Ambient Air Pollution and Future Climate Change: Indian Scenario for the middle of 21st Century

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Motivation

Specific Question:

- How Will Climate Change Affect Ambient Air Pollution?

Related Issues:

- How tight is the relationship between weather and pollution levels?
- What are the key climate variables that matter?
- What are the policy implications? How could regulations incorporate these findings?

Data

- **Measure of Pollution – PM2.5**

- Pollution is taken from remote sensing satellite imagery. Dey et al. (2020)
- Covers urban and rural population(at district level)
- High spatial (1km) and temporal resolution (24-h average) enabling more precise analysis with weather.

- **Current and Future Weather**

- Historical Readings on Temperature, Rainfall, and Planet Boundary Layer Height (PBL).
  ERA5- ECMWF
- RCP-4.5 and RCP-8.5. Focusing the more optimistic scenario.
  Coupled Model Intercomparison Project Phase 6 (CMIP6)

	Sample Mean	Standard Deviation	Min	Max	N
Particulate Matter - $PM_{2.5}$ ($\mu g/m^3$)	80.1	48.4	0.1	1,872.8	1,007,400
Temperature (^0F)	75.5	13.8	-23.8	105.6	1,007,400
Total Precipitation (mm)	3.08	7.19	0.00	305.1	1,007,400
Heating Degree Days	2.2	7.3	0.0	88.8	1,007,400
Cooling Degree Days	12.6	9.0	0.0	40.6	1,007,400
Planet Boundary Layer Height	379.7	300.7	9.9	1,826.2	1,007,400

Background

Pollution in India and Weather

- The IGP – Indus Gangetic Plain. Home to majority of 20 most polluted cities.
- Why? Emissions and Weather.
- Weather factors – precipitation, temperature, PBL

Pollution and weather are tightly linked

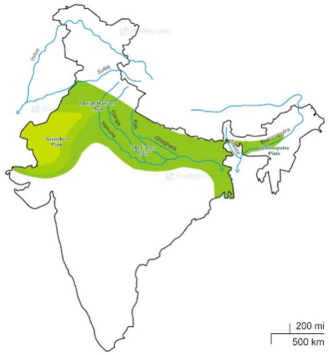
- Precipitation reduces pollution, extreme weather increases pollution.
- Implication: Emissions can have very different impacts in different regions.
- Thermal inversions are common and deadly in the Indus-Gangetic -Plain. (IGP)

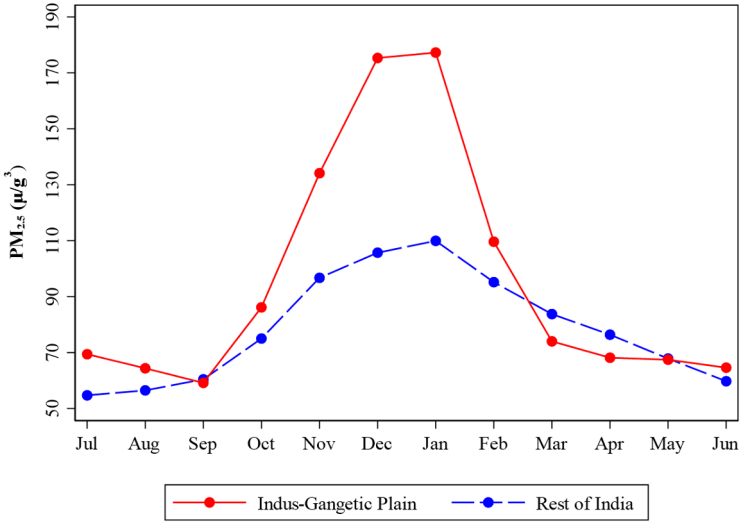
Climate Change will have a significant impact on Pollution and Health

- By 2050, we anticipate a 3.1 microgram increase in PM2.5 and a 0.35 year decline in life expectancy.
- Without any change in emissions, cost of climate change in India is 364 million years in life expectancy.

