Global warming and local cooling: Impact of Climate Change on electricity demand of India

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(Work in progress)

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STATISTICAL INDIAN INSTITUTE

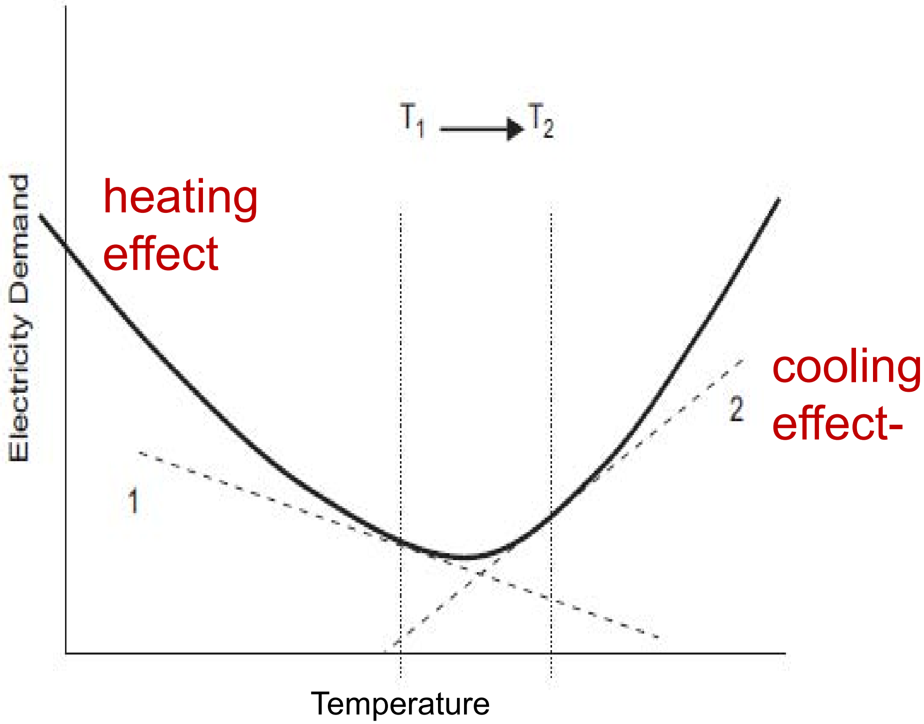
UNITY IN DIVERSITY

Goal

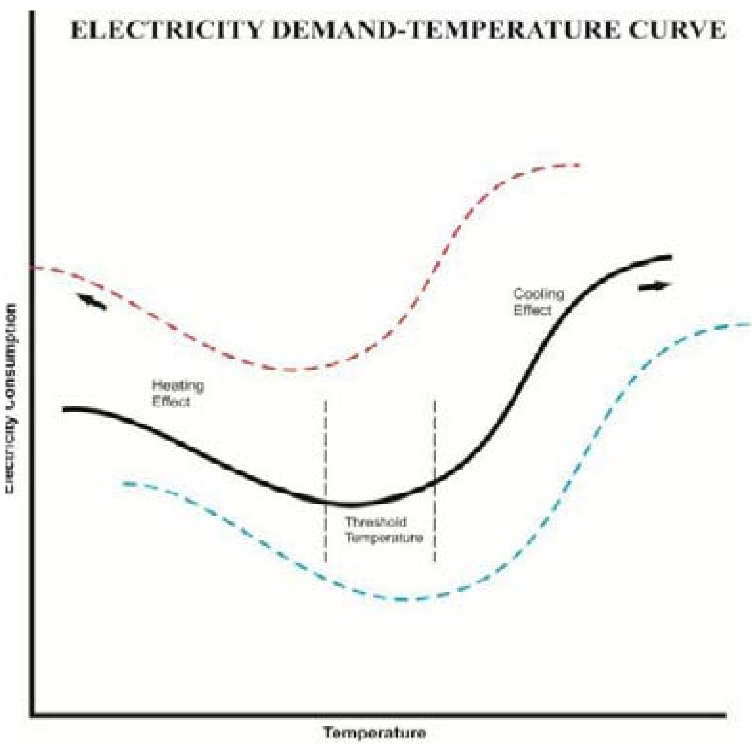
To investigate link between rising global temperature and electricity demand of India

‘u’ shaped non-linear pattern

A u-shaped “temperature dependence pattern” suggests that climate change may have ambiguous consequences for future electricity demand of India



Hypothesis



- With rapid changes in economic structure, the relation is likely to be **shifting**…
- Changes in the **threshold temperatures** with shifting curves
- Changes in **slope** of the curve over time

India is undergoing significant development in its socio-economic structure. Increasing ownership of cooling appliances- air conditioners, coolers; energy efficiency improvements, increasing internal heat gains (For example increased use of computers).

Motivation

- No previous work for India
- Spatial variation
- Temporal Variation
- Expected changes in the frequency of hot summer days, spells and warm nights
- Previous studies do not accurately represent spatial differences and temporal dynamics leading to TDP variation.

Literature Review

Parametric Models	Nonparametric Models
Linear models: HDD and CDD Approach	Local Polynomial Regressions
Time series Models: ARIMA, Co integration	Smoothing Splines
Transition Regression Models	Nonparametric Time series models
Smooth Transition Regression Models	

Nonparametric Models: semiparametric model using Splines

Author (year/Place)	Paper	Method/data
Robert F. Engle, C. W. J. Granger, John Rice, Andrew Weiss (1986)	**Semiparametric Estimates of the Relation Between Weather and Electricity Sales** **"Journal of American Statistical Association"**	smoothing spline, monthly data 7-9 yrs, 4 US utilities

$$\mathbf{E} = \mathbf{Z}\gamma + f(AT) + \varepsilon$$

Semiparametric variable coefficient Model using penalized splines (Delhi Model using 10 years data 2000-2009)

Engle ,Granger, Rice and Weiss (1986)

E=Zγ+f(AT)+ε ..(1)

$$\mathbf{E} = \mathbf{Z}\gamma + \mathbf{f}(\mathbf{AT})\mathbf{Y} + \varepsilon = \mathbf{Z}\gamma + \sum_{t=1}^{10} \mathbf{f}(\mathbf{AT})\mathbf{y}_t + \varepsilon = \mathbf{Z}\gamma + \sum_{t=1}^{10} \mathbf{f}_t(\mathbf{AT}) + \varepsilon \qquad ..(2)$$

where, $\mathbf{E}$ is an 3643×1 vector of electricity demands, ε is an 3643×1 vector of errors, and $\mathbf{Z}$ is an 3643×19 matrix of linear predictors, γ is an 19×1 vector of coefficients of Z predictors, $\mathbf{f}_t(\mathbf{AT})$ is a vector of smooth function of the temperature index of year t with dimension 3643×1. Here, t indexes year with $t = 1$ for year 2000 and $t = 10$ for year 2009. $\mathbf{Y}$ is an 3643×10 matrix of year dummies. and $\mathbf{y}_t$ is the column t of $\mathbf{Y}$. Here, $\mathbf{y}_t$ is the year dummy for year t. Electricity demand on a particular day is represented as

$$e_{td} = \mathbf{z}'_{td}\gamma + f_t(AT_{td}) + \varepsilon_{td}$$

Semiparametric variable coefficient Model using penalized splines

- Smooth function of the temperature index $f(AT)$ is estimated by penalized cubic natural splines.

- Splines are piecewise polynomial functions that are constrained to join smoothly at points called knots.

- With splines, one must choose the degree of a polynomial for a piecewise regression functions, the number of knots, and the location of knots.

- For regression splines, the number of knots selected will control the amount of smoothing, while for penalized splines, a smoothing parameter controls the amount of smoothing.

Semiparametric variable coefficient Model using penalized splines

Table 1- Dependent and the control variables used in regression

Variables	Description
Ed_{td}	Electricity demand (shortage + consumption) on day d of year t
WD_{td}	Dummy variable equals one for the day p, and zero otherwise; 6 day dummies are used with wednesday as a base day
H_{td}	Dummy variable equals one for the Major holiday, and zero otherwise
M_{td}	Dummy variable equals one for the Minor holiday, and zero otherwise
Y_t	Dummy variable equals one for the year t, and zero otherwise; 9 year dummies are used with 2000 as a base year
R_{td}	Rainfall (measured in millimeters (mm)) on day d of year t

$$e_{td} = \beta_0 + \beta_1 H_{td} + \beta_2 M_{td} + \beta_3 R_{td} + \sum_{t=1}^{10} f(AT_{td}) y_t + \sum_{t=1}^{9} \phi_t y_t + \sum_{\rho=1}^{6} \varphi W D_{dt} + \varepsilon_{td}$$

Data on daily electricity demand

- National Load dispatch centre (NLDC)
- Central Electricity Authority (CEA)
- Delhi Transco Ltd (DTL)
- NDPL

Electricity Demand=
Electricity Consumption+ Daily shortage/shedding

Data on other variables

Daily Minimum Temperature, Maximum Temperature, humidity, Rainfall

- Indian Meteorological Department
- Weather website-www.tutiempo.net/en/climate/India.

Apparent temperature

$$AT_{td}\left({}^{0}C\right) = T_{td} + 0.33v_{td} + 0.07w_{td} - 4$$

$$v_{td} = \frac{h_{td}}{100} \times 6.105 + e^{\left(\frac{17.27T}{237.7+T}\right)}$$

where T denotes average temperature in degree Celsius (^{0}C), v denotes evaporation, w denotes wind speed (m/s), and h denotes relative humidity(%)

Results

(Delhi)

Parametric Part

Table-3a Parameter estimates from Parametric and Semiparametric models

Models	I		II		III		IV	
Constant	88.11 **	(1.45)	49.96**	(.24)	49.96**	(.24)	50.15**	(.17)
2001	2.22**	(.28)	2.29**	(.27)	2.29**	(.27)	2.08**	(.20)
2002	4.7**	(.281)	4.8**	(.27)	4.8**	(.27)	4.7**	(.20)
2003	5.9**	(.28)	6.2**	(.27)	6.2**	(.27)	5.88**	(.20)
2004	8.5**	(.281)	8.64**	(.27)	8.64**	(.27)	8.45**	(.20)
2005	10.11**	(.28)	10.27**	(.27)	10.27**	(.27)	10.11**	(.20)
2006	12.58**	(.28)	12.86**	(.27)	12.84**	(.27)	12.57**	(.20)
2007	11.75**	(.28)	12.07**	(.27)	12.05**	(.27)	11.80**	(.20)
2008	12.69**	(.28)	13.09**	(.27)	13.06**	(.27)	12.81**	(.20)
2009	16.14**	(.28)	16.30**	(.27)	16.30**	(.27)	16.03**	(.20)
Friday	0.96**	(0.23)	0.93**	(0.22)	0.93**	(0.22)	0.95**	(0.16)
Monday	−0.58*	(0.23)	−0.54*	(0.22)	−0.54*	(0.22)	−0.53*	(0.16)
Saturday	−0.99**	(0.23)	−0.98**	(0.22)	−0.98**	(0.22)	−0.94**	(0.16)
Sunday	−3.62**	(0.23)	−3.55**	(0.22)	−3.55**	(0.22)	−3.56**	(0.16)
Thursday	.28	(0.23)	.24	(0.22)	.25	(0.22)	.33	(0.16)
Tuesday	−.11	(0.24)	−.08	(0.22)	−.08	(0.22)	−.06	(0.16)
Major	−3.5**	(0.32)	−3.4***	(0.31)	−3.4***	(0.31)	−3.3**	(0.22)
Minor	−.38	(0.26)	−.27	(0.25)	−.27	(0.25)	−.42 *	(0.18)
Rainfall	−.043**	(.01)	−.052**	(.01)	−.052**	(.01)	−.052**	(.01)
AT	−5.91**	(0.19)						
AT^2	.21**	(0.01)						
AT^3	−.002**	(0.0001)						

Notes:

** significant at 99% significance level

* Significant at 95% significance level

Dependent variable for all models is electricity demand

Nonparametric Part

Table 3c. Approximate significance of smooth terms in Semiparametric Models

	EDF	F	p-value
Model II			
f(AT)	11	1856	0.000
Model III			
f(AT)	7.67	2399	0.000
Model IV			
f(at):2000	6.203	225.8	0.000
f(at):2001	6.168	281.8	0.000
f(at):2002	6.288	375	0.000
f(at):2003	6.226	318.7	0.000
f(at):2004	6.186	447.1	0.000
f(at):2005	6.343	470.2	0.000
f(at):2006	6.19	716.8	0.000
f(at):2007	6.323	789.6	0.000
f(at):2008	6.182	774.6	0.000
f(at):2009	6.207	1410.7	0.000

Nonparametric Part

Table 3b. Goodness of Fit Diagnostics

	Models			
	I	**II**	**III**	**IV**
Adjusted R^2	0.873	0.884	0.884	0.938
AIC	20031.87	19709	19709	17464.2
GCV	14.301	13.09	13.091	7.09
Durbin Watson Statistic				2.01
N	3643	3643	3643	3643
Model DF (degrees of freedom)	22	30	26.67585	81.316
Residual DF (N-DF)	3621	3613	3616.33	3561.68

