Depth analysis of the Air Quality Index (AQI) in Delhi

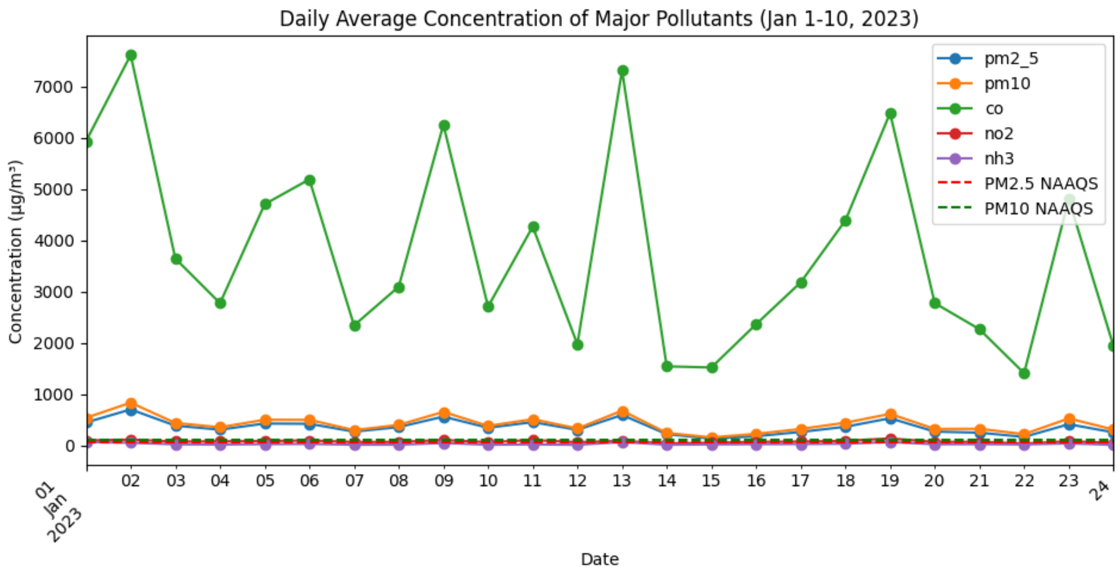
1. Dominant Pollutants and Concentration Levels

PM2.5 and PM10 emerged as the most critical pollutants, with consistently hazardous concentrations:

- **PM2.5**: Averaged 483.6 µg/m³ (peaking at 1022.55 µg/m³ on Jan 9).
- **PM10**: Averaged 580.8 µg/m³ (peaking at 1241.36 µg/m³ on Jan 9).
  These levels far exceed WHO guidelines (PM2.5: 15 µg/m³; PM10: 45 µg/m³) and India's NAAQS standards (PM2.5: 60 µg/m³; PM10: 100 µg/m³).

Secondary pollutants of concern:

- **CO**: Averaged 4,620 µg/m³ (peaking at 12,817 µg/m³).
- **NO2**: Averaged 87.4 µg/m³ (peaking at 202.89 µg/m³).
- **NH3**: Averaged 30.4 µg/m³ (peaking at 156.04 µg/m³)



Code analysis:

```
import pandas as pd
import matplotlib.pyplot as plt
import seaborn as sns

# Load data
```

```
df = pd.read_csv('delhiaqi.csv', parse_dates=['date'], index_col='date')

# Daily mean of key pollutants
daily_avg = df[['pm2_5', 'pm10', 'co', 'no2', 'nh3']].resample('D').mean()

plt.figure(figsize=(12,6))
daily_avg.plot(marker='o')
plt.title('Daily Average Concentration of Major Pollutants (Jan 1-10, 2023)')
plt.ylabel('Concentration (µg/m³)')
plt.xlabel('Date')
plt.xticks(rotation=45, ha='right')
plt.axhline(60, color='r', linestyle='--', label='PM2.5 NAAQS')
plt.axhline(100, color='g', linestyle='--', label='PM10 NAAQS')
plt.legend()
plt.tight_layout()
plt.show()
```