Why is IGP a Concern?
"Confronting Pollution Head-On - Igniting Change for a Cleaner Tomorrow"

- IGP: Housing **21 out of 30** most polluted cities worldwide.
- It experiences roughly higher pollution levels on average and **14.9 µ/g3 higher pollution** (2015-2019)
- The negative association between daily rainfall and PM2.5 is over **50 percent larger** in the IGP
- The unique climatic conditions prevalent in **arid areas** contribute to the accumulation and persistence of pollutants, intensifying their adverse effects on air human health.

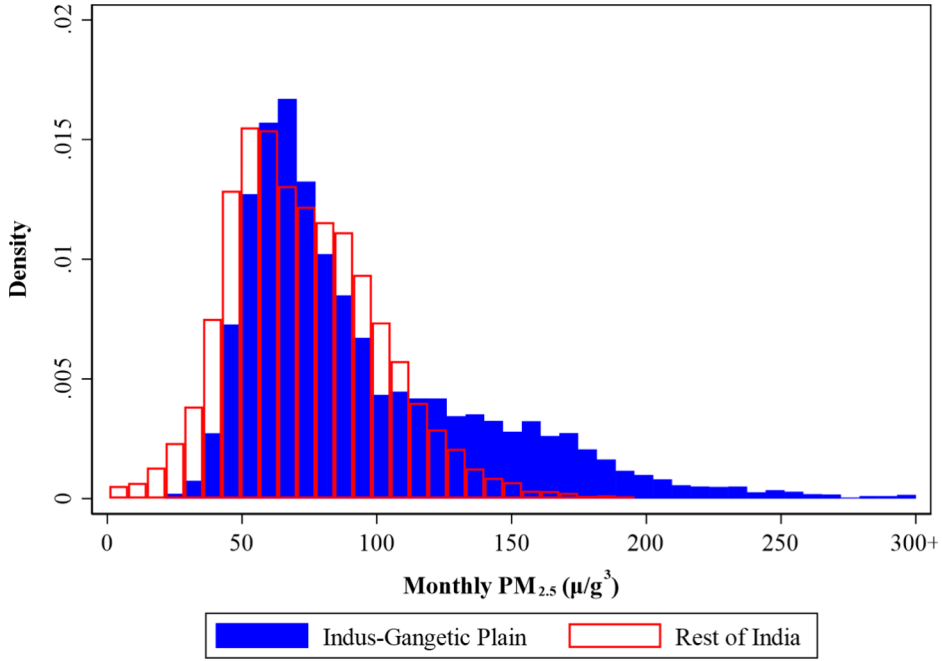




The figure displays average monthly PM2.5 levels (µg/m3) in Indus-Gangetic Plain (red) and the rest of India (blue) from 2015-2019. Data is weighted by district population (2011 census) and sourced from Dey et al. (2020).

Consequence – periods of VERY high pollution in IGP.

1. Reversal of normal pattern of higher air in troposphere being cooler than air closer to earth's surface.
2. Himalayan mountain air creates a **'cap'** of cold air above pollution in northern India.
3. Inhabitants of the IGP suffered through more polluted months, whereas those outside the IGP.
4. Implication – regulations should account for **regional vulnerability** to consistent and episodic pollution
   Theory suggests that varying fee by **region/period** allows policymaker to have lower average fees and higher output.



The figure shows monthly average PM2.5 levels (µg/m3) in districts within the Indus-Gangetic Plain (IGP) and the rest of India. The data includes readings from 2015-2019 across 629 districts, with 242 in the IGP. PM2.5 readings are based on remote-sensing data mentioned in Dey et al. (2020). Readings exceeding 300 are grouped together.