TDP for 2000

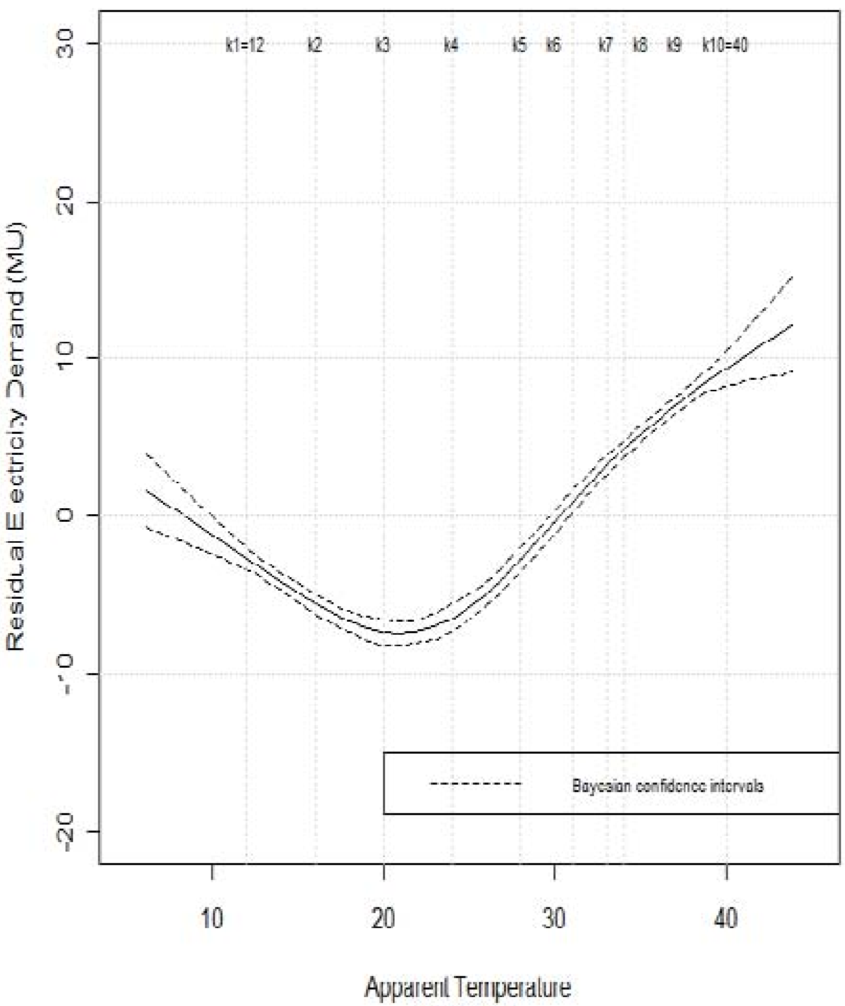


Figure 5.1

TDP for 2001

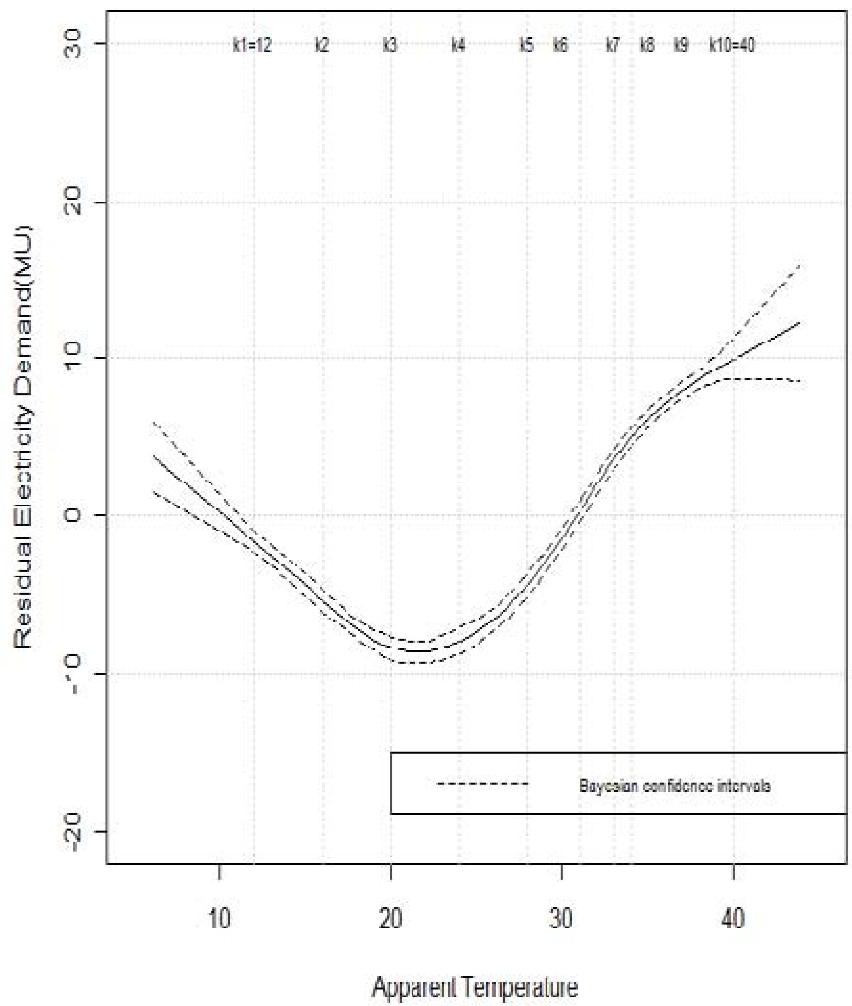


Figure 5.2

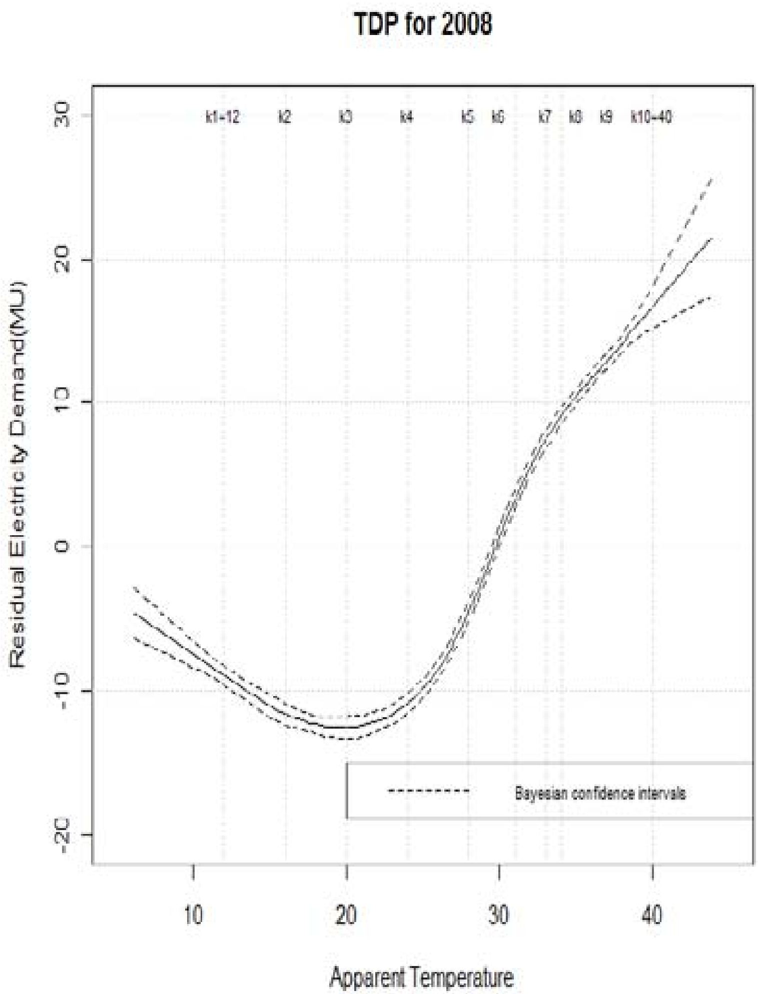


Figure 5.9

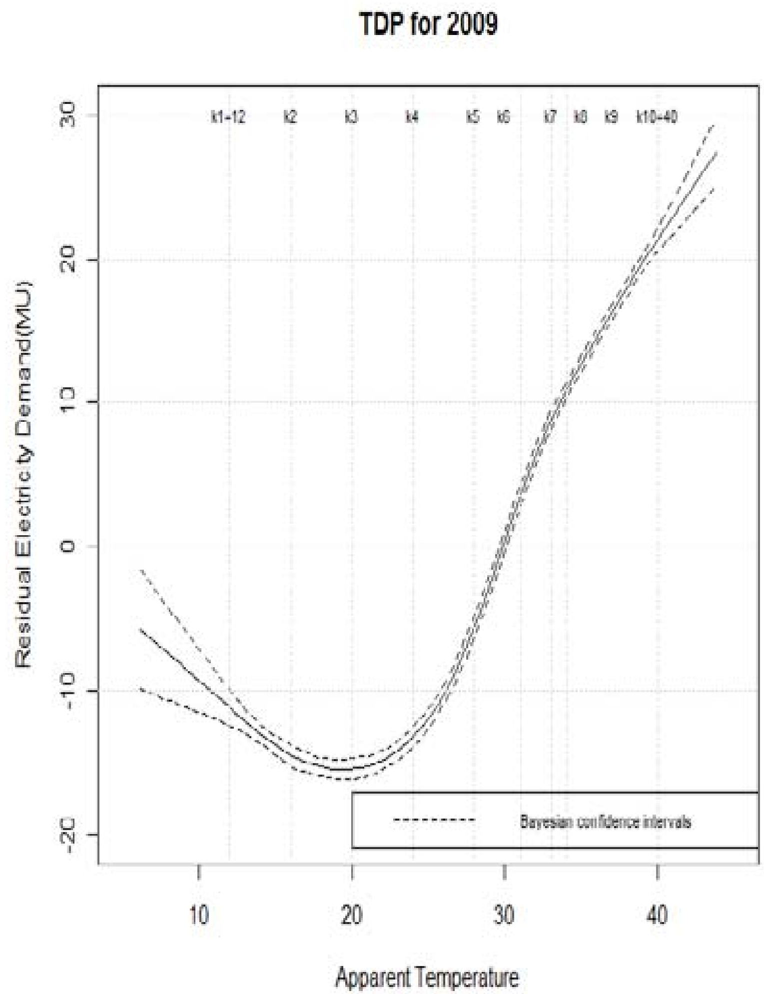
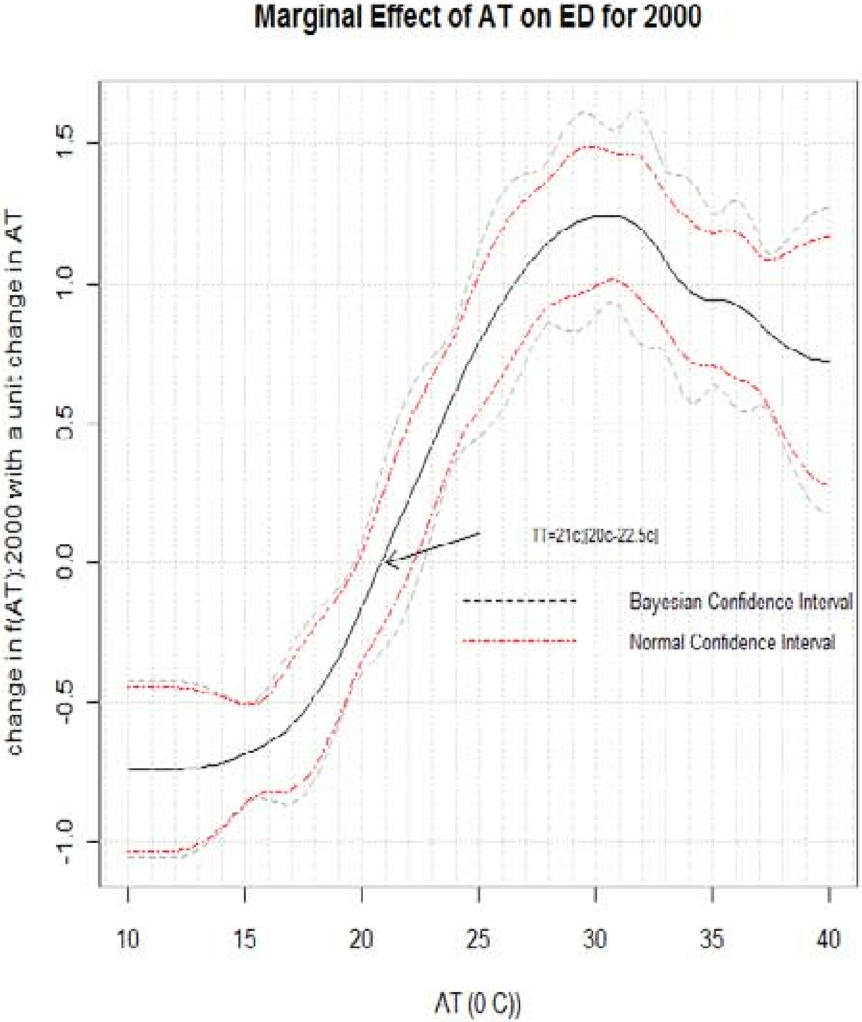
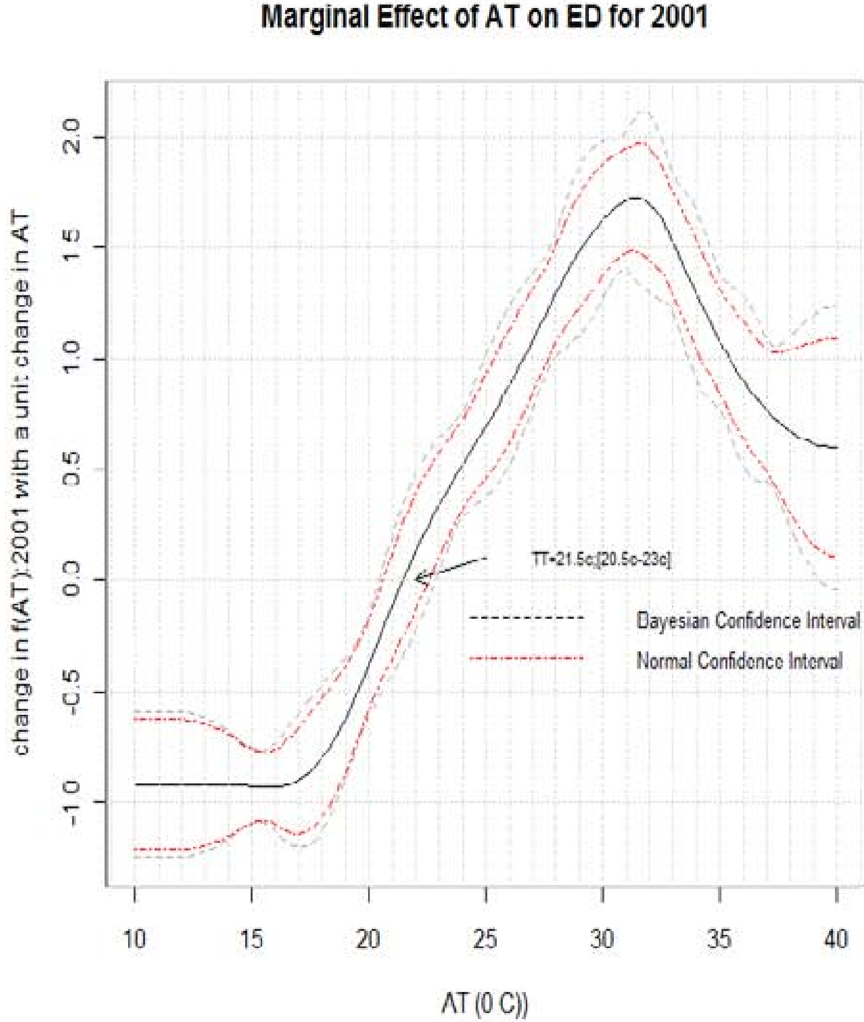


