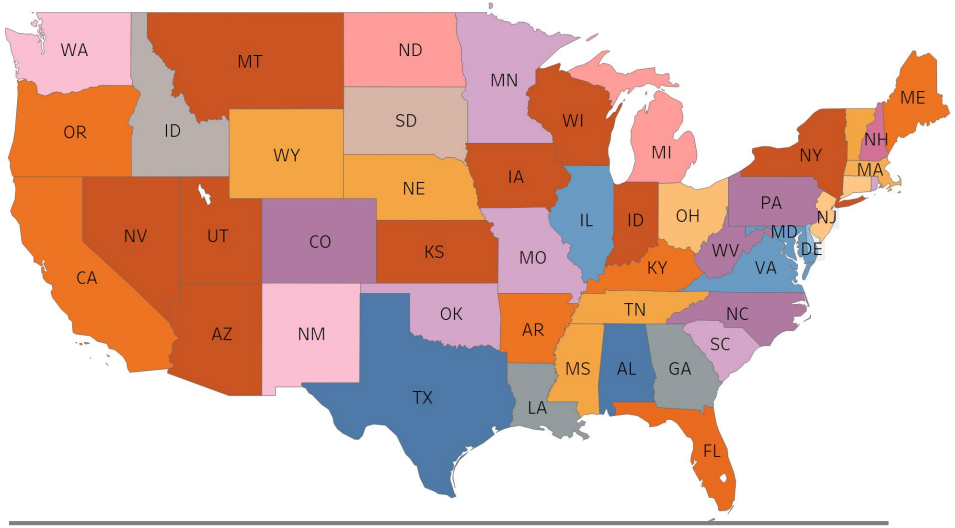
Purple – increased sensitivity to temperature

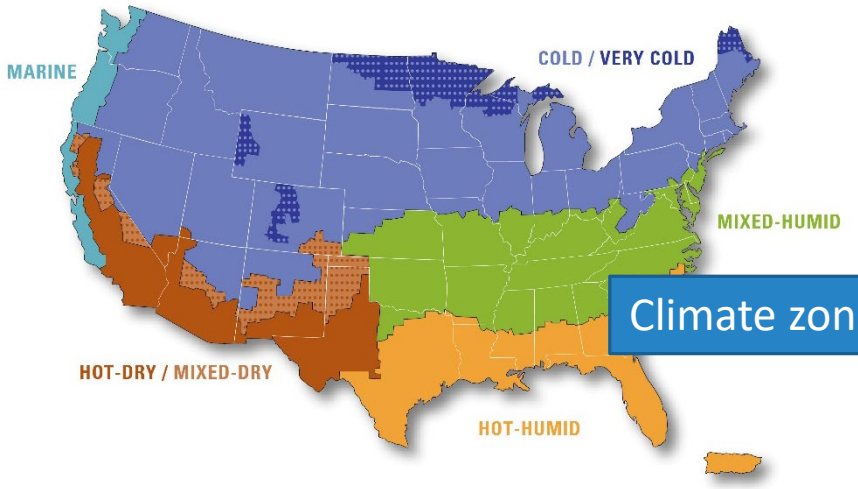
Grey – decrease sensitivity to temperature