Estimating Equations: the relationship between pollution and weather

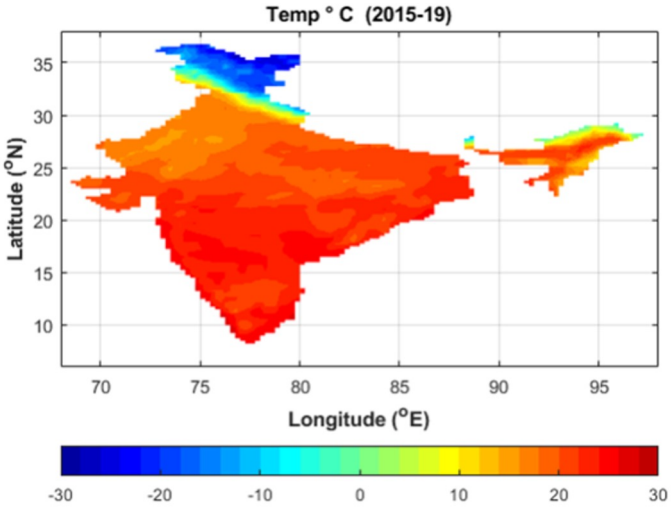
$$\bar{P}_i = \alpha_0 + \alpha_1 IGP_i + \alpha_2 Dis_i + \alpha_3 \overline{HDD}_i + \alpha_4 \overline{CDD}_i + \alpha_5 \bar{R}_i + \alpha_6 \overline{INV}_i + X\beta_i + u_i$$

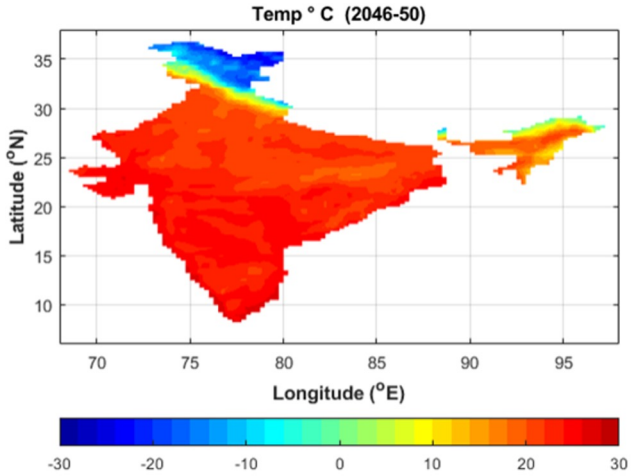
$\bar{P}_i$	**Long-term average pollution in district i.**
α_0	Average difference between pollution levels inside and outside the IGP, accounting for weather differences.
$\alpha_1 IGP_i$	Indicator variable equal to 1 for districts within the Indus-Gangetic Plain.
$\alpha_2 Dis_i$	Measure of a district's distance from the Ganges River.
$\overline{HDD}$	Heating degree days, a measure of heating demand
$\overline{CDD}$	Cooling degree days, a measure of cooling demand.
$\bar{R}$	Daily precipitation.
$\overline{INV}$	Number of thermal inversions in the district during the sample period.
X	Covariates that could be correlated with emissions and are available at the district level, such as GDP and literacy rates and population density.

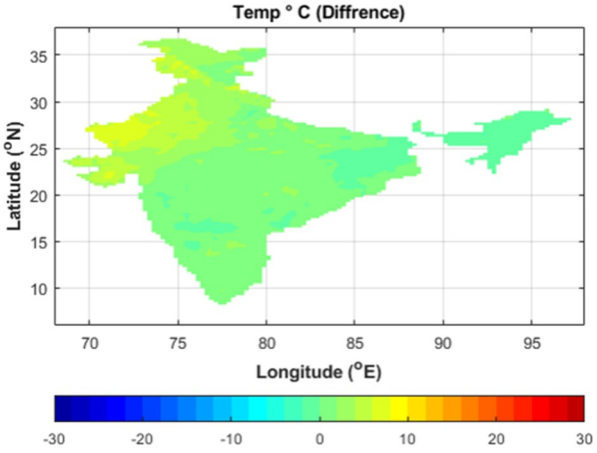
- The measure of severity of temperature is **heating and cooling degree** days.
- These are calculated as the sum of daily deviation from the **'ideal'** temperature of 65°F for winter and summer respectively.
- HDD=max(0, 65° - Fd) and
- CDD=max(0, Fd - 65°)