Figure 5.10

Marginal effects (slope of TDP curves)


Marginal Effect of AT on ED for 2000
change in f(AT):2000 with a unit change in AT
TT=21c;[20c-22.5c]
Bayesian Confidence Interval
Normal Confidence Interval
AT (0 C))
Fig 6.1


Marginal Effect of AT on ED for 2001
change in f(AT):2001 with a unit change in AT
TT=21.5c;[20.5c-23c]
Bayesian Confidence Interval
Normal Confidence Interval
AT (0 C))
Fig 6.2

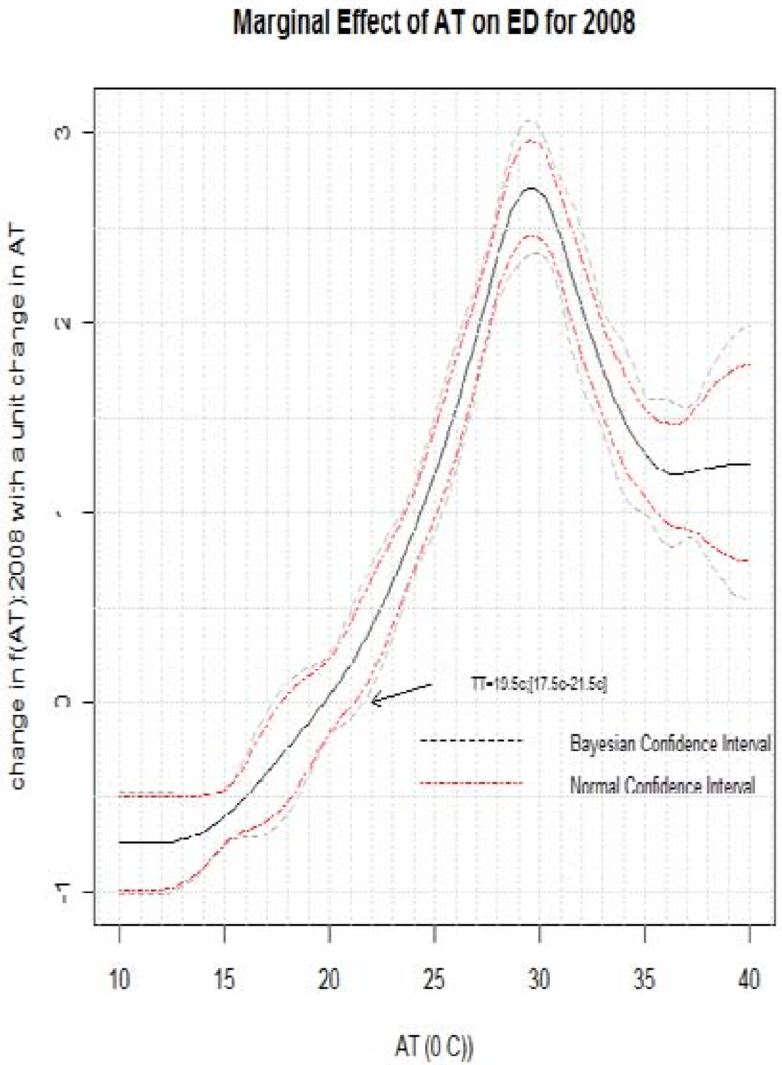


Fig 6.9

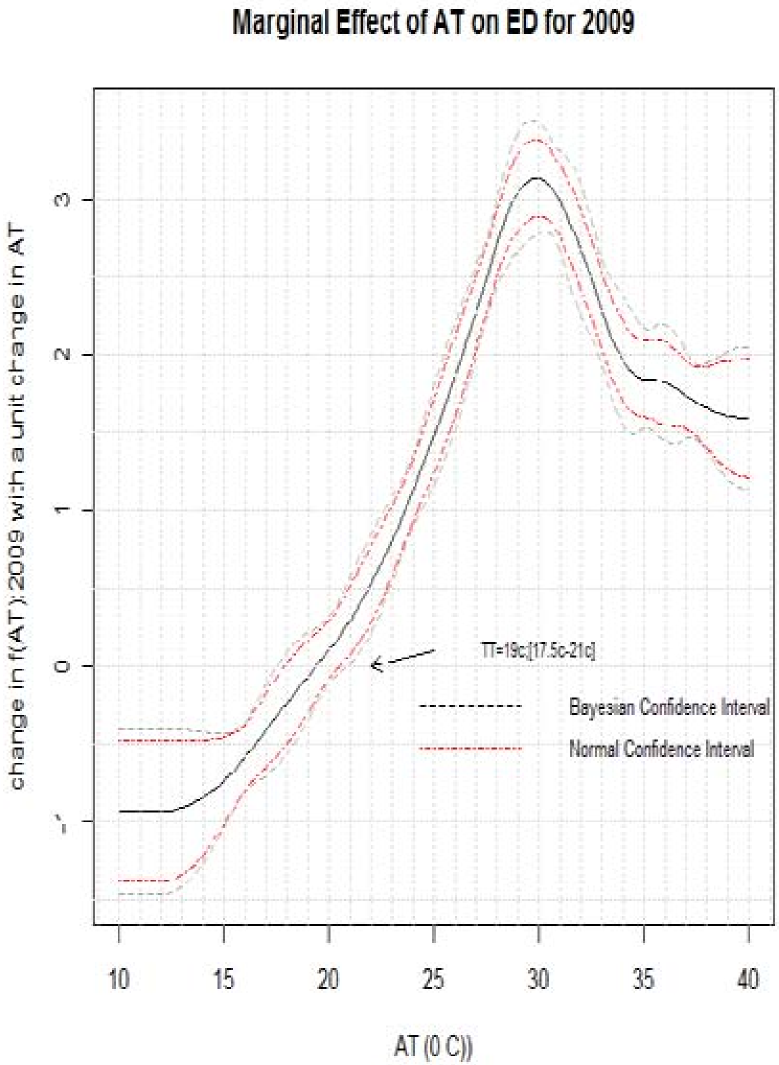


Fig 6.10

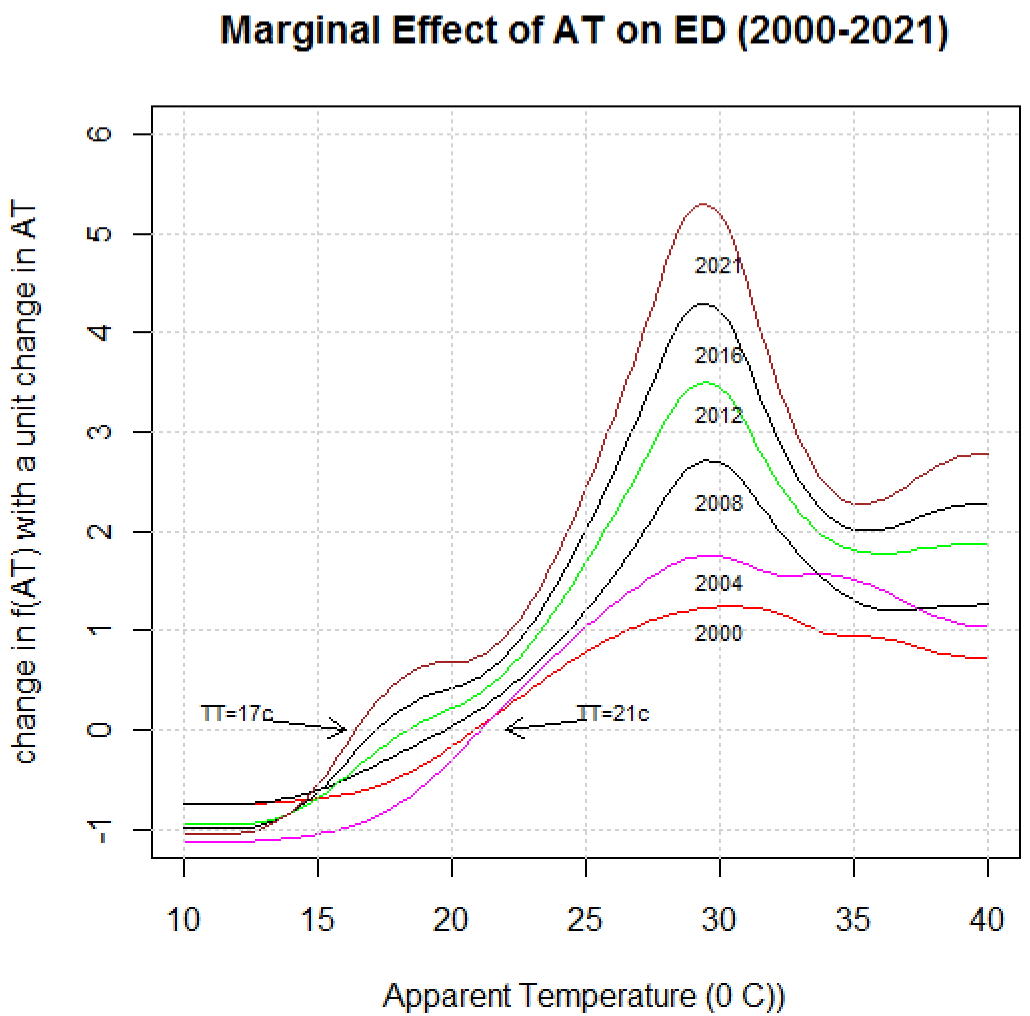

Marginal Effect of AT on ED (2000-2021)
change in f(AT) with a unit change in AT
6
5
4
3
2
1
0
-1
10
15
20
25
30
35
40
2021
2016
2012
2008
2004
2000
TT=17c
TT=21c
Apparent Temperature (0 C))

Figure 7

Estimated impact of increase in AT on electricity consumption under three different scenarios

AT change(over average temperature 2000-2009)	2009	2015	2021
$+1^0$c	1.7%	2.08%	2.7%
$+2^0$c	3.5%	4.29%	5.5%
$+3^0$c	5.2%	6.59%	8.4%

Estimated impact of increase in AT on electricity consumption by months

-

Base Electricity Demand*	2009			2015			2021		
	23809			27225			30737		
	+1^{0}c	+2^{0}c	+3^{0}c	+1^{0}c	+2^{0}c	+3^{0}c	+1^{0}c	+2^{0}c	+3^{0}c
JAN (1.5%)	-24.0	-44.2	-63.9	-22.9	-41.2	-58.2	-22.5	-39.2	-53.7
FEB	-7.7	-9.7	-8.8	-2.4	1.4	8.2	3.5	13.7	27.3
MAR	32.6	72.1	124.4	44.2	97.9	168.6	56.6	125.6	216.8
APR (4.2%)	81.1	157.2	227.8	99.9	191.1	274.0	127.8	243.0	346.2
MAY (2%)	52.8	103.3	153.8	56.1	111.2	167.3	63.9	128.2	195.4
JUN	46.5	92.6	134.0	51.4	106.8	159.4	61.6	130.7	196.0
JUL	48.0	92.5	132.8	55.4	112.1	166.5	68.5	139.9	207.7
AUG	49.2	97.3	139.9	52.9	110.2	164.2	63.1	134.7	201.7
SEP	51.7	101.1	150.2	55.1	109.0	163.4	63.0	126.2	191.3
OCT(4%)	77.2	153.6	230.1	97.2	192.9	287.2	124.1	246.0	365.1
NOV	16.0	37.0	68.0	23.3	52.7	95.2	31.1	69.5	124.6
DEC(1.2%)	-18.5	-31.0	-40.3	-14.4	-22.1	-25.7	-10.4	-13.0	-10.3
Total	404.7	822.0	1248.0	495.9	1022.0	1570.1	630.3	1305.4	2008.3
Total as %of base electricity demand in the same year	1.70%	3.45%	5.24%	1.82%	3.75%	5.77%	2.05%	4.25%	6.53%
Total as % of base electricity demand in 2009	1.70%	3.45%	5.24%	2.08%	4.29%	6.59%	2.65%	5.48%	8.43%

Max temp ↑

Global warming can result in serious disequilibrium in some months in future.

