Air Pollution in Delhi: Does GRAP Grip at all?

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Air pollution

- A leading global threat to public health.
- Delhi among the worst-affected regions in the world (Dhaka, Lahore, Cairo, Jakarta, Mexico City).
- While we wait for long-term structural measures to address air pollution, dangerously high pollution levels need emergency measures
- Graded Response Action Plan (GRAP) – a set of emergency measures triggered when Air Quality Index (AQI) breaches certain thresholds.
- GRAP is widely acknowledged to be ineffective, but to date, limited assessment of effectiveness.
- Can GRAP like emergency measures be made more effective in practice?

Air quality: Key pollutant types

- Particulate Matter (PM)2.5
  - Diameter of 2.5 micrometers or less (1/30th the width of a human hair)
  - Remains suspended in air for long periods, can penetrate deep into lungs.
  - Health risks significant for asthma, respiratory diseases, heart attacks.
  - Primary target of air quality standards and policy interventions.
- PM10, Ozone (O_3), Nitrogen Dioxide (NO_2), Sulfur Dioxide (SO_2), Carbon Monoxide (CO)

Pollution Monitoring

- A network of monitoring stations across Delhi
  - $\sim$ 40 monitoring stations
    - operated by Central Pollution Control Board (CPCB), Delhi Pollution Control Committee (DPCC), System of Air Quality and Weather Forecasting and Research (SAFAR).
  - $\sim$ 300 across India
- Data: near continuous measurements of $PM_{2.5}$, PM_{10}, NO_2, SO_2, O_3, CO, other key pollutants + meteorological variables.
- CPCB: sets national standards and guidelines, ensuring data quality and consistency across stations.

- Commission for Air Quality Management (CAQM) is the specialized authority that decides GRAP stage-wise invocations in Delhi and the NCR based on AQI
  - Aside: woeful reporting of historical AQI data (unlike COVID data under Citizen Science Initiatives)

Air Quality Index (AQI)

- AQI : a standardized scale for air pollution
- Locates 24-hour average PM2.5 concentration ($\mu g/\mathrm{m}^3$) in a set of intervals (defined by a piecewise linear formula)
  - 0 (ideal clean air).
  - 500 (very hazardous air).
  - PM2.5 < 12 $\mu g/\mathrm{m}^3$: AQI < 50 (Good quality)
    - Sikkim, Mizoram, Meghalaya: AQI 20–70
    - Hill Stations in Himachal Pradesh and Uttarakhand: AQI 30–80
    - Coastal and Southern Regions (parts of Kerala, Goa, Coastal Karnataka): AQI 40–100
    - Delhi/NCR AQI: Winter 300-500+
- Seasonal and meteorological factors affect PM2.5 and AQI.

Mapping of GRAP Stages to AQI Categories

GRAP Stage	**AQI Category**	**AQI Range**
Stage I	Poor	201–300
Stage II	Very Poor	301–400
Stage III	Severe	401–450
Stage IV	Severe+ (Emergency)	>450

GRAP Stages I & II (AQI 201–400)

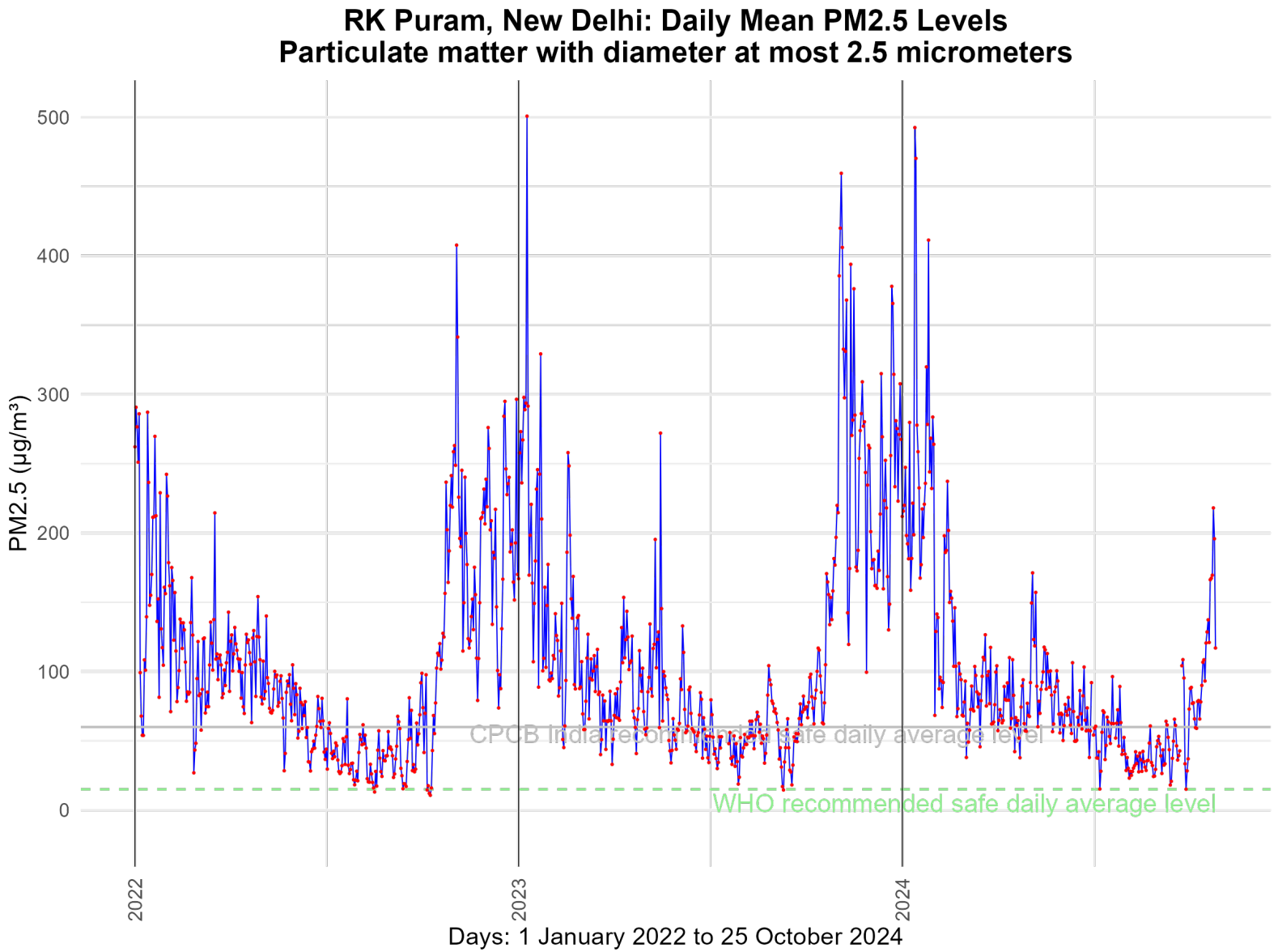
Stage I: Poor (201–300)	▶ Enhanced mechanized road sweeping, water sprinkling ▶ Strict dust control at construction sites ▶ No open waste burning ▶ Promote public transport, regulate parking fees
Stage II: Very Poor (301–400)	▶ All Stage I measures ▶ Ban diesel generators (except essential services) ▶ Increase parking fees, discourage private cars ▶ Intensify traffic management, public transport