Results: Monthly Weather – Actual vs Predicted

	Sample Mean	Standard Deviation	Min	Max
Actual Weather (Monthly Averages, 2015-2019)				
Temperature (^{0}F)	75.4	13.4	-10.9	100
Total Precipitation	3.08	4.13	0.0	38.3
Heating Degree Days	2.09	7.14	0.0	75.9
Cooling Degree Days	12.52	8.75	0.0	35.3
Planet Boundary Layer Height	379.4	276.2	14.5	1,521.2
Predicted Weather (Monthly Averages, 2050)				
Temperature (^{0}F)	81.5	14.7	3.5	120.2
Total Precipitation	4.7	7.0	0.0	42.7
Heating Degree Days	1.26	5.14	0.0	61.5
Cooling Degree Days	1.58	6.04	0.0	71.5
Planet Boundary Layer Height	709.9	267.1	184.7	1,529.4



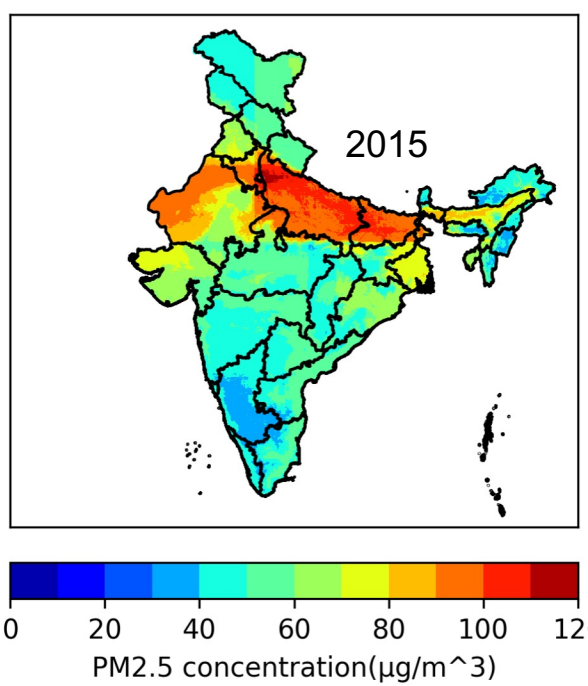


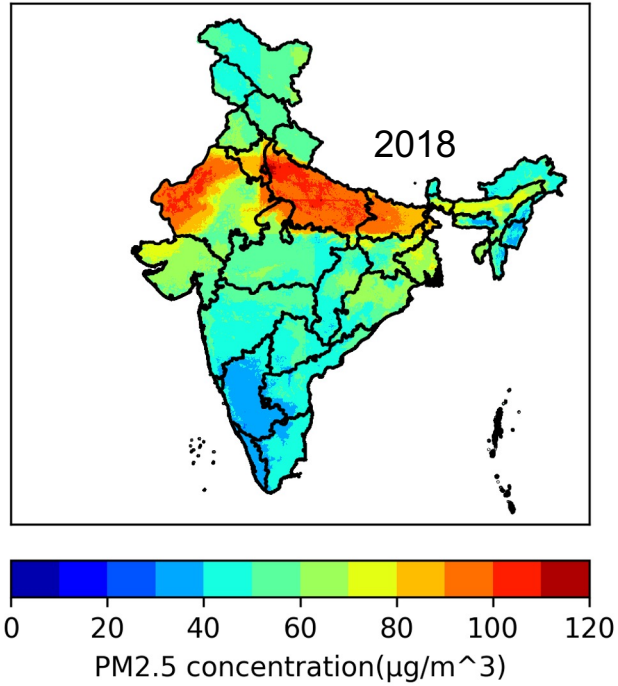


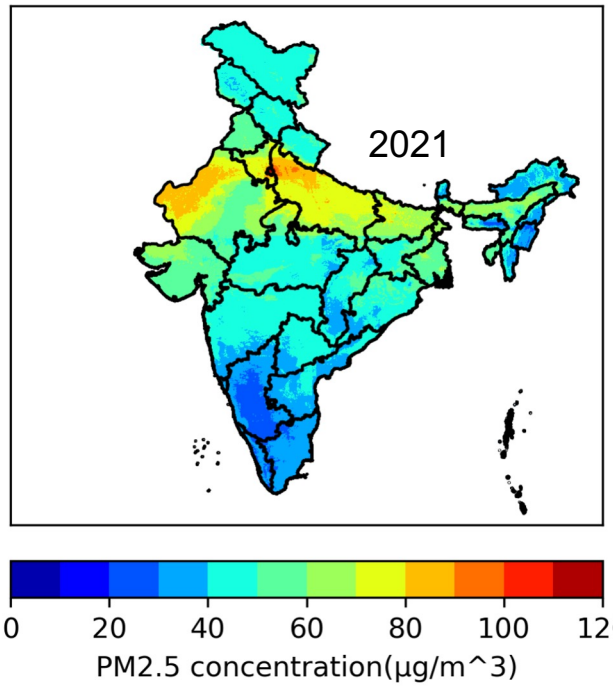