Key conclusions

-

- (TDP) of Delhi is moving leftwards and the minimum temperature threshold (bottom of the TDP) is shifts from about 20-23^{0}C in the first half of the decade (2000-2005) to about 17-21^{0}C in the second half (2006-2010).

- Rising part of the TDP is getting steeper over time implying ever increasing cooling demand per unit increase in summer temperatures.
a 1^{0}C $\uparrow$ in temperature at 30^{0}C $\uparrow$ electricity demand by 3.2 Million kilowatt-hours (MKWH) in 2009 as compared to only 1.2 MKWH in 2000.
a1^{0}C increase in temperature at 15^{0}C $\downarrow$ electricity demand by 0.8 MKWH in 2009 as compared to 0.7 MKWH in 2000.

- Asymmetric effects of global warming in different seasons- serious disequilibrium situation is future particularly during hot months such as May and April.

All state analysis (spatial variation)

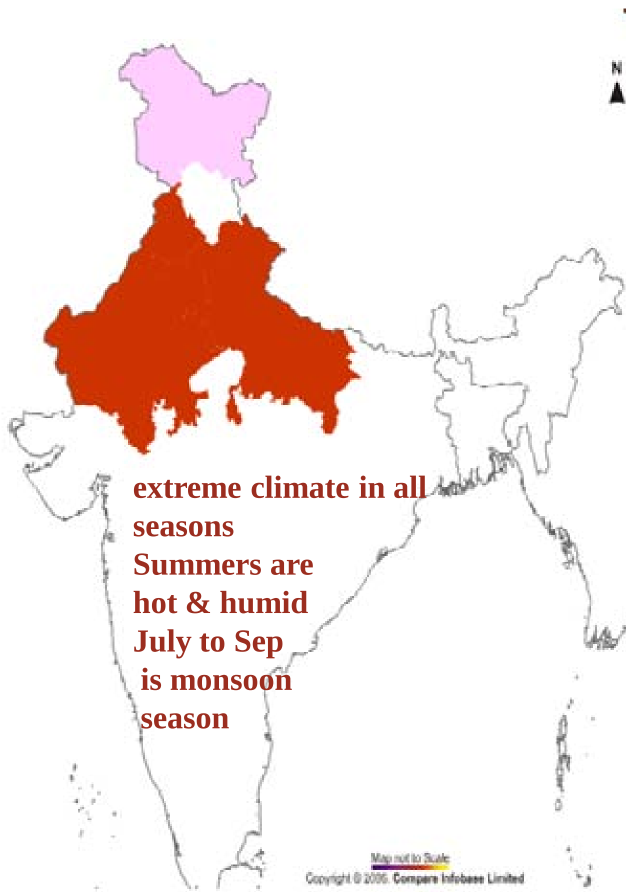
Northern India-Delhi (D), Haryana (H), Rajasthan (R), Uttar Pradesh (UP), Uttarakhand (UA), Chandigarh, and Punjab (P)

Domestic 27.4%

D-45%
H-18.5%
R-15.2%
UP-33%
U-22.7%
C-36.6%
P-21.4%

Industry 35%

D-15%
H-32%
R-42.8%
UP-42.6%
U-52%
C-22%
P-37.5%



extreme climate in all seasons
Summers are hot & humid
July to Sep is monsoon season

Commercial 14.6%

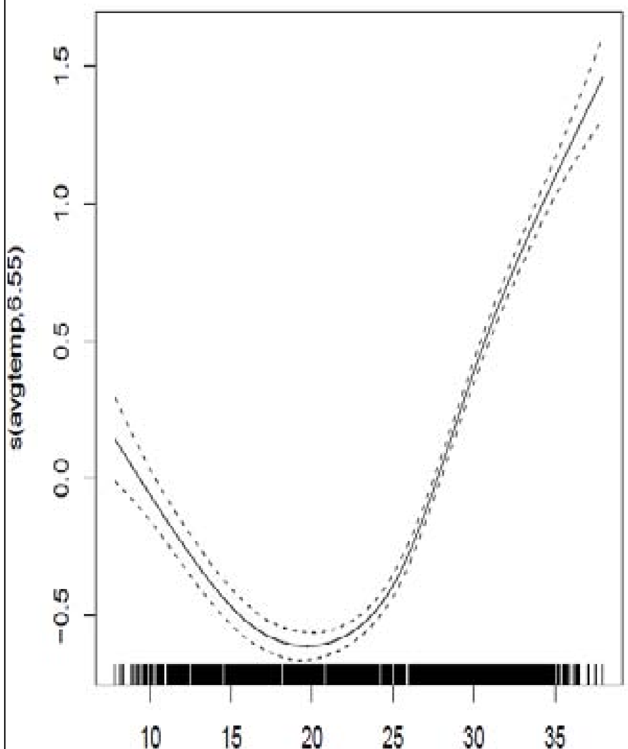
D-32%
H-6%
R-5%
UP-6.1%
U-13.9%
C-32.6%
P-6.3%

Agriculture 16.8%

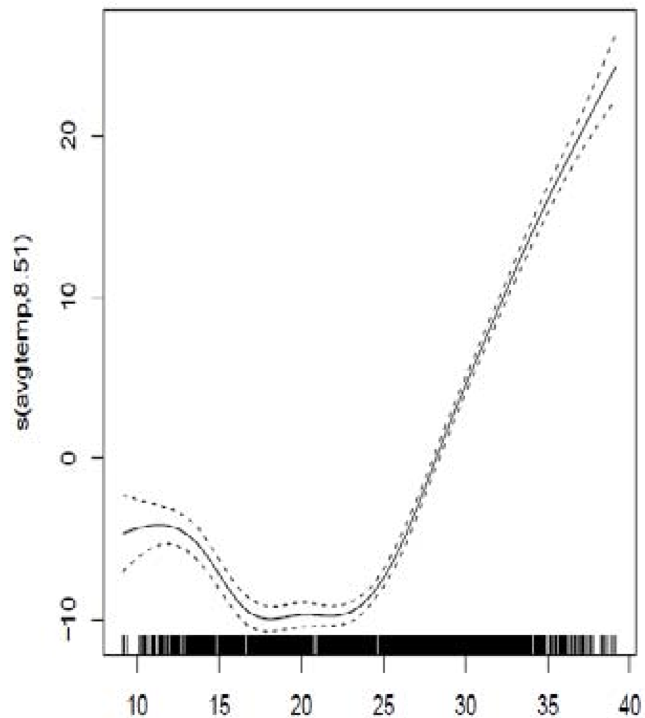
D-0.3%
H-36%
R-29.8%
UP-14%
U-5.8%
C-0.1%
P-31%