Electricity

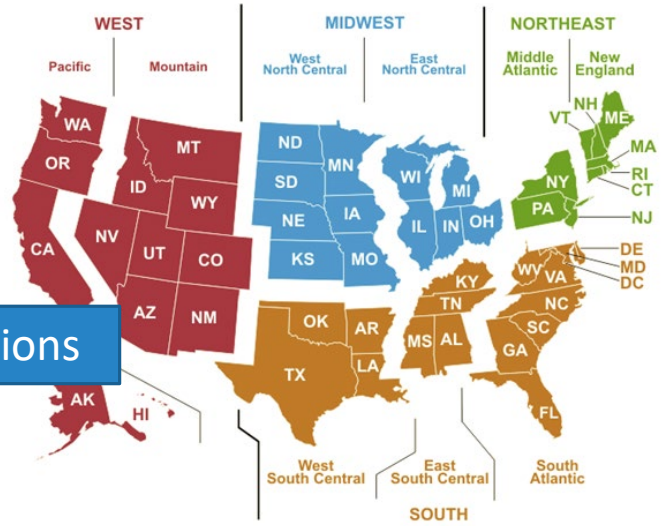


Natural gas

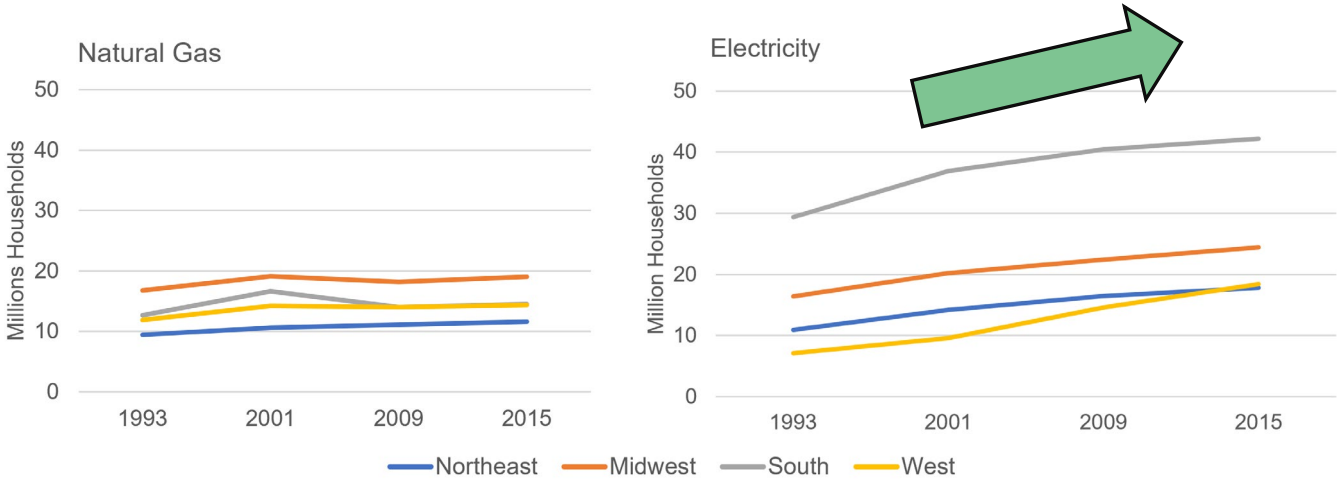




Climate zones & Census divisions



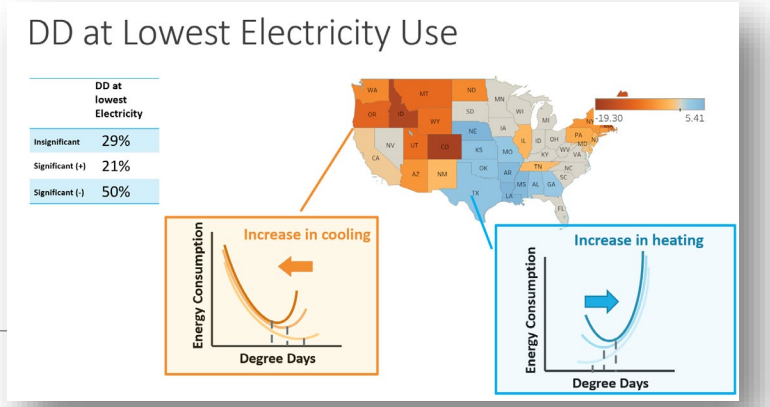
Comparison with RECS data



Households using natural gas and electricity as main heating sources.