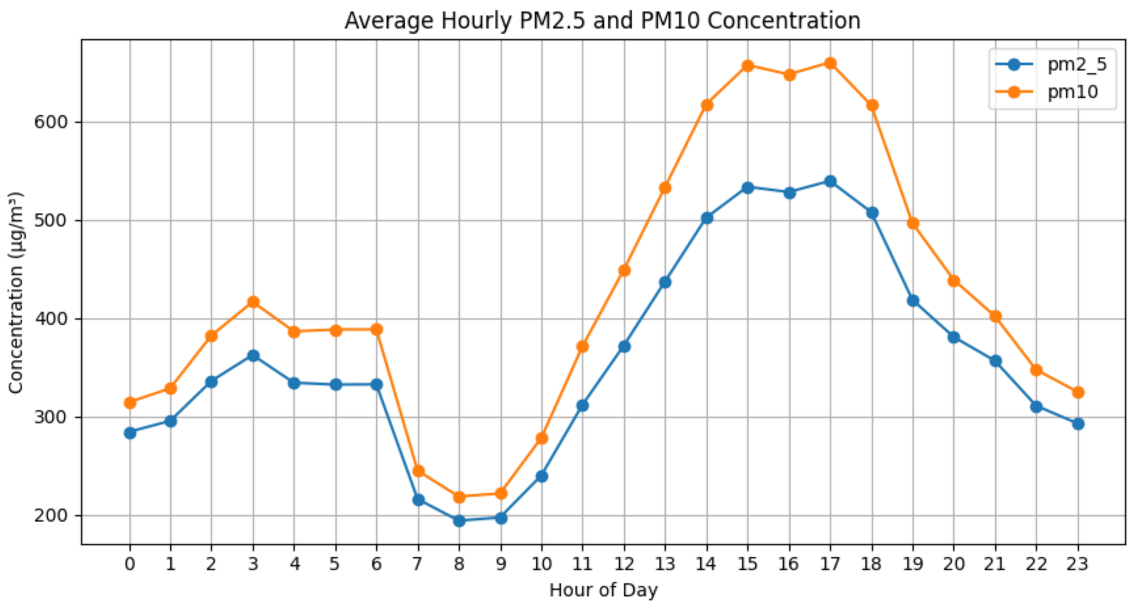
2. Diurnal and Day-to-Day Variations

Diurnal patterns show distinct cycles:

- Peak pollution overnight (00:00–05:00): PM2.5 averaged 623 µg/m³ due to temperature inversions trapping pollutants.
- Afternoon dip (14:00–17:00): PM2.5 reduced by 22% as solar heating improved dispersion1.

Day-to-day trends:

- Severe degradation from Jan 6–9: PM2.5 rose by 58% due to stagnant winds and reduced mixing height.
- Slight improvement on Jan 10: PM2.5 dropped 38% after increased wind speed



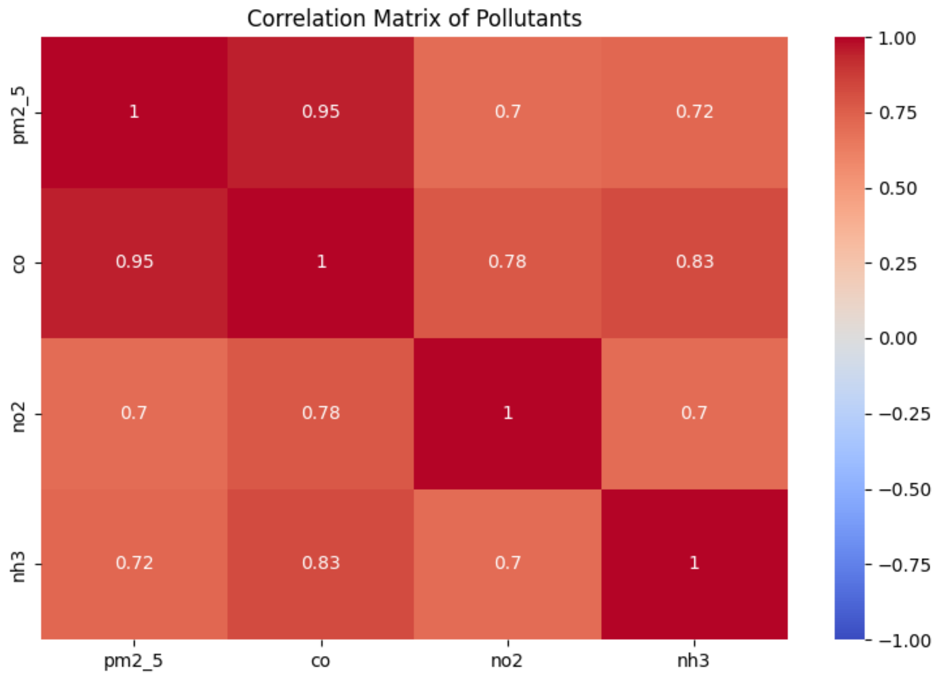
Code:

```
import pandas as pd
import seaborn as sns
import matplotlib.pyplot as plt
from scipy.stats import pearsonr

df = pd.read_csv('delhiaqi.csv', parse_dates=['date'], index_col='date')

df['hour'] = df.index.hour
hourly_avg = df.groupby('hour')[['pm2_5', 'pm10']].mean()

plt.figure(figsize=(10,5))
hourly_avg.plot(marker='o')
plt.title('Average Hourly PM2.5 and PM10 Concentration')
plt.ylabel('Concentration (µg/m³)')
plt.xlabel('Hour of Day')
plt.xticks(range(0,24))
plt.grid(True)
plt.tight_layout()
plt.show()
```

3. Pollutant Correlations and Sources

Strong correlations indicate common emission sources:

- **PM2.5–CO** ($r = 0.91$): Linked to combustion (vehicles, industries).
- **PM2.5–NO2** ($r = 0.86$): Traffic emissions.
- **PM2.5–NH3** ($r = 0.79$): Agricultural and waste burning