North India: Cooling demand dominates

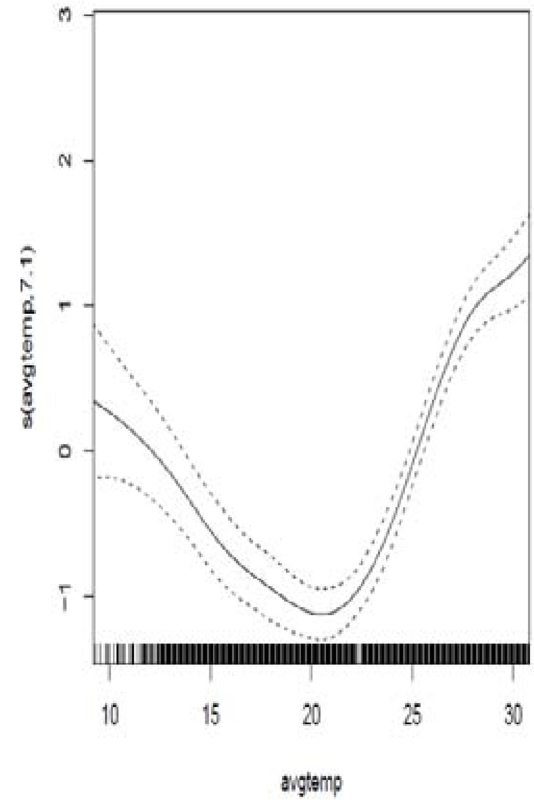
Chandigarh



Delhi

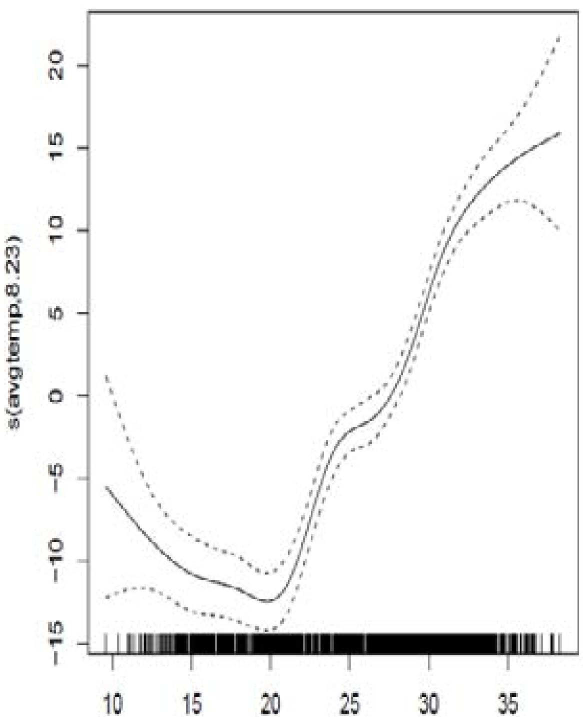


Uttarakhand

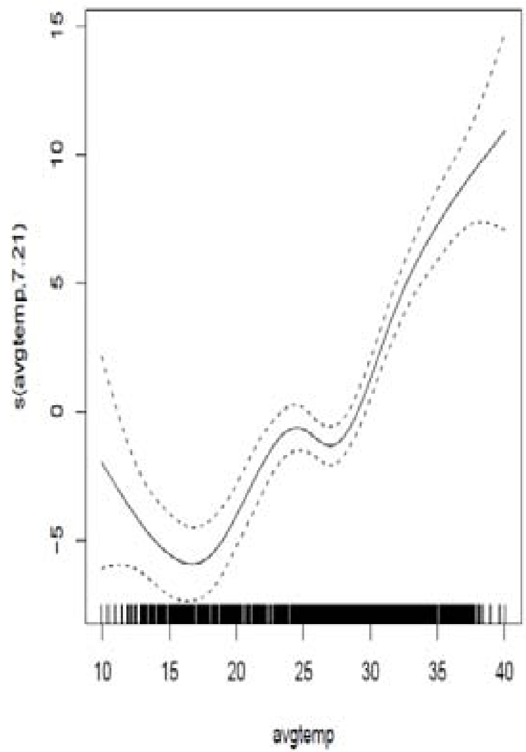


North India: Cooling demand dominates

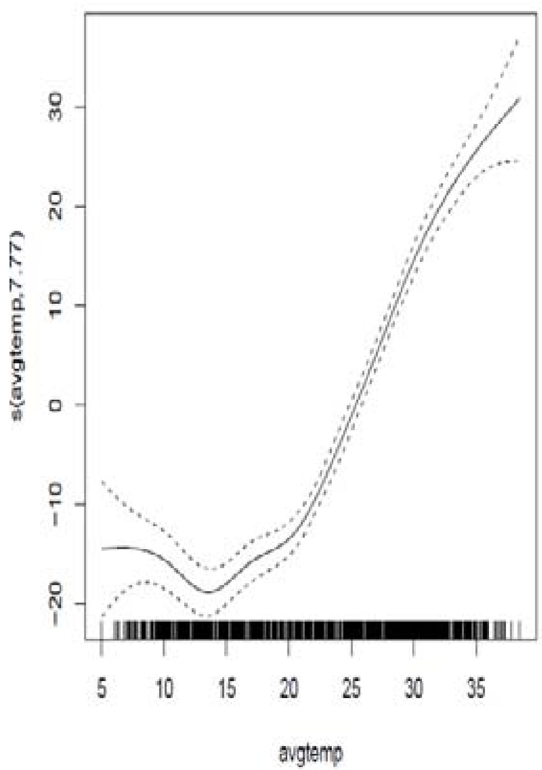
UP



Rajasthan

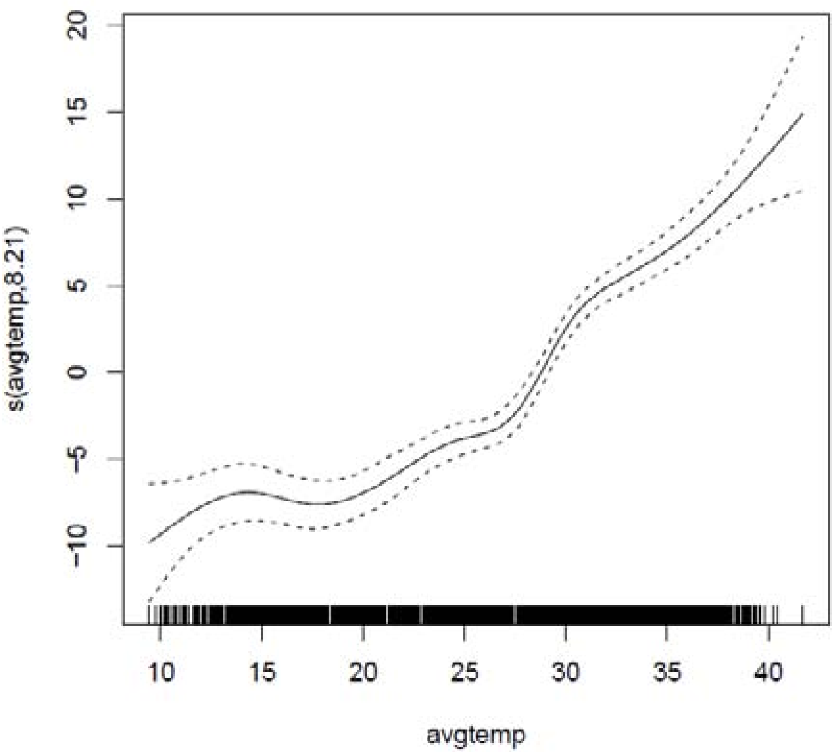


Punjab

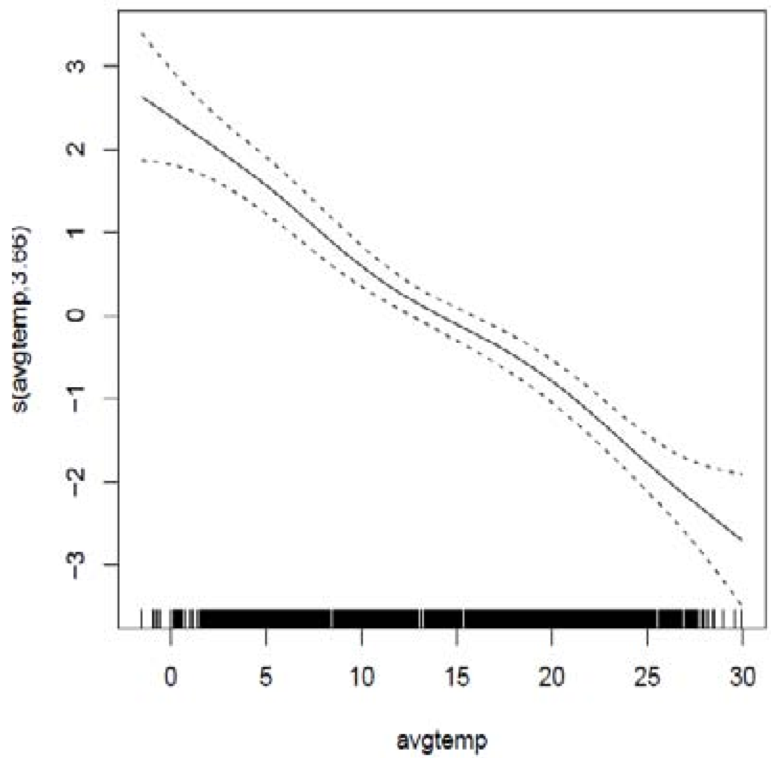


North India: Heating demand dominates in J&K

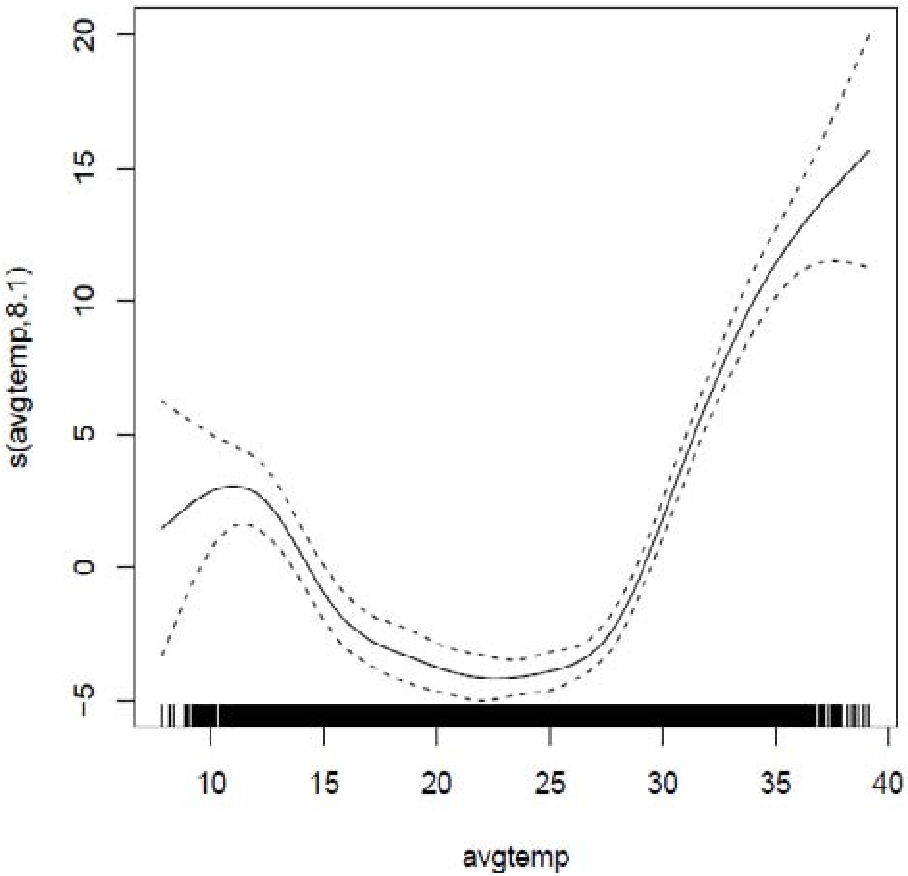
Haryana



J&K



North India: Cooling demand dominates

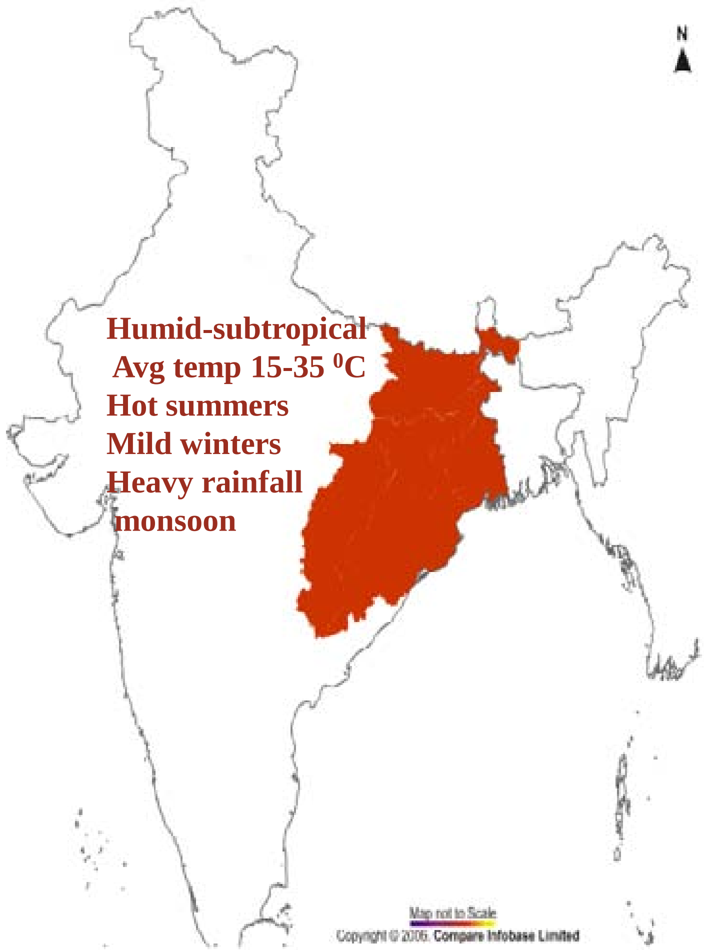


Results from pooled data for Northern region
With state fixed effects
(with four states-UP,D,U,C)

Eastern India-Bihar (B), Jharkhand (J),West Bengal (WB) , Orissa (O) And Chhattisgarh (C)

Domestic 18.8%

B-34%
J-10%
WB-26%
O-15%
C-9.3%



Humid-subtropical
Avg temp 15-35 ^{0}C
Hot summers
Mild winters
Heavy rainfall
monsoon