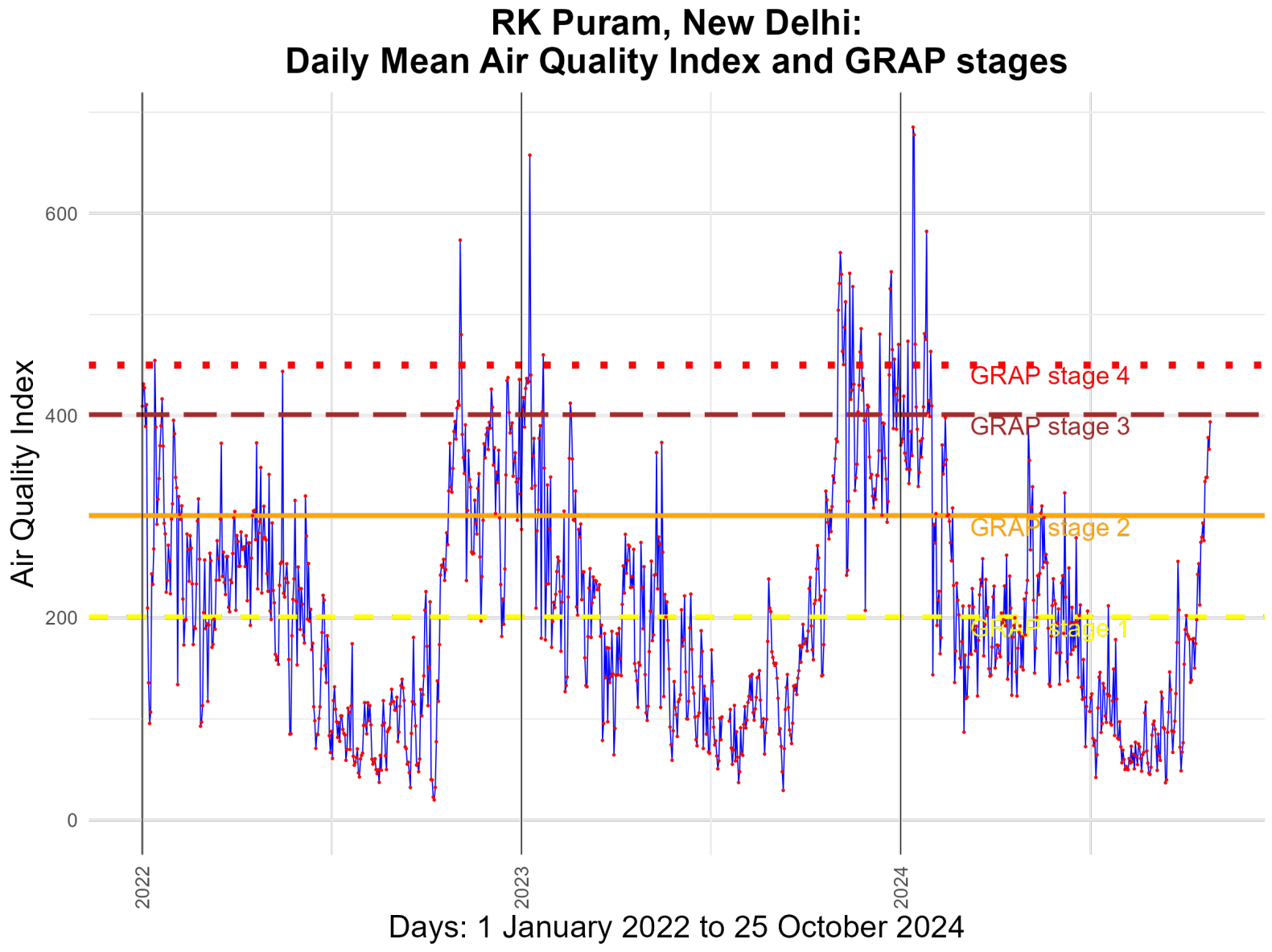
GRAP Stages III & IV (AQI >400)