Note: 2022 was the sixth warmest year since global records began in 1880 at 0.86°C (1.55°F)

https://www.ncei.noaa.gov/access/monitoring/monthly-report/global/202213

Current Scenario: Particulate Matter 2.5







Relationship between PM2.5 Concentrations, Geography and Weather

column 1

the model is estimated without district fixed effects

column 2,

including district fixed effects sharpens the effect of temperature, as the coefficient on HDD is twice as large.

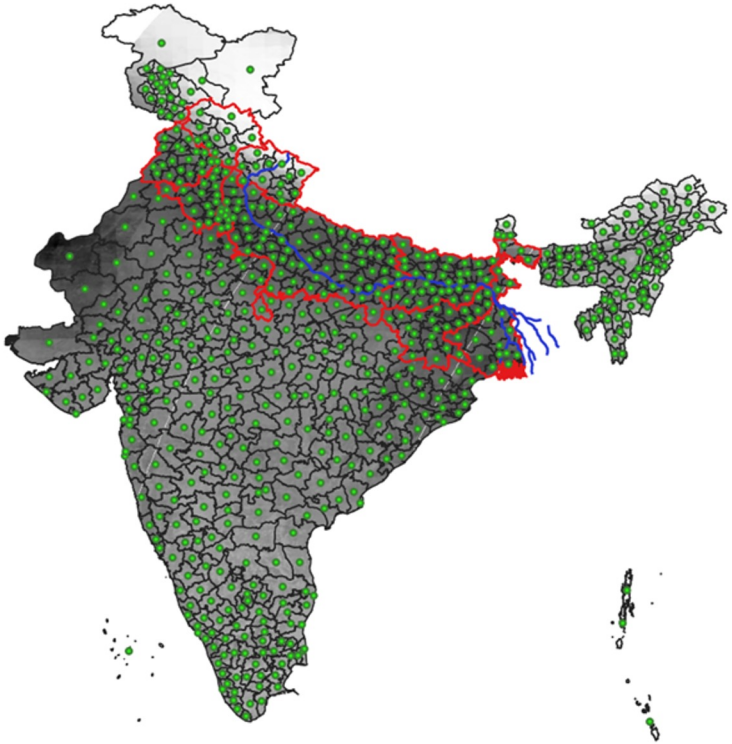
In columns 3, 4 and 5

sample -by IGP and the rest of the country, the coefficient on HDD is over **twice** as large in the IGP, implying the IGP is particularly sensitive to harsh winters.