Industry 61%

B-31%
J-81%
WB-48
O-74%
C-73%

Commercial 5.5%

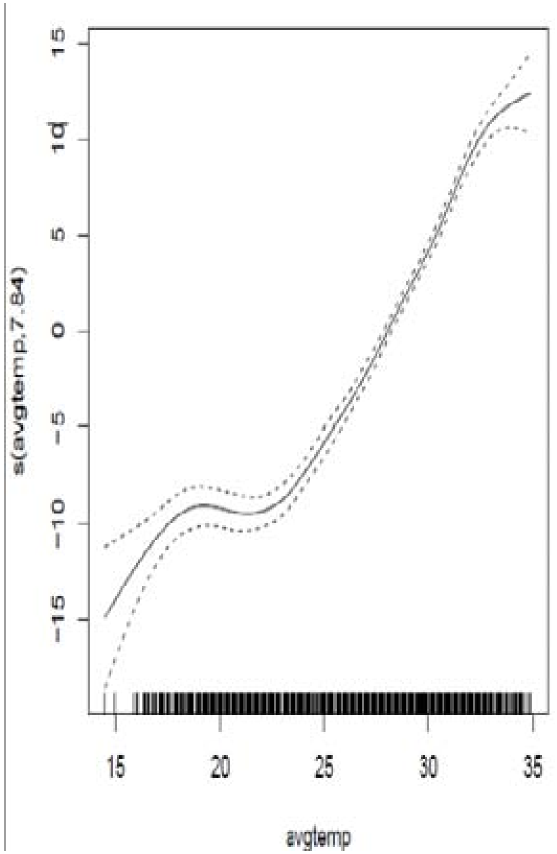
B-8%
J-1.7%
WB-11.9
O-4%
C-1.7%

Agriculture 5.6%

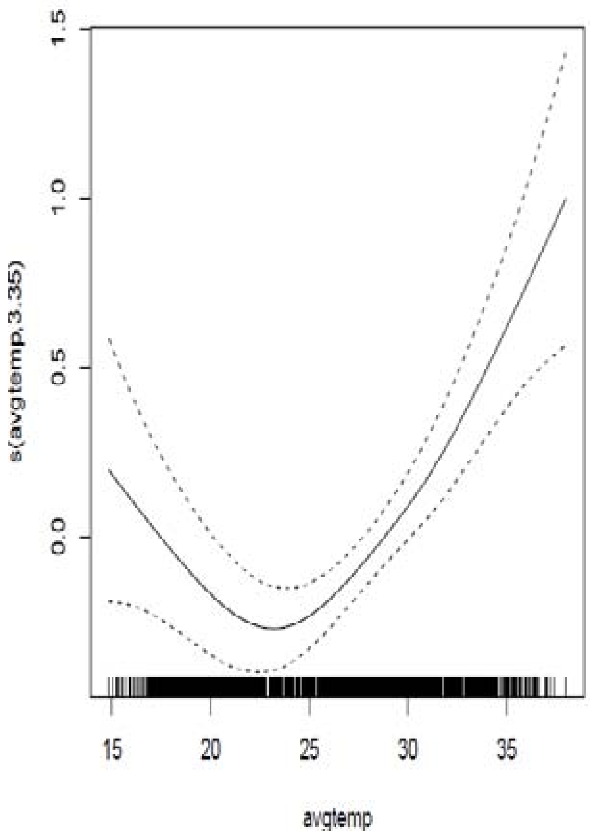
B-15.5%
J-0.4%
WB-3%
O-1%
C-8.7%

Eastern India: Cooling demand dominates

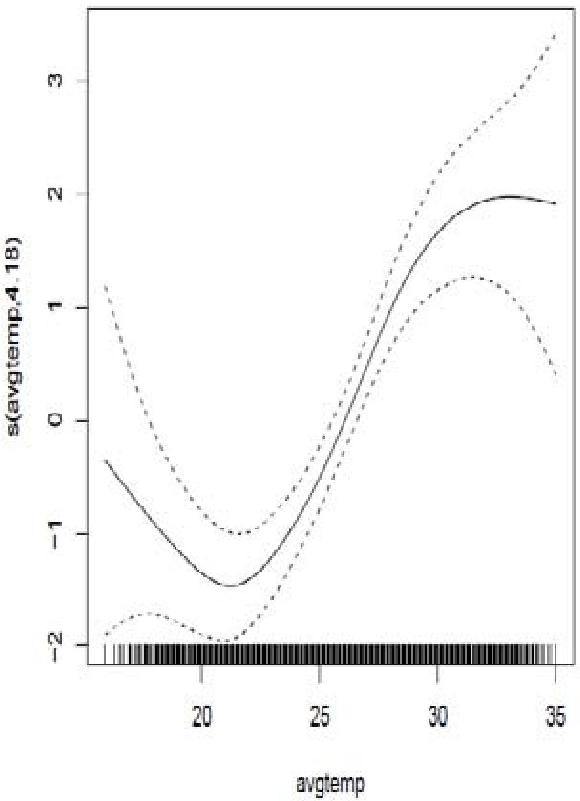
West Bengal



Jharkhand

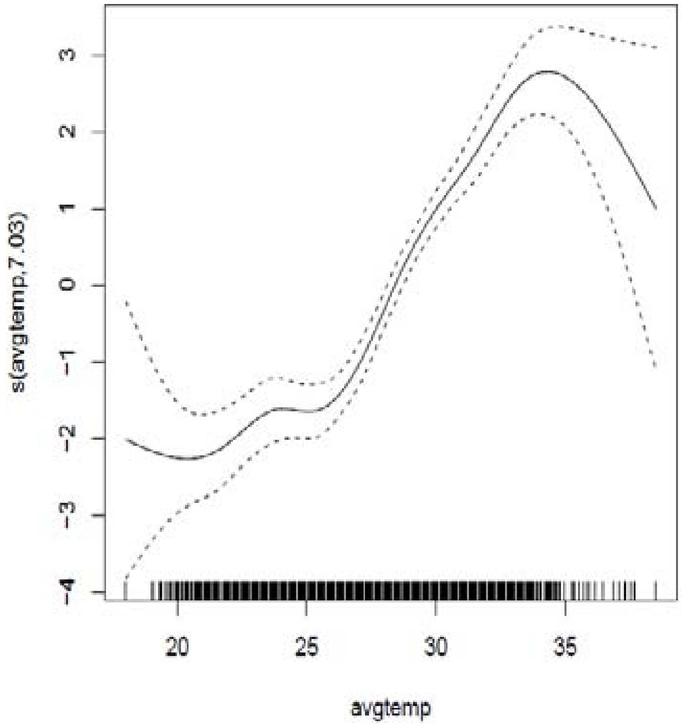


Chhattisgarh

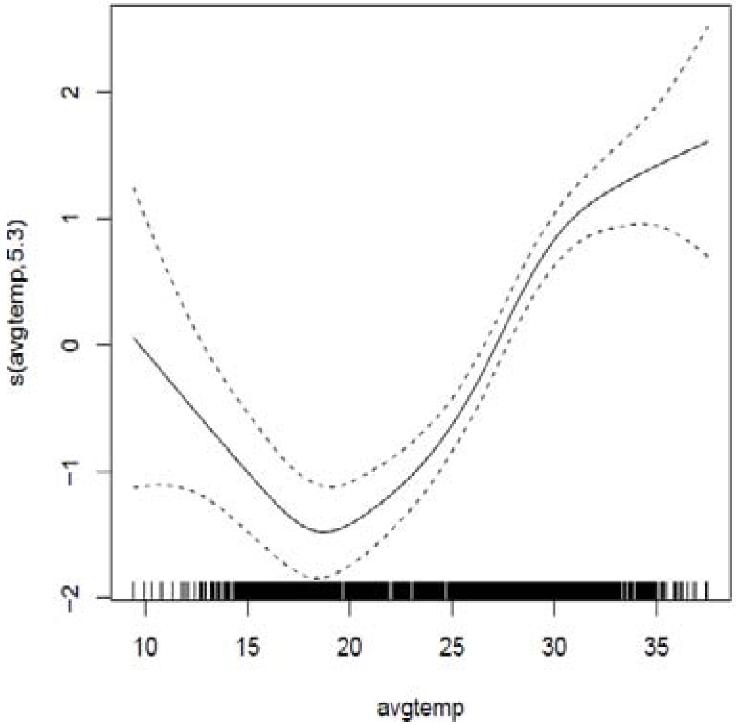


Eastern India: Cooling demand dominates

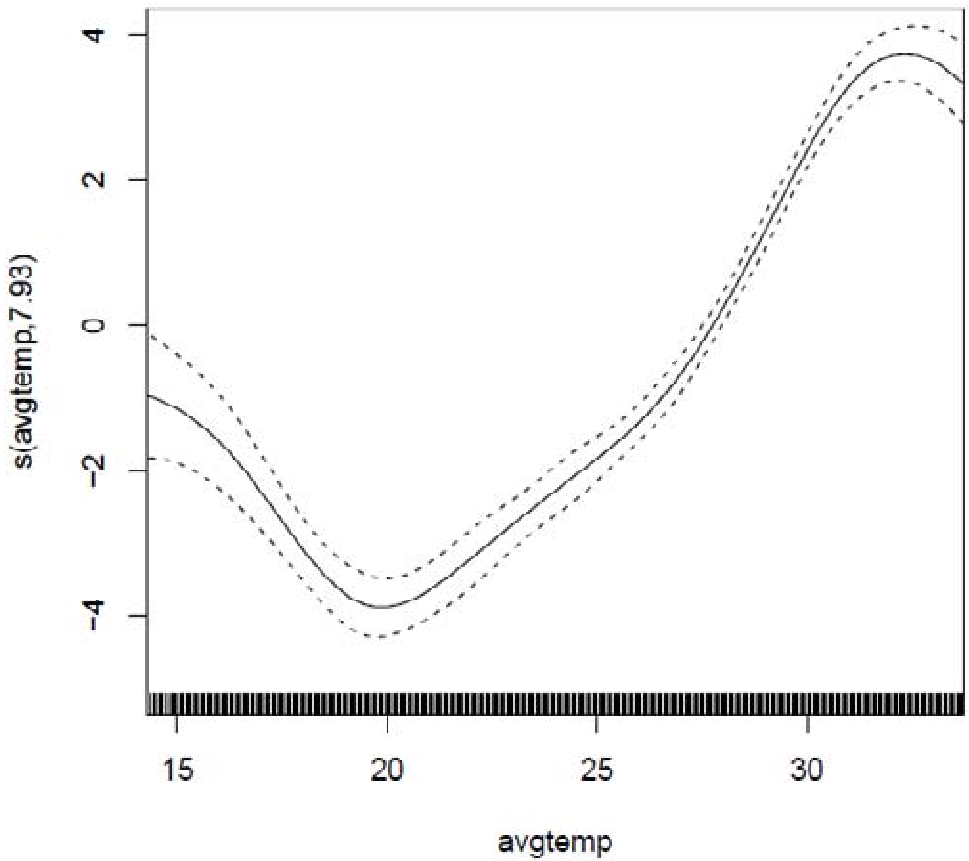
Orissa



Bihar



Eastern India: Cooling demand dominates

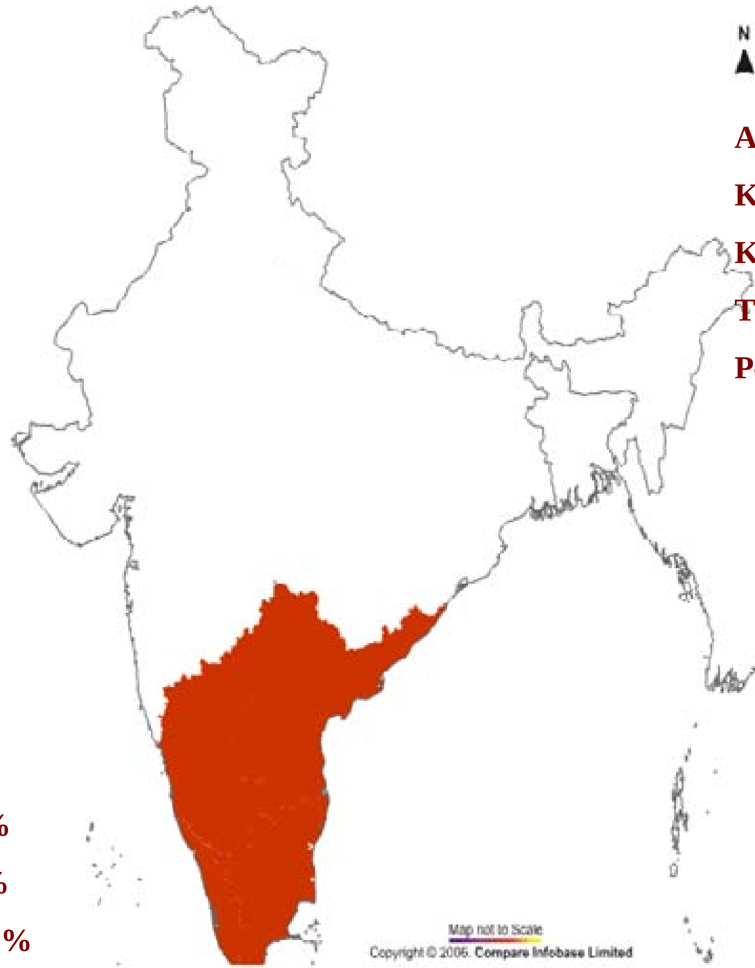


Results from pooled data for the eastern region
With state fixed effects

Southern India-Andhra Pradesh (A), Karnataka (K), Kerala (KR), Tamilnadu (T) And Pondicherry (P)

Domestic 24.8%

AP-19.8%
K-16.9%
KR-47%
TN-22.8%
P-17.2%



Industry 43%

AP-37.7%
K-31.6%
KR-30%
TN-45.3%
P-71.5%

Commercial 10.9%

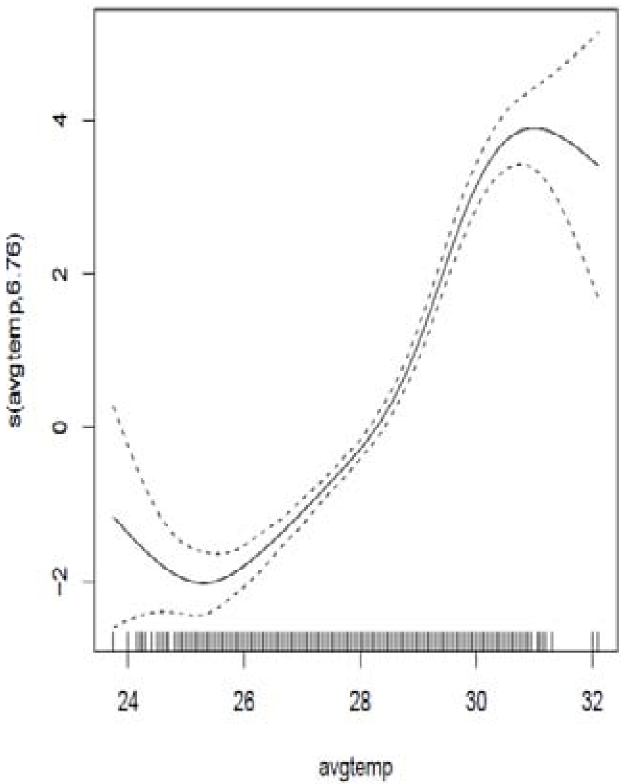
AP-6.6%
K-14.7%
KR-16.6%
TN-10.8%
P-5.8%

Agriculture 16%

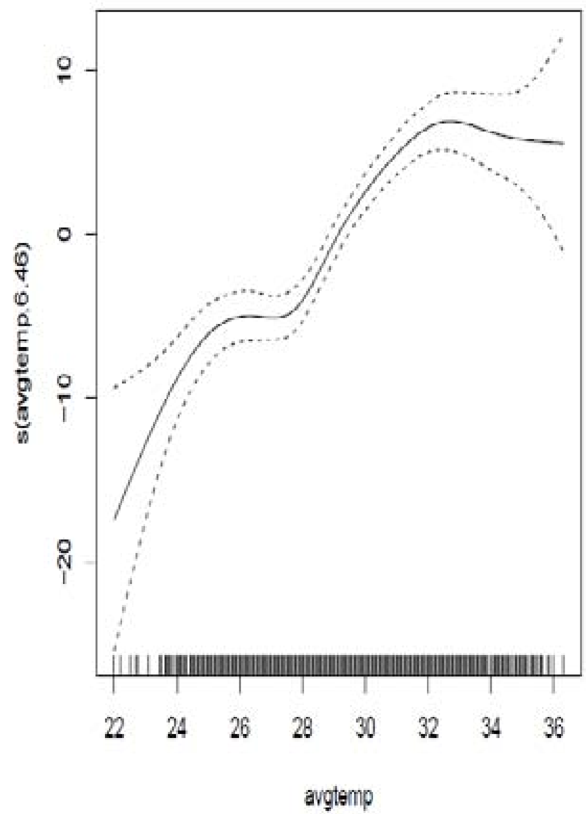
AP-28.1%
K-28.7%
KR-1.8%
TN-17.8%
P-3.6%