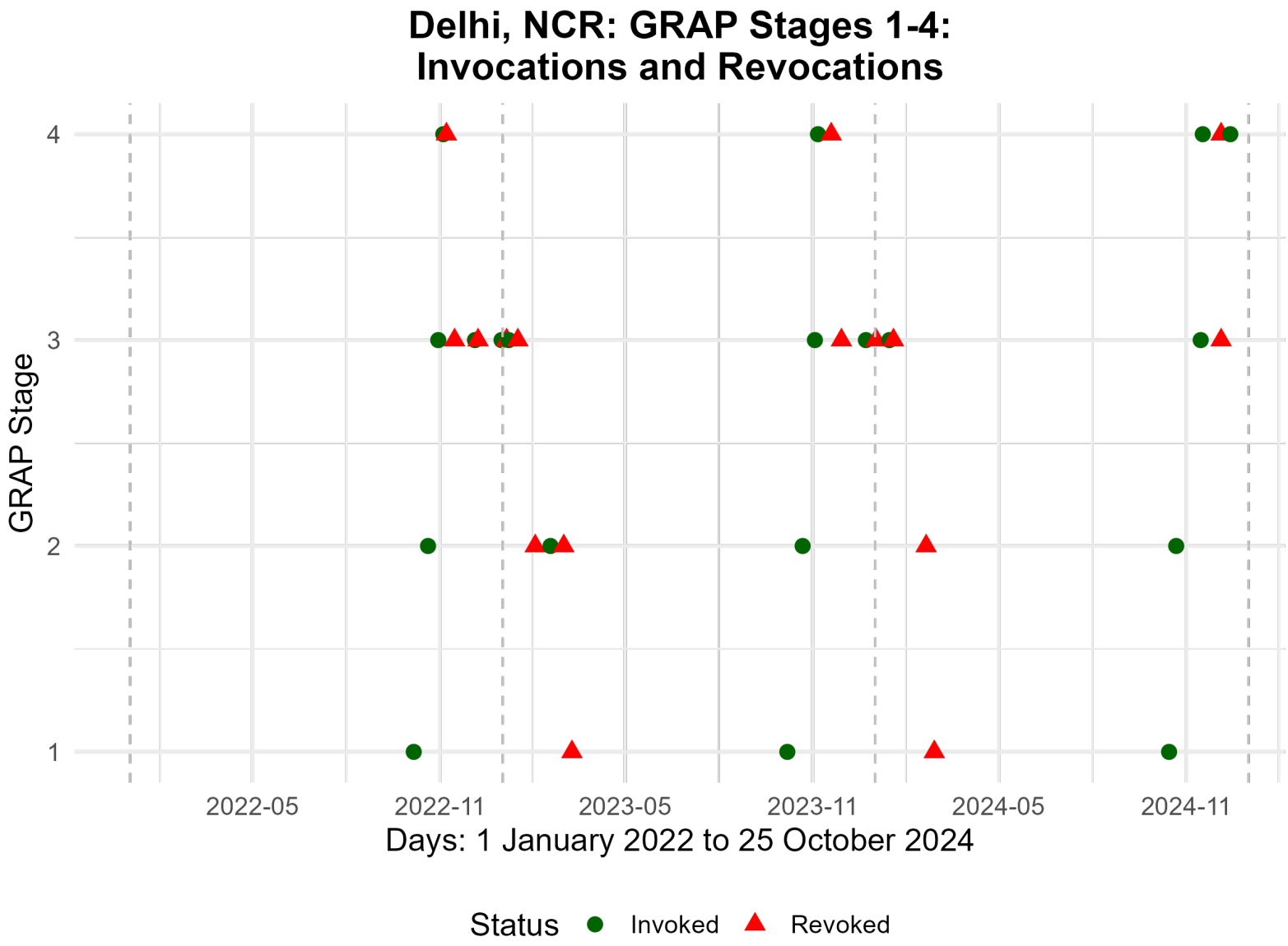
Stage III: Severe (401–450)	▶ All Stage I & II measures ▶ Halt construction/demolition (except essentials) ▶ Close brick kilns, hot mix plants, stone crushers ▶ Restrict entry of some trucks
Stage IV: Severe+ (>450)	▶ All Stage I, II & III measures ▶ Stop entry of all trucks (except essentials) ▶ Consider odd-even restrictions for vehicles ▶ Close schools, halt all construction, emergency steps

Data

- Time period: Daily data from January 2022-October 2024
- Location: RK Puram, New Delhi.
- Primary variables: PM2.5, AQI.
- Meteorological variables as controls: Temperature, precipitation, relative humidity, wind speed, wind direction, boundary layer height, solar radiation.
- Source: Central Pollution Control Board (CPCB) and Copernicus Satellite.
- Obtaining: Traffic index


RK Puram, New Delhi: Daily Mean PM2.5 Levels
Particulate matter with diameter at most 2.5 micrometers
PM2.5 (µg/m³)
500
400
300
200
100
0
CPCB India recommended safe daily average level
WHO recommended safe daily average level
2022
2023
2024
Days: 1 January 2022 to 25 October 2024

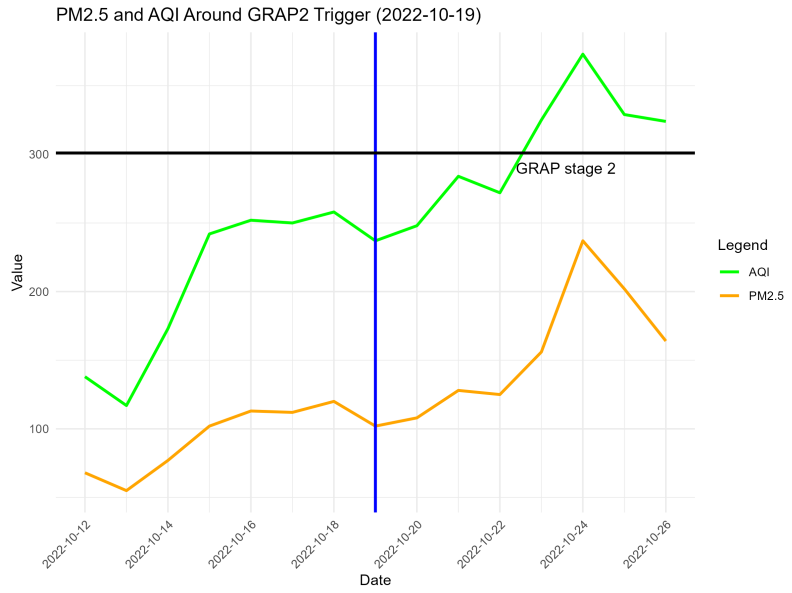

RK Puram, New Delhi:
Daily Mean Air Quality Index and GRAP stages
Air Quality Index
600
400
200
0
GRAP stage 4
GRAP stage 3
GRAP stage 2
GRAP stage 1
2022
2023
2024
Days: 1 January 2022 to 25 October 2024