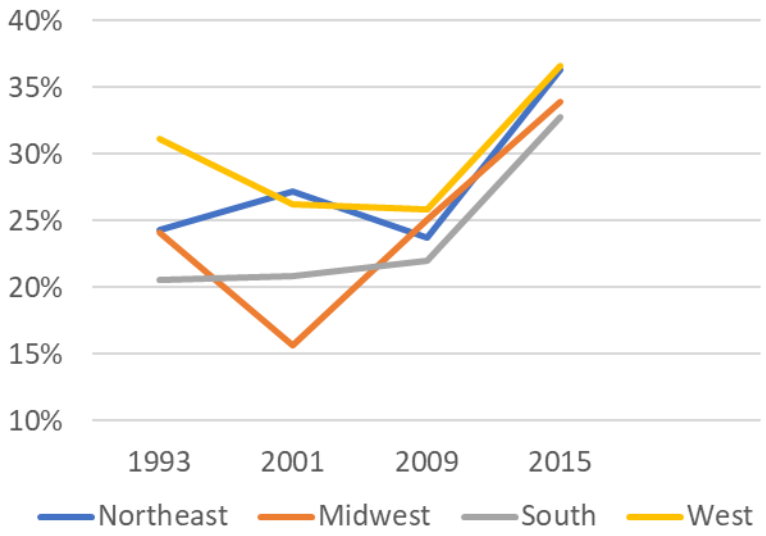
- Slowdown of natural gas installation in new constructions
- Increased electricity use in the current housing stock

More Comparison

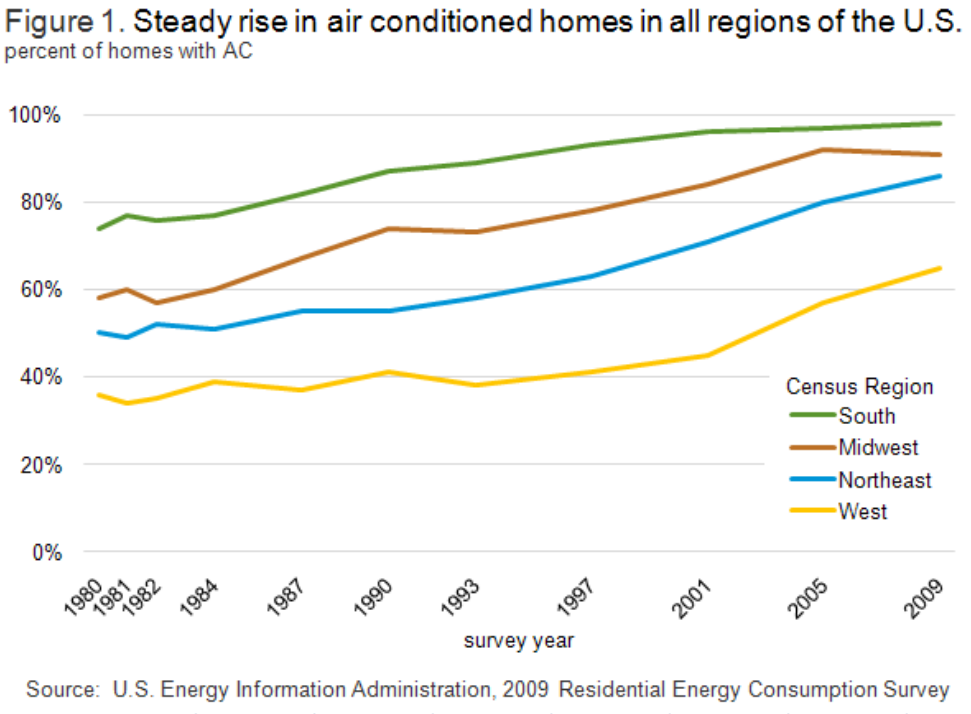


HEATING TREND

$$\frac{Electricity\ use\ \frac{MJ}{m2}}{Electricity + Natural\ gas\ \frac{MJ}{m2}}$$



COOLING TREND



Major Conclusion

1. No evident annual warming or cooling trend for state-level DD for the period analyzed;

2. Increased sensitivity of electricity use per capita and overall electricity use with respect to seasonal fluctuations in temperatures;

3. Decreased NG use per capita with respect to seasonal fluctuations in temperatures;

4. $DD@Electricity_{min}$ trends:
   a) Positive: increasing electricity use for heating in the South
   b) Negative: cooling in Northwest and Northeast

Questions?

I would like to thank my advisor, Prof. LincolnPratson for his guidance during my research and study at Duke University. I also want to thank my committee members Prof. Timothy Johnson and Prof. Wenhong Li for contributing invaluable ideas to my research and sharing relevant literature. Lastly, I want to thank my labmates Jun Shepard and Candise Henry for their endless support throughout my two years at Duke.

Implications (Energy Use)