South India: Cooling demand dominates

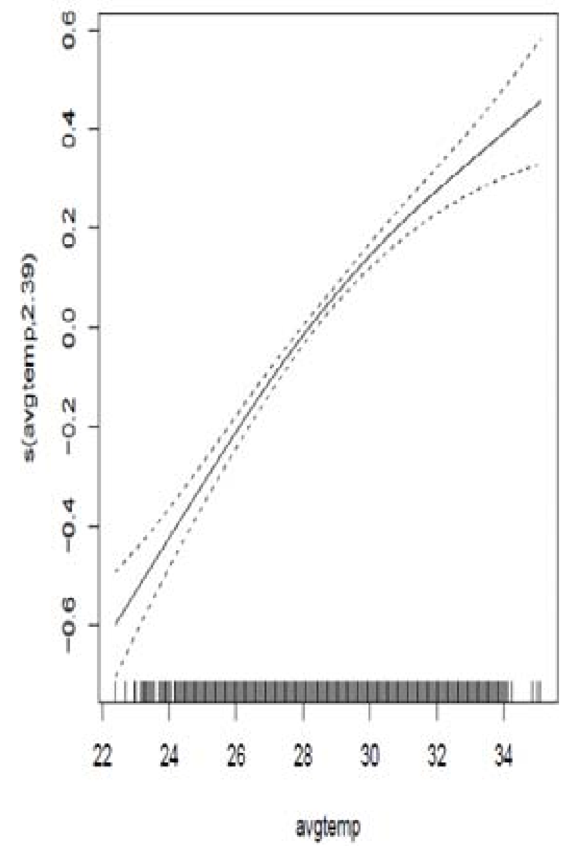
Kerala



Tamilnadu

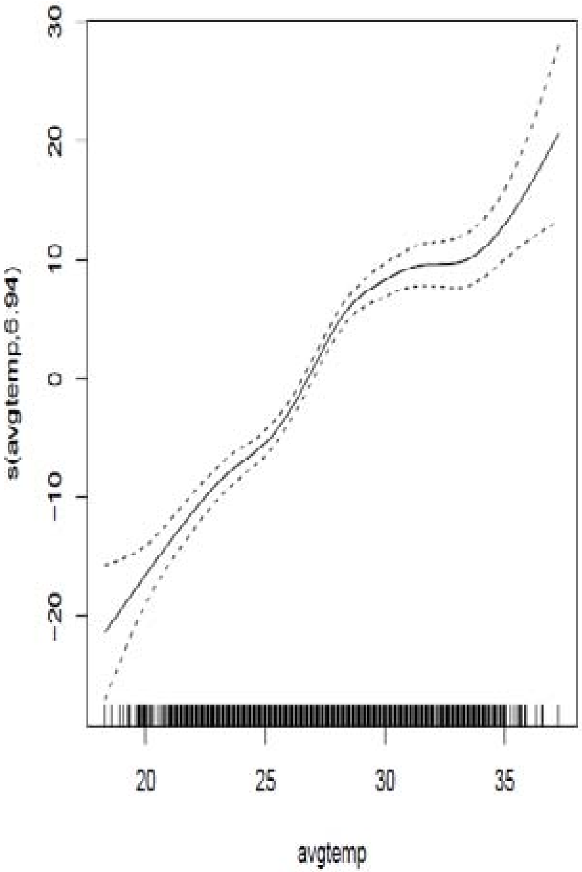


Pondicherry

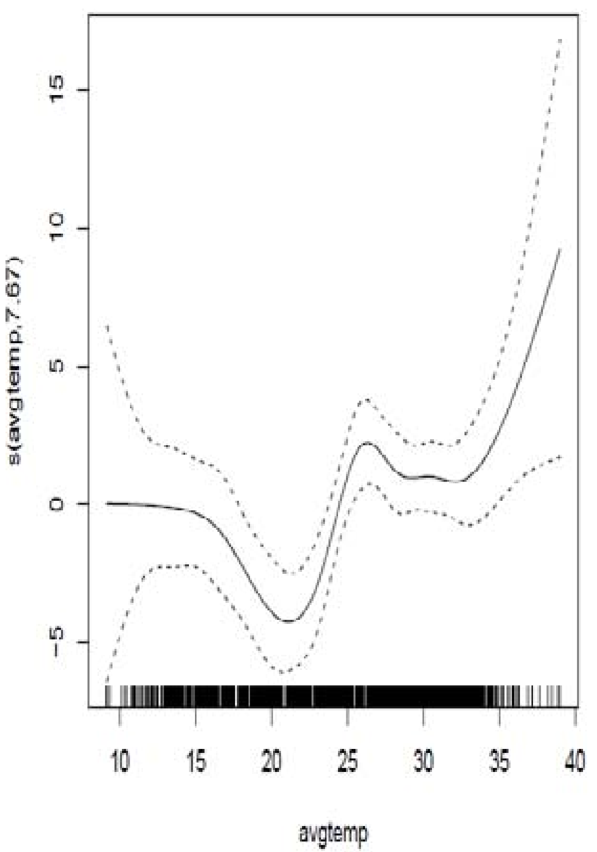


South India: Cooling demand dominates

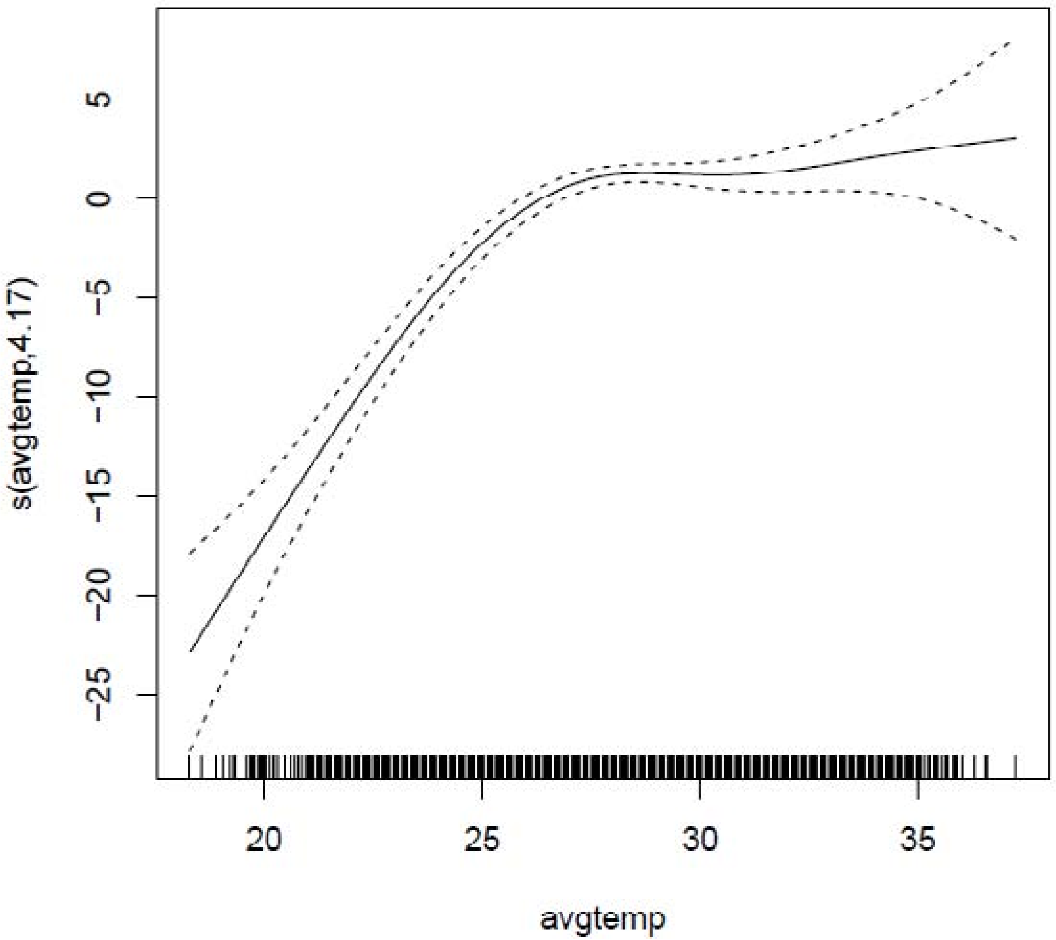
Andhra Pradesh



Karnataka



South India: Cooling demand dominates



Results from pooled data
for southern region
With state fixed effects
(with four states)

North-Eastern India-Assam (A), Manipur (MN) And Tripura (T)

Domestic

A-28%

MN-61%

T-54%

47%

Industry

A-52%

MN-4%

T-19%

25%

A-10%

MN-7%

T-9%

8.8%

Commercial

A-0.5%

MN-0.06%

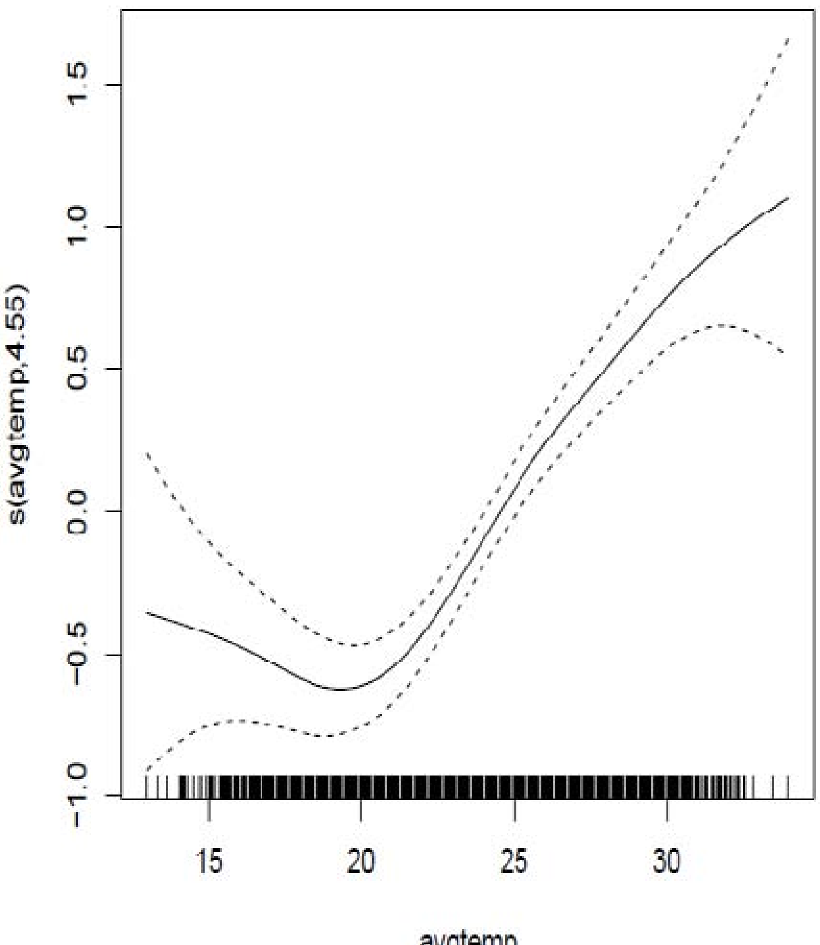
T-7%

Agriculture

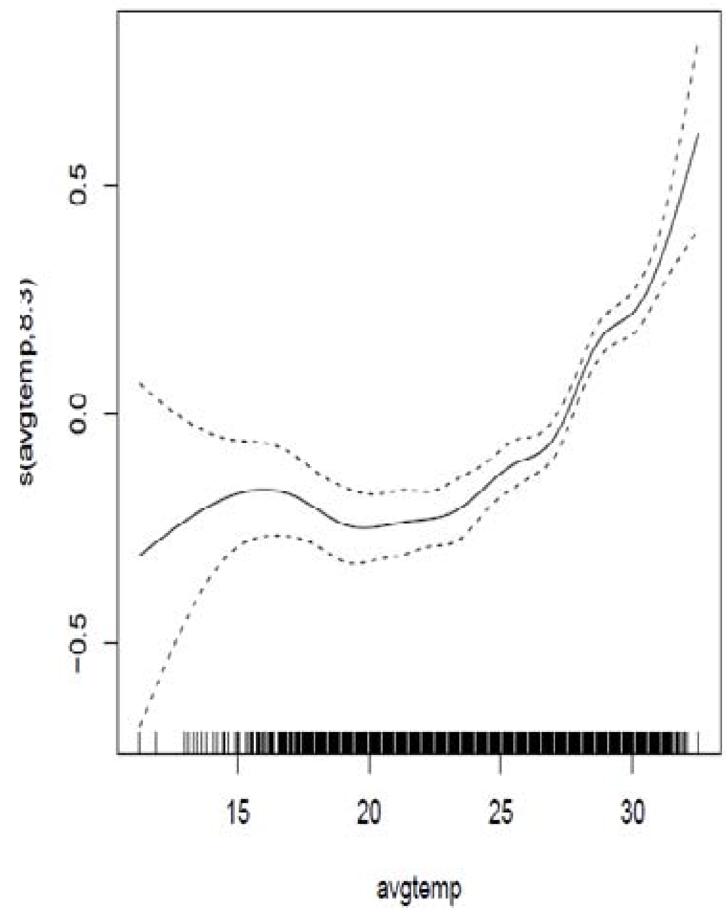
2.7%

North Eastern India: Cooling demand dominates

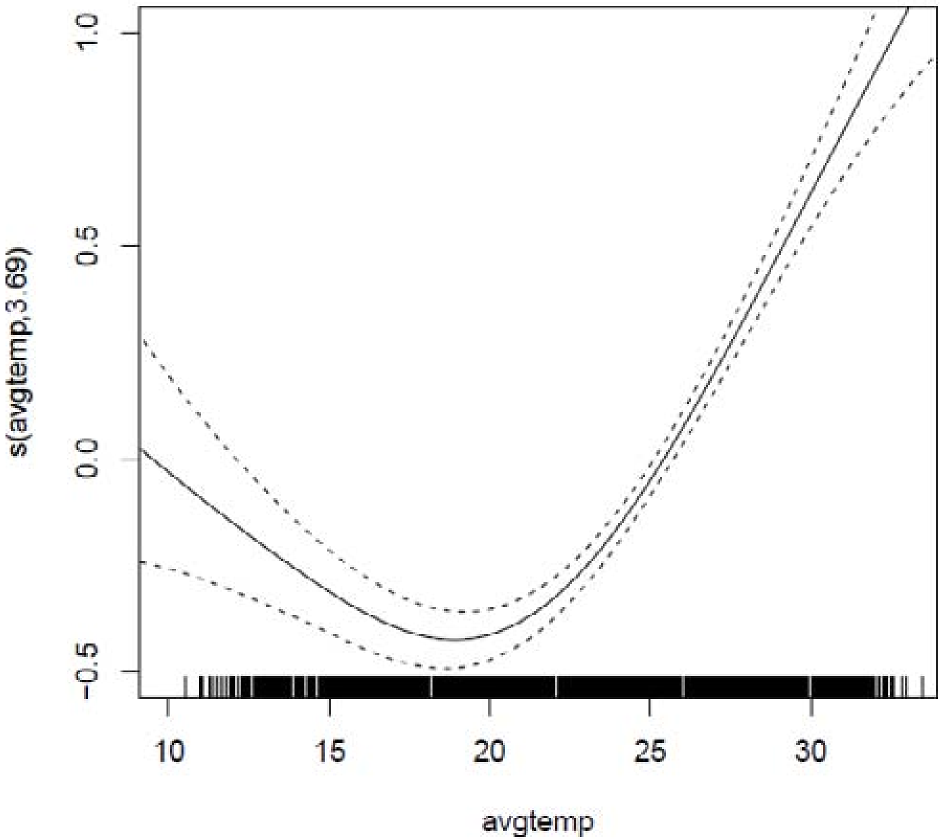
Assam



Tripura



North Eastern India: Cooling demand dominates



Results from pooled data for North eastern region
With state fixed effects

Western India- Goa (G), Gujarat (GU), Maharashtra (M) And Madhya Pradesh (MP)