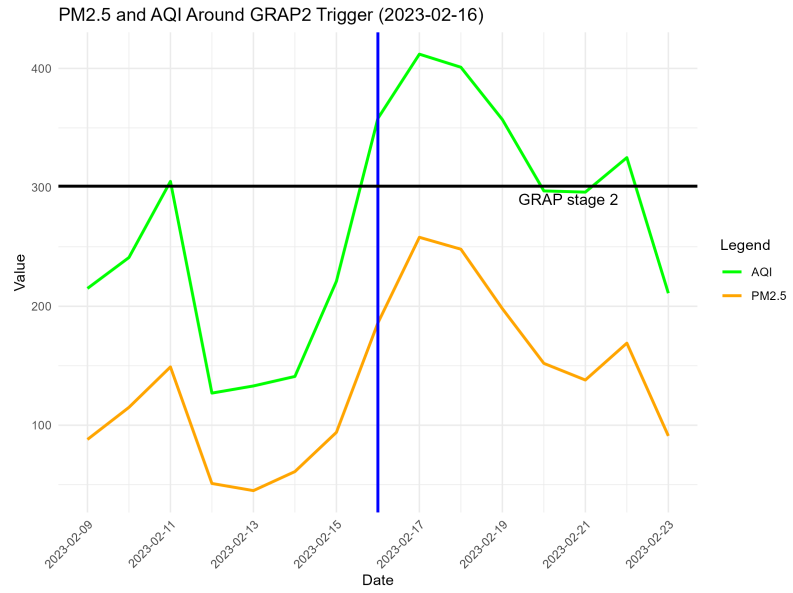


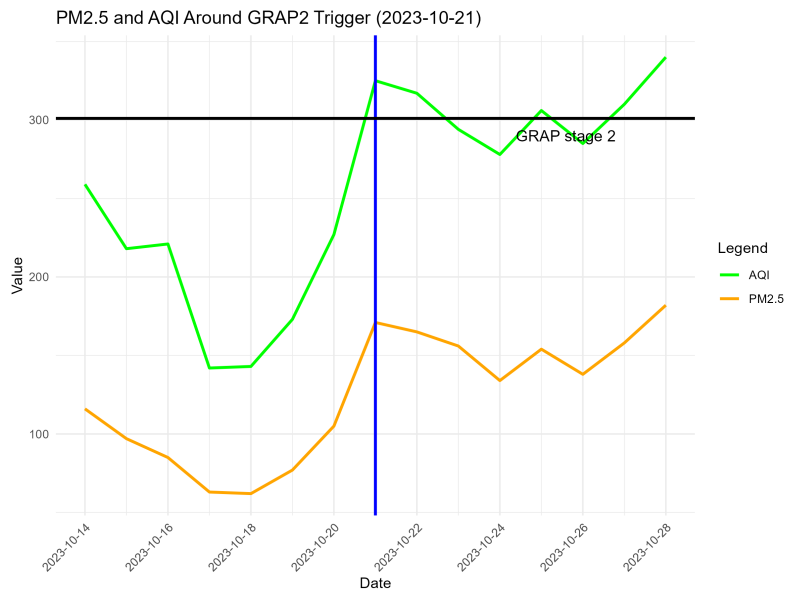
2022-23 and 2023-24: GRAP1 invoked twice, spanning 299 days. GRAP2 invoked thrice, spanning 239 days. GRAP3 invoked seven times, spanning 73 days. GRAP4 invoked twice, spanning 16 days.

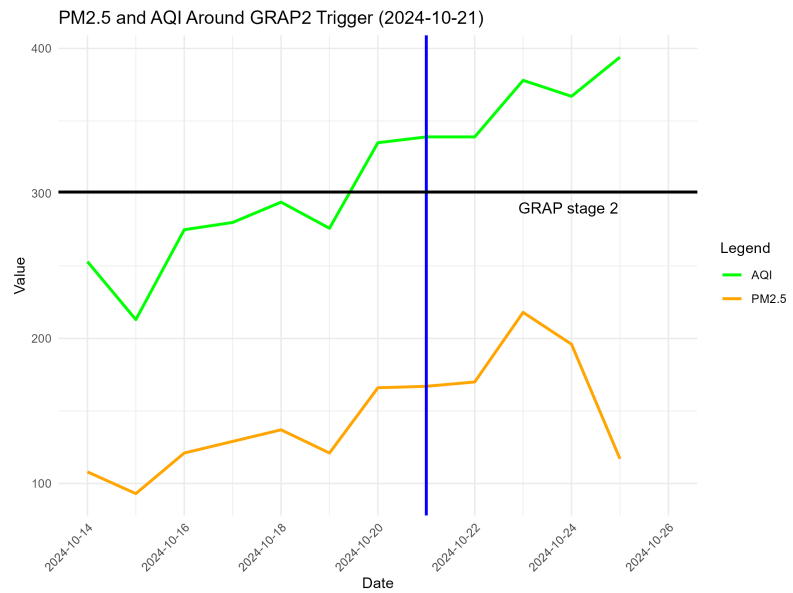
RK Puram, ND: GRAP1 triggers and air quality ‘response’

RK Puram, ND: GRAP2 triggers and air quality ‘response’