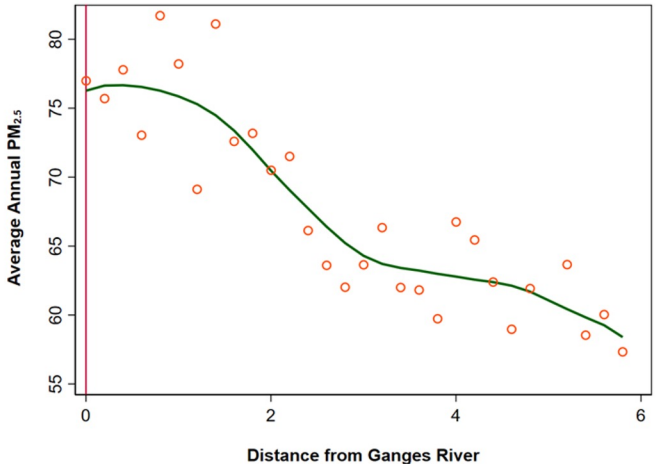
	National (1)	National (2)	National (3)	IGP (4)	Rest of India (5)	IGP 'Near Ganges' (6)	IGP 'Distant Ganges' (7)
	Dep Variable: Avg $PM_{2.5}$ (monthly)						
Mean of $PM_{2.5}$	80.1	80.1	80.1	95.0	73.4	97.6	92.0
IGP (1=yes)	13.9 (1.15)						
Total Precipitation (meters)	-3.1 (0.10)	-2.8 (0.06)	-2.8 (0.06)	-3.2 (0.12)	-2.5 (0.06)	-3.4 (0.14)	-2.8 (0.18)
Heating Degree Days (000s)	126 (38)	440 (16)	440 (16)	1123 (23)	128 (9)	1383 (28)	888 (36)
Thermal Inversion	67.4 (2.2)	61.7 (1.8)	29.0 (1.7)	53.5 (2.3)	39.0 (1.8)	58.1 (3.0)	45.2 (3.3)
Thermal Inversion in IGP			46.7 (2.7)				

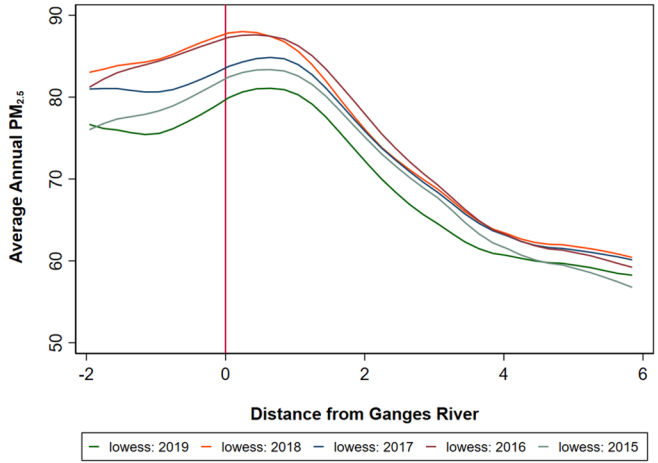
Note: A month is considered to have a thermal inversion if it satisfies the following conditions:

1. The average Planetary Boundary Layer (PBL) height is below 200 meters.
2. The average temperature for the month is below 65°F.
3. The total precipitation for the month is less than 5mm.



Green dots indicate the district centroids, red boundary indicates the IGP region while blue line traces the Ganga river.
Inverted grayscale gradient is used to indicate the PM2.5 levels.





Predicting Pollution :Exploring the Weather-Pollution Link :Robust Modeling with Monthly Climate Forecast

	National (1)	IGP (2)	Rest of India (3)	IGP 'Near Ganges' (4)	IGP 'Distant Ganges' (5)
	Dep Variable: Avg $PM_{2.5}$ (monthly)				
Model 1 - Rainfall	0.189	0.233	0.197	0.270	0.209
Model 2 - Heating Degrees	0.201	0.473	0.007	0.528	0.426
Model 3 - Cooling Degrees	0.342	0.632	0.130	0.693	0.554
Model 4 - PBL	0.073	0.142	0.024	0.162	0.114
Model 5 - Month FE	0.510	0.766	0.440	0.808	0.702
Model 6 - District FE	0.144	0.035	0.215	0.015	0.070
Model 7 - All Weather (1-4)	0.453	0.678	0.320	0.749	0.611
Model 8 - All Weather + MFE	0.549	0.776	0.471	0.824	0.715
Model 9 - All Weather + DFE	0.677	0.749	0.585	0.782	0.734

Each cell reports the R2 of a regression of PM2.5 on a cubic polynomial of the listed weather variable (in models 1-4) or month or district fixed effects. Model 7 includes all the explanatory variables in Models 1-4. Models 8 and 9 are the same as Model 7 but with the addition of month or district fixed effects respectively.