Domestic 19.9%

G-23%

GU-12%

M-24%

MP-20%

Industry 50.3%

G-63%

GU-61%

M-42%

MP-35%

Commercial 7%

G-6%

GU-6%

M-12%

MP-5%

Agriculture 15.3%

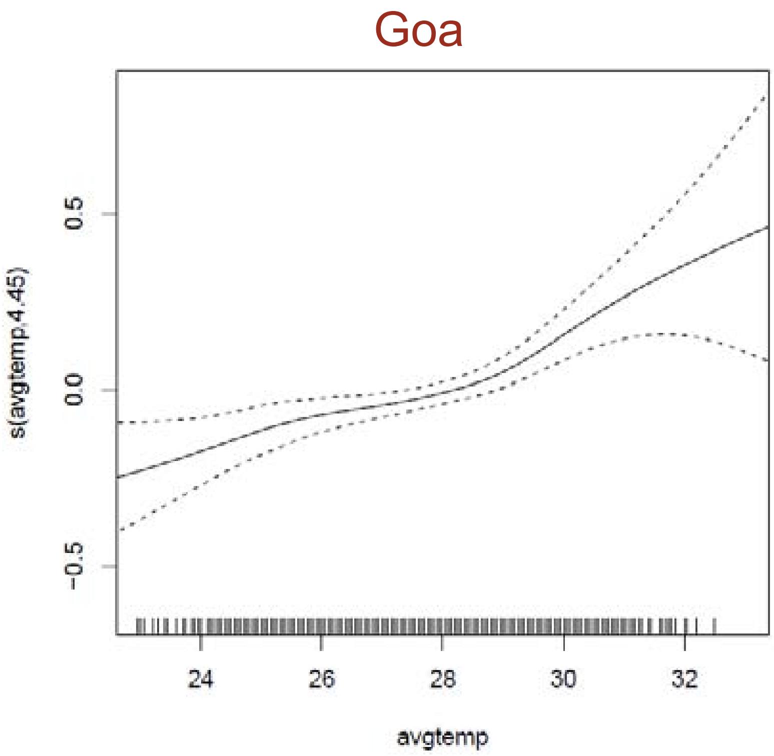
G-1.5%

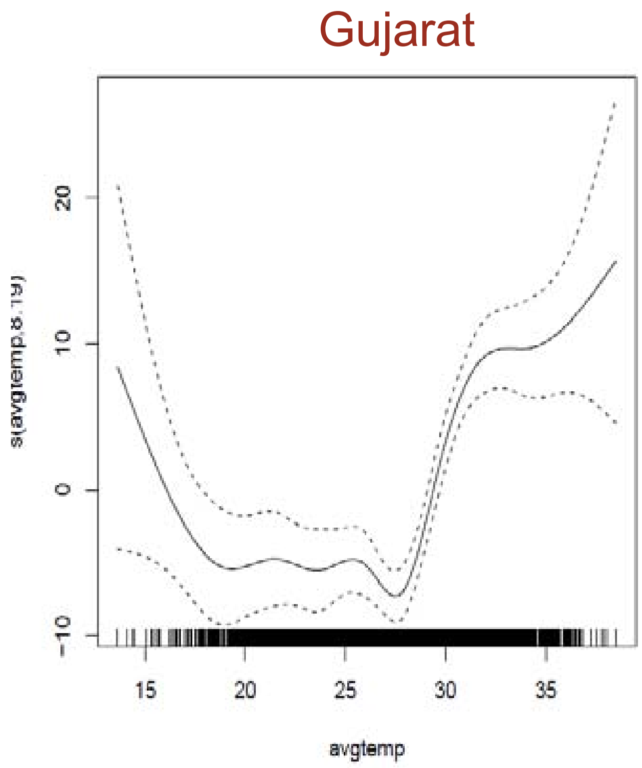
GU-18%

M-16.6%

MP-25%

West India: Cooling demand dominates

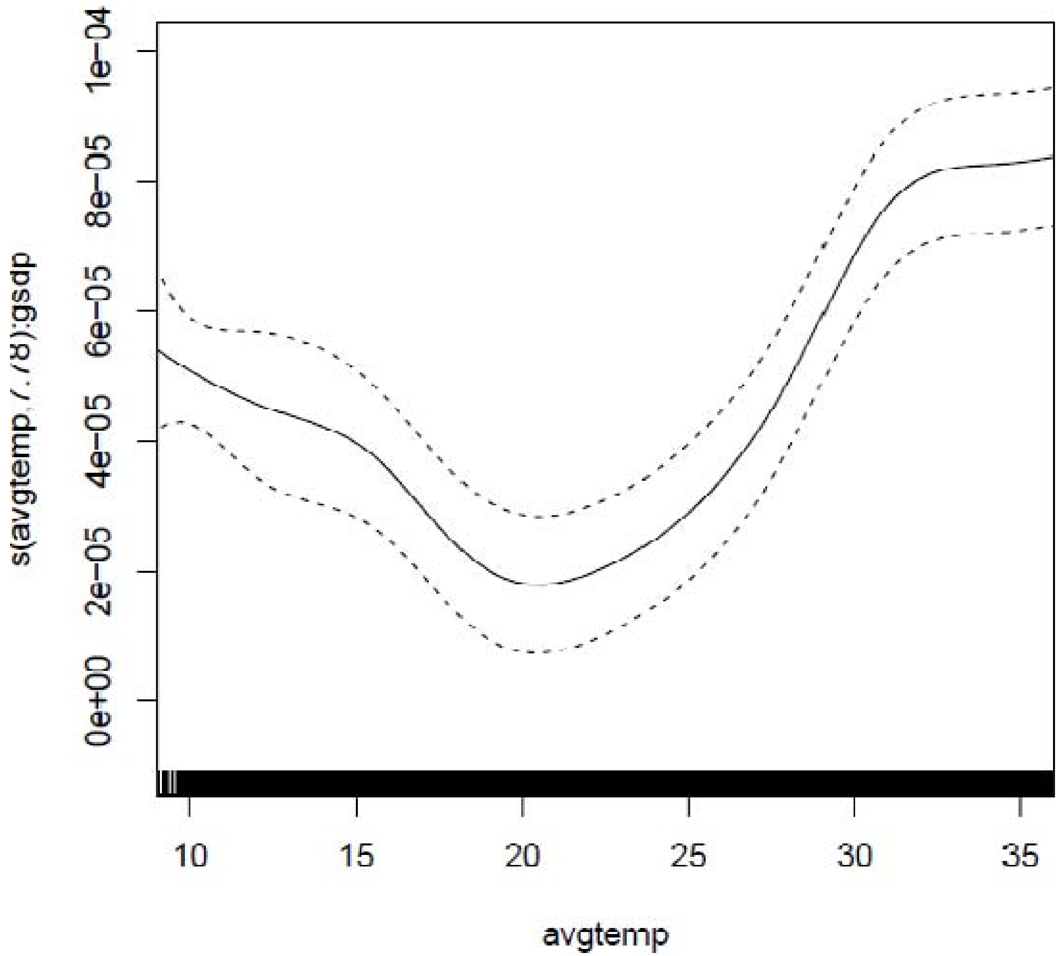




All India: Cooling demand dominates

Parametric coefficients				
	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	4.45E+01	1.33E+00	33.606	0.000
GSDP	5.33E-04	5.71E-06	93.292	0.000
Energy Price	-1.35E-02	2.56E-03	-5.256	0.000
Monthly Rainfall	-1.04E-03	2.46E-05	-42.117	0.000
Monthly IIP	1.15E-02	3.74E-03	3.063	0.0022
Monsoon_Dummy	-4.94E-02	1.47E-01	-0.336	0.7372
m10	1.83E+00	1.95E-01	9.37	0.000
m5	-2.13E+00	1.99E-01	-10.682	0.000
gazetted_holidays	-3.33E-01	2.35E-01	-1.419	0.15588
restricted_holidays	-6.00E-01	2.74E-01	-2.188	0.02865
sunday	-1.75E+00	1.89E-01	-9.264	0.000
saturday	-2.66E-01	1.89E-01	-1.408	0.15912
monday	-4.98E-01	1.89E-01	-2.635	0.00842
friday	2.58E-01	1.89E-01	1.364	0.17265
thursday	6.28E-02	1.89E-01	0.332	0.73972
tuesday	-2.10E-01	1.89E-01	-1.109	0.26743

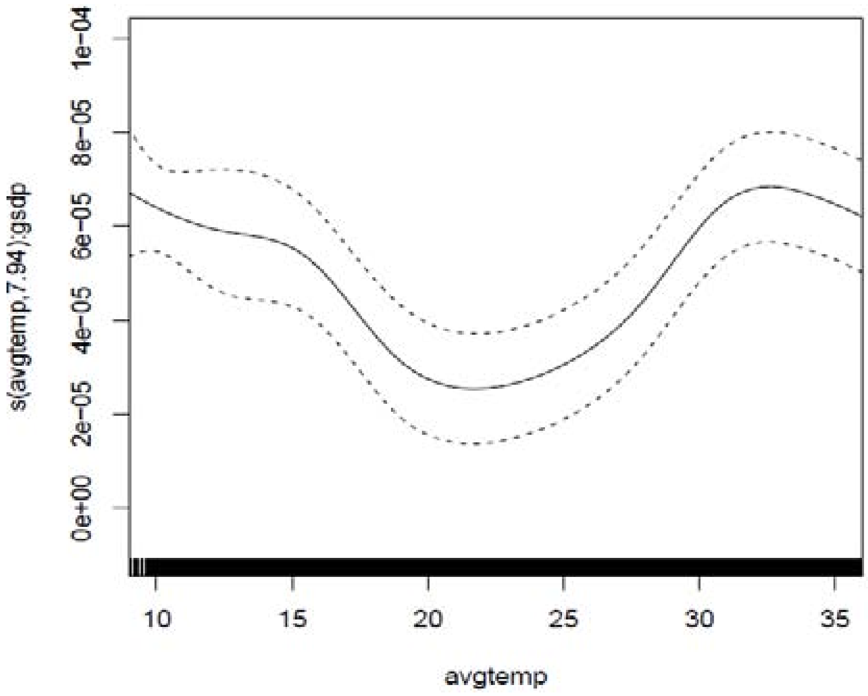
All India TDP * GDP

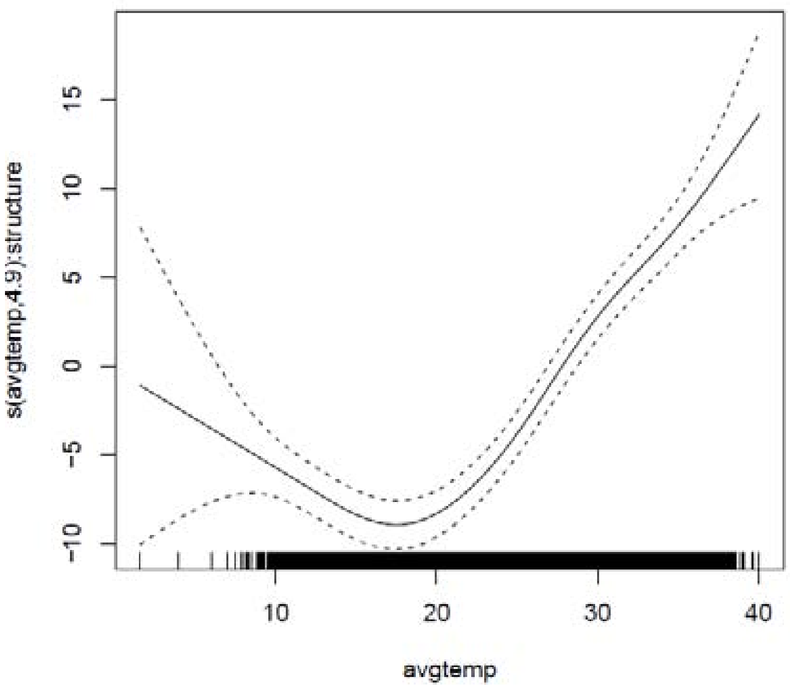


Adding structure variable

Parametric coefficient			
	Estimate	Std. Error	Pr(>|t|)
(Intercept)	4.21E+01	1.42E+00	0.000
GSDP	5.26E-04	6.37E-06	0.000
Energy Price	1.11E-03	3.48E-03	0.75042
Monthly Rainfall	-9.02E-04	2.48E-05	0.000
structure	-1.10E+01	1.91E+00	0.000
Monthly IIP	3.40E-02	3.78E-03	0.000
Monsoon_Dummy	-1.35E+00	1.54E-01	0.000
m10	2.24E+00	1.95E-01	0.000
m5	-2.87E+00	1.99E-01	0.000
gazetted_holidays	-3.26E-01	2.32E-01	0.16017
restricted_holidays	-4.45E-01	2.71E-01	0.10114
sunday	-1.74E+00	1.87E-01	0.000
saturday	-2.53E-01	1.87E-01	0.17559
monday	-4.85E-01	1.87E-01	0.00953
friday	2.74E-01	1.87E-01	0.14344
thursday	6.49E-02	1.87E-01	0.72862
tuesday	-1.80E-01	1.87E-01	0.33705

All India: Cooling demand dominates





Issues to be addressed

- What climate change scenarios to be used-6 homogeneous groups/state-wise/ regional models/global models?

- How to construct an average temperature for any state-capital city temperature/ population weighted temperature?

- More factors to control agricultural seasonality/ Industrial seasonality/ general non-weather seasonality

- Data issues- daily temperature data for north east and Himachal Pradesh, Daman & Diu, DNH

Thanks