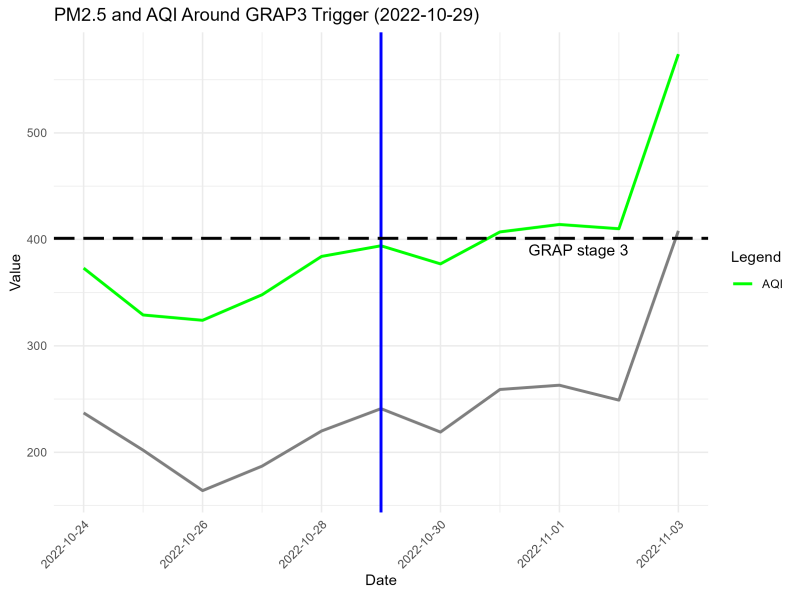


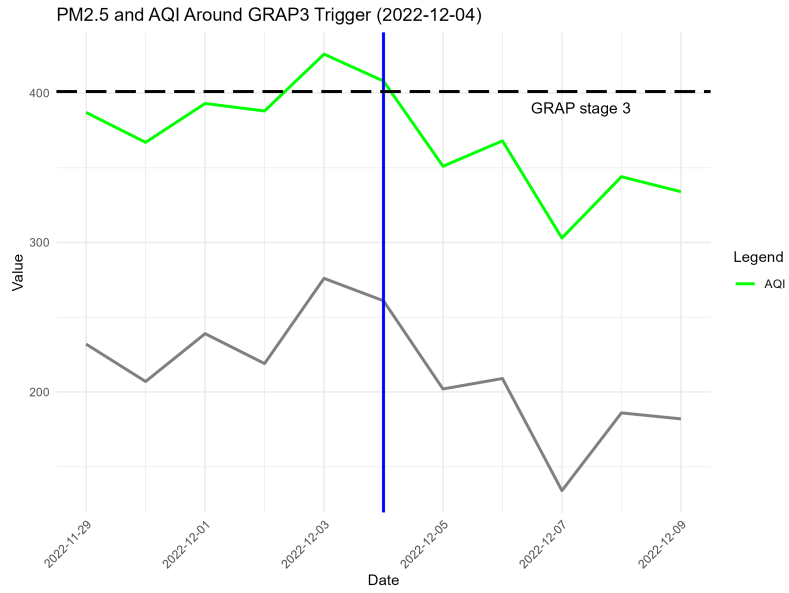


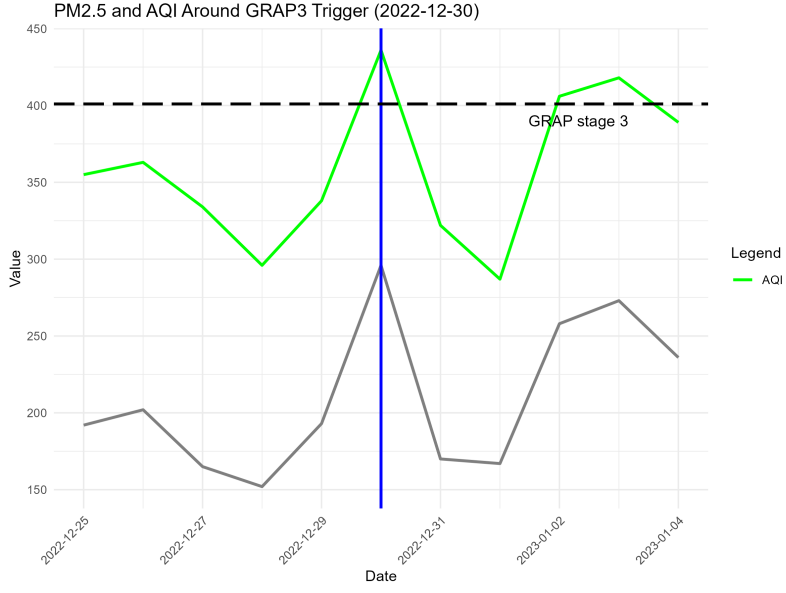


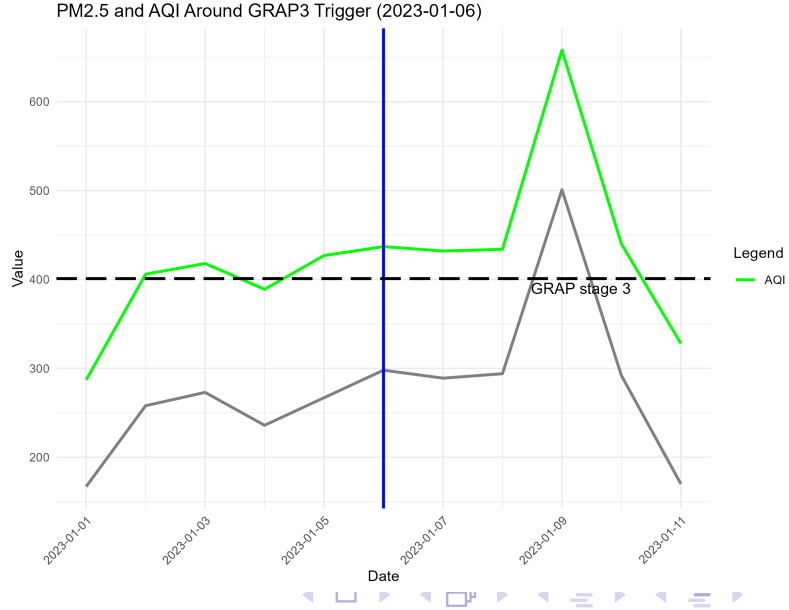


RK Puram: GRAP3 triggers and air quality 'response' (1)