Predicting Long-Term PM2.5 Concentrations in India

1. **Column 1-** districts in the IGP experience particulate matter levels that are on average **17.7 micrograms** higher than those outside the region
1. **Column 2**- we add meteorological covariates
2. **Column 3-** economic variables, continue to exhibit higher long-run average pollution of 16.4-16.8 micrograms higher than those outside the region
3. **Column 4-** we add a regressor for a district's centroid distance to the Ganges River
4. **Column 5** - IGP
5. **Column 6**- Rest of India

Mean of $PM_{2.5}$	80.1	80.1	80.1	80.1	95.0	73.4
IGP (1=yes)	17.67***	16.75***	16.43***	20.03***		
	(1.2)	(1.0)	(1.2)	(1.5)		
Distance from Ganges (kilometers)				0.01***	-0.03***	0.01***
				(0.0)	(0.0)	(0.0)
Total Precipitation (cubic meters)		-0.71	-0.78	-0.81*	-6.15***	-0.47*
		(0.49)	(0.49)	(0.42)	(0.86)	(0.27)
Heating Degree Days (0000s)		-5.50***	-5.28***	-5.99***	-94.19***	-6.03***
		(1.8)	(1.7)	(1.6)	(26.1)	(1.3)
Cooling Degree Days (0000s)		2.66	2.55	1.31	-34.78***	3.51**
		(3.2)	(3.1)	(2.8)	(5.8)	(1.7)
Thermal Inversions (0000s)		3.2	2.86	5.78	-3.27	15.42***
		(4.8)	(4.7)	(4.1)	(12.8)	(3.4)

* significant at 10%
** significant at 5%.
*** significant at 1%.

Combining Models on Historical Data with Climate Projections

	National (1)	IGP (2)	Rest of India (3)	IGP 'Near Ganges' (4)	IGP 'Distant Ganges' (5)
Panel A: Results of Simulation					
Actual - 2019	82.8	91.4	77.1	92.3	90.0
Fitted Values - 2019	82.8	91.4	77.1	93.0	88.8
Fitted Values - 2050, RCP-4.5	85.9	90.5	82.9	92.1	87.8
Fitted Values - 2050, RCP-8.5	86.5	91.6	83.0	92.4	90.4
Predicted Increase in $PM_{2.5}(\mu g/m^3)$, RCP-4.5	3.1	(0.9)	5.7	(0.9)	(1.0)
Predicted Increase in $PM_{2.5}(\mu g/m^3)$, RCP-8.5	3.6	0.2	5.9	(0.6)	1.6
Panel B: Human Health Cost of Climate Change in India					
Number of Districts	551	170	381	91	79
Affected Population (millions)	1,208	483	725	302	180
Life Expectancy Change (per person), RCP-45	(0.30)	0.09	(0.56)	0.09	0.10
Change in Life Expectancy (millions), RCP-45	(364)	44	(408)	26	18
Life Expectancy Change (per person), RCP-85	(0.35)	(0.02)	(0.58)	0.06	(0.15)
Change in Life Expectancy (millions), RCP-85	(428)	(9)	(419)	19	(28)

The simulation uses the fitted values and the climate projections under RCP-4.5 and RCP-8.5. The health calculations are made using an assumption that sustained exposure to an additional 10 micrograms per cubic meter (μg/m3) of PM2.5 reduces life expectancy by 0.98 years (Ebenstein et al. 2017, Zhou et al. 2016).

Key Highlights

- **2050 Projections:** The findings indicate that PM2.5 is projected to rise by **3.1 micrograms** under the RCP-4.5 scenario,from a baseline level of 82.8 μ/g3 in 2019 among the districts included in the sample.
- An even more substantial increase of **3.6 micrograms** under the RCP-8.5 scenario.
- The projections indicate that by the end of the century, the average temperature is expected to be **3 to 6 degrees Celsius** above pre-industrial levels, exceeding the internationally agreed goal of limiting the increase to 2 degrees Celsius.
- **Counting the Cost:** climate change in India - staggering 364 Million Years of life expectancy at stake without emission reductions. Implies a reduction of 0.30 years in life expectancy.

"Breathing clean air and preserving a healthy climate is not just a choice;
it's a responsibility we owe to ourselves,
our communities, and the world we inhabit."

- THANK YOU