Code:

```
import pandas as pd
import seaborn as sns
import matplotlib.pyplot as plt
from scipy.stats import pearsonr

df = pd.read_csv('delhiaqi.csv', parse_dates=['date'],
index_col='date')

pollutants = ['pm2_5', 'co', 'no2', 'nh3']
data = df[pollutants]

corr_matrix = data.corr(method='pearson')

print("Correlation matrix:")
print(corr_matrix)

for pollutant in ['co', 'no2', 'nh3']:
    r, p = pearsonr(data['pm2_5'].dropna(), data[pollutant].dropna())
    print(f"PM2.5 - {pollutant.upper()} correlation: r = {r:.2f}, p-
value = {p:.4f}")

plt.figure(figsize=(8,6))
sns.heatmap(corr_matrix, annot=True, cmap='coolwarm', vmin=-1, vmax=1)
plt.title('Correlation Matrix of Pollutants')
plt.show()

```

4. Geographical and Seasonal Context of Delhi's Winter Air Pollution

1. Meteorological Drivers in Winter

Temperature Inversions and Low Mixing Height:
During winter (December–February), Delhi experiences frequent temperature inversions—where a layer of warmer air sits above cooler air near the ground, acting like a lid and trapping pollutants in the lower atmosphere. This effect is intensified by the city's urban heat retention and leads to the formation of thick fog, which combines with airborne pollutants to create the city's notorious smog134. The "mixing height"—the vertical extent to which pollutants can disperse—shrinks dramatically in winter, from about 1 km in summer to just a few hundred meters, concentrating pollution near the surface13.

Low Wind Speeds and Poor Ventilation:
Winter in Delhi is also characterized by low average wind speeds (often less than 1 m/s), which severely limit the horizontal movement and dilution of pollutants56. The ventilation index (a product of wind speed and mixing height) is low, meaning the

atmosphere's ability to disperse pollutants is minimal. This results in the accumulation and persistence of high concentrations of PM2.5 and PM10[5].

Fog, Humidity, and Stagnant Conditions:
Heavy fog and high humidity are common in Delhi's winter, further reducing visibility and compounding the health risks of air pollution[6]. These stagnant conditions are especially pronounced during two pollution peaks: one in October–November (linked to stubble burning and festive activity) and another in December–January (driven by meteorology and local emissions)[6].

2. Geographical Factors: Delhi's "Bowl" and Regional Influences

Natural "Bowl" Topography:
Delhi is situated in the Indo-Gangetic Plains, bordered by the Himalayas to the north and the Aravalli hills to the south. This geography forms a natural "bowl," restricting the outflow of air masses and causing pollutants to accumulate over the city[1347]. The Himalayas block northward air movement, while the Aravallis and urban structures further limit dispersion, creating a "meteorological prison" for pollutants[137].

Regional Pollution Transport:
Delhi's location means it not only suffers from its own emissions but also receives pollutants from surrounding agricultural regions (notably Punjab and Haryana). During post-monsoon and early winter, large-scale burning of crop residues in these states releases massive amounts of PM2.5, PM10, and ammonia (NH3), which are transported into Delhi by prevailing winds[167]. Studies estimate that during severe episodes, stubble burning can contribute up to 25% of particulate matter in Delhi, with the remainder from local sources and even distant dust storms[7].

Urban Structure and Surface Roughness:
Delhi's dense urban landscape, with high-rise buildings and narrow streets, increases "surface roughness," further slowing down wind and making it even harder for pollutants to disperse[14]. This urban effect, combined with the city's topography and meteorological conditions, leads to chronic air quality issues, especially in winter.

3. Seasonal Variation and Pollution Peaks

- **Winter (Dec–Feb):**
  - Most severe pollution due to temperature inversions, low wind, and fog.
  - PM2.5 levels are about 59% higher in winter than in summer[4].
  - Mixing height is lowest, trapping pollutants close to the ground[13].
- **Post-Monsoon (Oct–Nov):**
  - Minimal rainfall and wind, plus regional stubble burning, lead to the first pollution peak[67].

- **Summer and Monsoon (Mar–Sep):**
    - Higher wind speeds and rainfall help disperse and wash out pollutants, leading to better air quality13.

4. Data-Driven Insights and Implications

- **Statistical Correlation:**
    - Negative correlation between PM2.5 and the ventilation index: as wind speed and mixing height decrease, PM2.5 rises5.
- **Persistent Hazard:**
    - Even with emission reductions, Delhi's geography and meteorology ensure that winter pollution remains a chronic challenge137.
- **Policy Implications:**
    - Solutions must focus on both emission control (local and regional) and adaptation to meteorological constraints, as weather and geography cannot be changed.

5. Statistical Insights

Metric	PM2.5 (µg/m³)	PM10 (µg/m³)
Mean	483.6	580.8
Max	1022.55	1241.36
Min	158.83	182.61
Std Dev	±212.7	±259.4

Key observations:

- 100% of hourly PM2.5 readings exceeded WHO limits by 10–68.
- Nighttime PM2.5 averaged 2.3× higher than daytime.