RK Puram: GRAP3 triggers and air quality 'response' (2)

RK Puram, ND: GRAP4 triggers and air quality ‘response’

Regression Discontinuity and Kink Designs

GRAP Stage	Trigger Date	PM2.5 RD[1]	95% CI Lower	95% CI Upper	Δ Slope (1)[2]	Δ Slope (2)[3]
1	2022-10-05	-135	-286	16	7***	6**
1	2023-10-06	-25	-118	67	0	0
1	2024-10-14	-30	-119	60	5*	6*
2	2022-10-19	-15	-65	34	9**	9**
2	2023-02-16	44	-124	211	-10**	-9*
2	2023-10-21	23	-135	182	20***	20***
2	2024-10-21	-76	-258	106	-25*	-7
3	2022-10-29	-46	-194	103	-18***	-17***
3	2022-12-04	-64	-293	165	-8	-10
3	2022-12-30	55	-85	195	-2	-1
3	2023-01-06	28	-104	159	-16**	-15**
3	2023-11-02	166	83	249	-22**	-20**
3	2023-12-22	-8	-401	384	-12**	-11*
3	2024-01-14	-297	-1278	684	-2	-4
4	2022-11-03	154	-46	354	-24***	-24***
4	2023-11-06	-103	-515	309	-26***	-27***

[1] Robust RDD estimated using local polynomial regression.

[2] Full Regression Kink Design

[3] Slope-only Regression Kink Design

Model: State-Space and Kalman Filter

- State-space (Local linear trend) model for Logarithm of PM2.5
  - Estimated using Kalman filter: handles missing data, updates with new observations, provides real-time forecasting.
  - Controls for meteorological variables and GRAP interventions.
  - Aim: estimate shifts in levels and slopes at GRAP stages 1, 2, 3, and 4 cutoffs in the spirit of RDD
  - Ongoing work – scoping out non NCR control regions

Results: Meteorological Effects

Regressor	Coefficient	Std. error	
ln Temperature	7.600	1.126	***
ln Temperature (lag 1 day)	-1.936	1.115	
PreciptnD	-0.089	0.028	***
PreciptnD (lag 1 day)	-0.111	0.028	***
ln Boundary layer height	-0.155	0.048	***
ln Boundary layer height (lag 1 day)	-0.125	0.048	***
ln Solar Radiation	0.117	0.044	***
ln Solar Radiation (lag 1 day)	0.244	0.043	***
ln Relative Humidity	5.175	0.885	***
ln Relative Humidity (lag 1 day)	-1.102	0.873	
ln RelHXln TempC	-1.536	0.261	***
ln RelHXln TempC (lag 1 day)	0.303	0.260	
ln Wind speed	-0.268	0.034	***
ln Wind speed (lag 1 day)	-0.088	0.033	***
cos Wind Direction	0.096	0.028	***
cos Wind Direction (lag 1 day)	0.065	0.028	**
sin Wind Direction	0.000	0.022	
sin Wind Direction (lag 1 day)	-0.009	0.023	

Results: Meteorological Effects

- **Temperature**: high temperatures worsen air quality (photochemical reactions), delayed effects can be towards improving dispersion.
- **Precipitation**: Significant negative effect on AQI (rain reduces particulate concentration).
- **Boundary layer height**: Higher boundary layers reduce pollutant concentration.
- **Solar radiation**: Strong sunlight leads to photochemical oxidation and secondary aerosols
- **Relative humidity**: High humidity causes hygroscopic growth of fine particles
- **Temperature and Relative humidity**: Wehn both heat and humidity peak together, cloud formation can remove some pollutants. Chemical mechanisms become less efficient beyond certain humidity/temperature thresholds, with a negative combined effect
- **Wind speed**: Higher wind speeds improve air quality by dispersing pollutants.
- **Wind direction**: Pollution sources (agricultural burning) lie to the west

Results: GRAP ineffectiveness

Ongoing work, Need Control region and Traffic index

GRAP1	-0.074	0.093	
GRAP2	0.291	0.081	***
GRAP3	0.057	0.063	
GRAP4	0.012	0.118	
Spring	-0.034	0.109	
Summer	0.026	0.137	
Monsoon	-0.213	0.140	
PostMonsoon	-0.128	0.124	

Results: GRAP Effectiveness

- **GRAP Stages 1,3,4**: no significant impact during actrivation, relative to other periods
- **GRAP Stage 2**: positive, may reflect that stage 2 is invoked during late
- Reactive nature of GRAP reduces its effectiveness – measures triggered too late to control rising pollution.
- **Monsoon** season: beneficial for air quality relative to winter

GRAP orders are reactive

No.120017/27/GRAP/2021/CAQM 16th December, 2024

ORDER

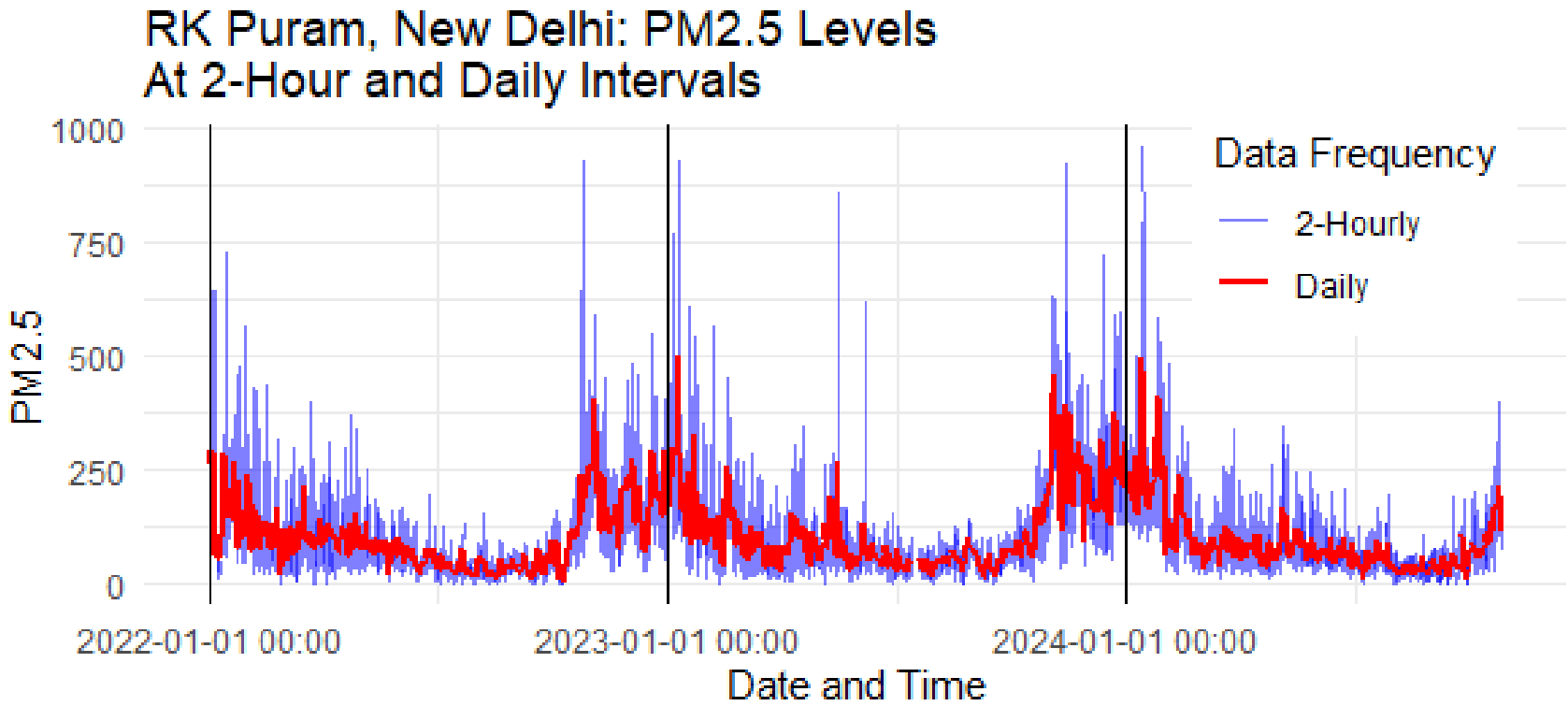
Sub.: Implementation of Actions under Stage-IV ('Severe+' Air Quality) of Graded Response Action Plan in Delhi-NCR- steps to be taken.

3. In pursuance of the above directions of the Hon'ble Supreme Court, the Commission vide its earlier Order on date had invoked GRAP Stage-III when the AQI of Delhi breached the 350 mark, owing to unfavorable meteorological conditions and other factors for dispersion of the pollutants.

4. The Air Quality parameters, however, further worsened owing to a drastic reduction in the mixing layer height and continued absolute calm - wind conditions over Delhi. The Sub-Committee on GRAP was accordingly maintaining a close watch on the air quality scenario in Delhi. The Sub-Committee noted that the AQI level almost touched the 400 mark i.e. was 399 at 9 pm and was recorded as 401 at 10 pm, breaching the 400 mark.

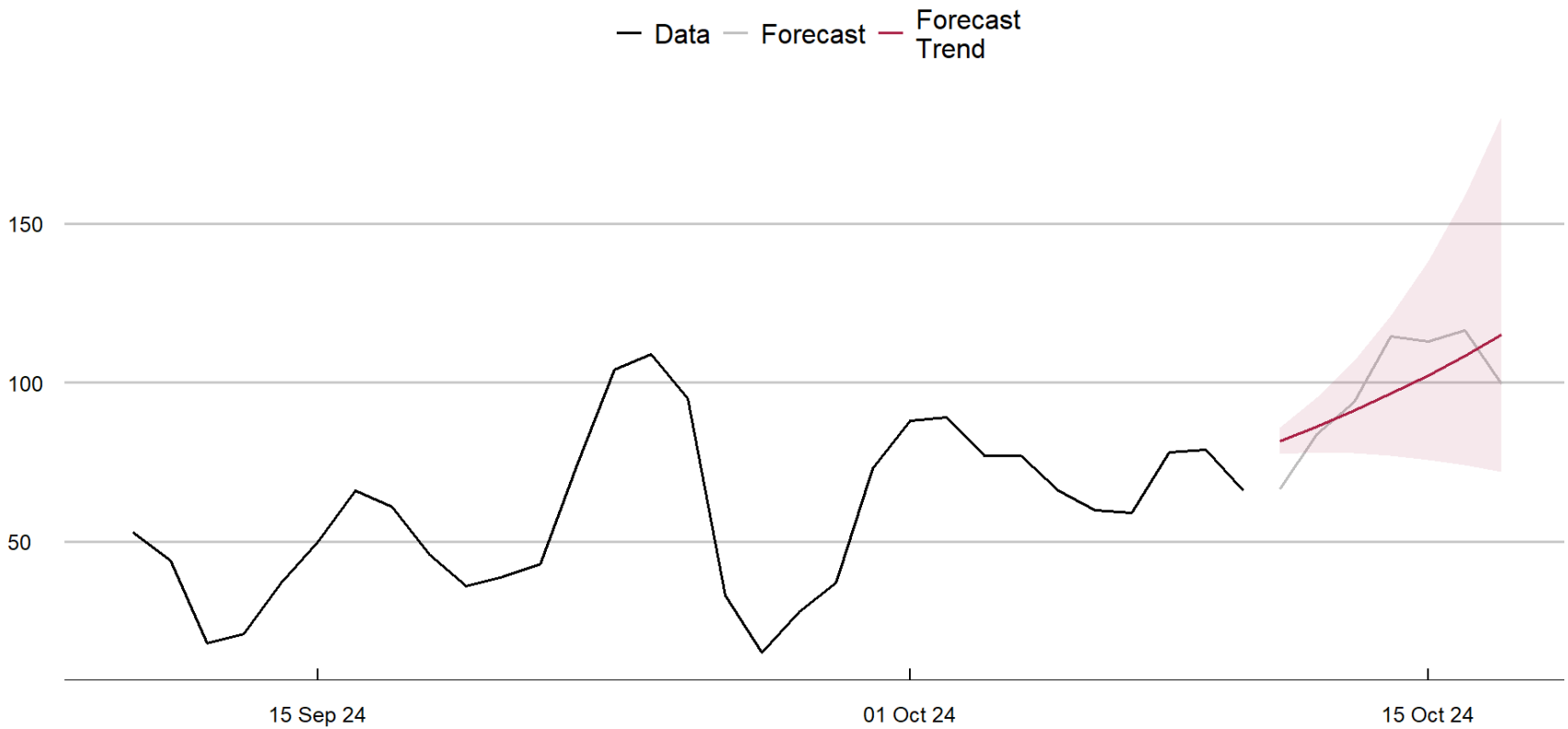
5. Accordingly, in pursuance of the Hon'ble Supreme Court's directives, the Sub Committee hereby invokes the Stage-IV of the Schedule under the GRAP, as comprehensively revised and issued on 13.12.2024, with immediate effect. The actions under Stage-IV shall be over and above the actions under Stages III, II and I, already in force.

GRAP orders are reactive



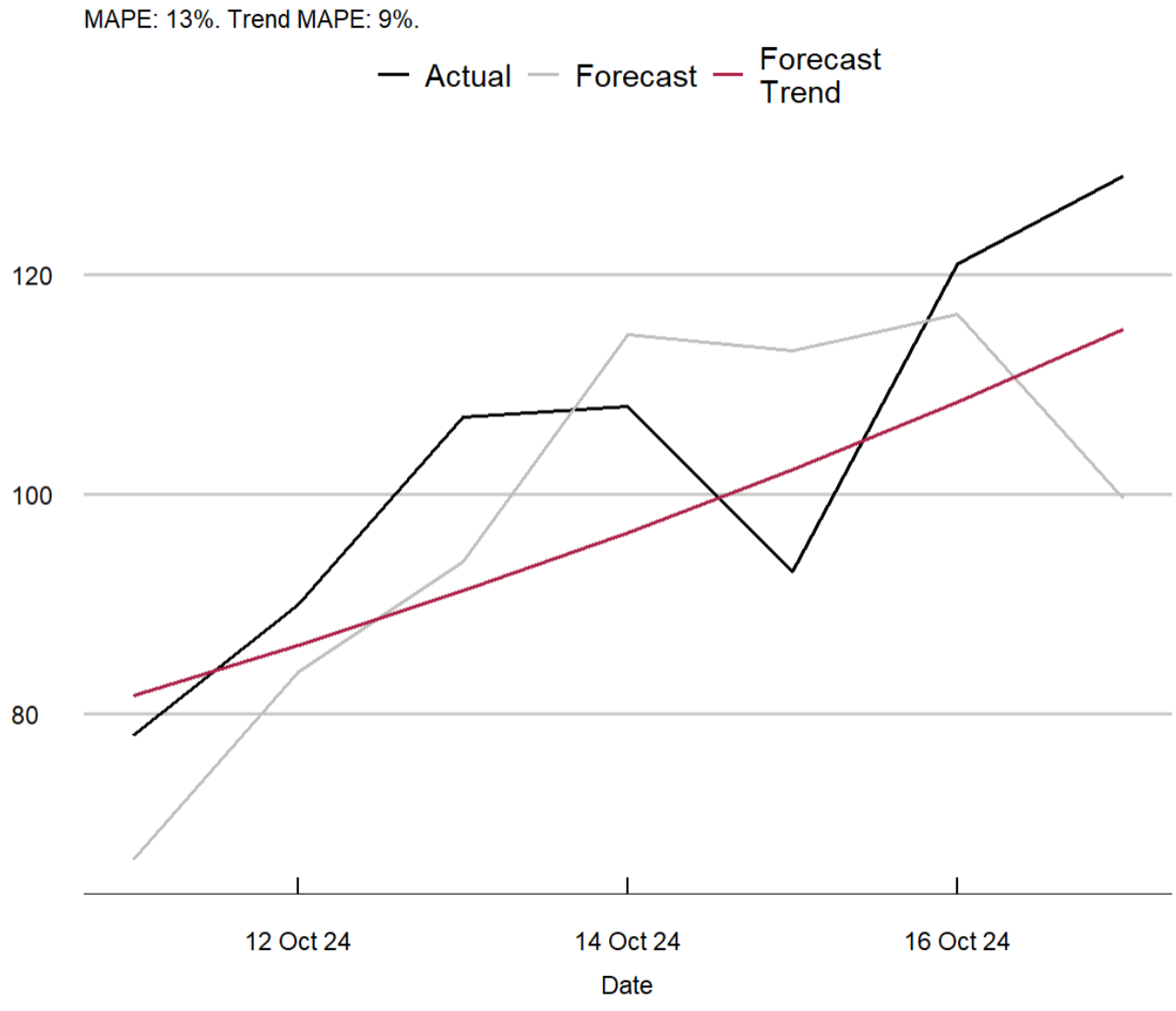
AQI is volatile

Accurate short term forecasts can guide policy



7 days ahead forecast using data from 2024-08-01 to 2024-10-10

Short term forecasts can guide policy



7 days ahead forecast using data from 2024-08-01 to 2024-10-10

Conclusions

- GRAP is reactive, often triggered after pollution has reached hazardous levels.
- Mistiming of GRAP measures reduces effectiveness.
- Kalman filter-based forecasting can smooth out noisy AQI data and improve decision-making on when to invoke GRAP.
- Short-term real time AQI forecasts could help shift GRAP from a reactive to a proactive framework.
- Goes without saying that stronger enforcement of GRAP measures, particularly in higher stages is needed.
- Ongoing work: other regions, extend variables, refine model.