INTRODUCTION

Exposure to particulate matter PM$_{2.5}$ and PM$_{10}$ with an aerodynamic diameter less than 2.5 and 10 μm respectively is a global concern due to their adverse health effects. Prolonged exposure to these particles affects healthy people and seriously impacts those with existing diseases. It causes breathing discomfort for people with asthma and heart diseases. According to WHO, an increase in total PM by 10 μg/m$^3$ per year increases mortality by 6 per cent. Most cities in India have been experiencing severe air pollution due to fast-paced urbanization and rapid economic growth. SPM primarily originating from gaseous pollutants is posing a grave threat to human health. Gaseous pollutants CO, SO$_2$ and NO$_2$ are reported in several studies to be leading to high PM levels. Several studies considered the pollutant conditions in cities across the world and analysed the impact of these pollutants on human health (Samet 2000, Sarnat 2001, Katsouyanni 2001, Ito et al. 2007). However, studies on Visakhapatnam city are scanty and even those done refer to an earlier period.

The research presented here is an analysis of PM$_{2.5}$ and PM$_{10}$ concentrations from the industrial zone of Visakhapatnam. The industrial development, initiated around 1950, triggered a population explosion in Visakhapatnam. The population of Visakhapatnam in the year 2018 as per estimated data was 4.056 Million (Population of India 2018). The city is studded with major industries mainly Hindustan Zinc Limited (HZL), Coromandel Fertilizers Limited (CFL), Visakhapatnam Port Trust (VPT), Hindustan Petroleum Corporation Limited (HPCL), Bharat Heavy Plates and Vessels (BHPV), Hindustan Polymers Limited (HPL), Visakhapatnam Steel Plant (SP), Coastal Chemicals (CC), Andhra Cement Company (ACC) and Simhadri Thermal Power Corporation (STPC). About 200 ancillary industries were also established to supplement the main industries, which turned the central basin of Visakhapatnam into an “air-polluting chimney”. The city was declared as one of the critical (NEERI 2005) and severely polluted areas (CEPI 2013) in the country.

The city with an area of about 680 km$^2$ is surrounded on three sides by mountains and the Bay of Bengal on the fourth. It is effectively shielded from winds, with only marine air moving into the basin. The major industries along with the Port are located within a distance of 13 km from the coast.

Combustion emits large quantities of chemicals from industries such as zinc, fertilizer, polymers, cement, steel production and petroleum. This situation is further aggravated by atmospheric aerosol content which is highest during the dry periods, resulting in a high ionic content due to precipitation scavenging. Marine aerosols also add to the industrial contribution. The emissions and aerosols are shielded from the wind by mountains on three sides, only allowing coastal
spray (marine aerosols) from the east. Visakhapatnam, thus, is subject to heavy air pollution, when compared to inland areas. Also, urbanization increased automobile traffic, and industrialization produces large emissions of SO₂ and NOₓ. The concentrations of air pollution vary from location to location as they depend on atmospheric conditions (Murthy 2004) like wind direction, speed, temperature and humidity.

In India, 99.9% of the country’s population resides in areas that exceed the WHO Air Quality Guideline of 10 μg/m³ (annual average), and half of the population resides in areas where the Indian National Ambient Air Quality Standard (NAAQS) for PM2.5 (40 μg/m³) is exceeded (Greenstone et al. 2015, Srinivas 2013, Venkataraman et al. 2018). In another report, the annual averages for 2012 in Vishakhapatnam were 70.4±29.7, 18.9±14.4 and 15.6±6.3 for PM₁₀, SO₂, and NO₂ respectively (Guttikunda et al. 2015). Rao & Satish (2014) reported that the cause of air pollution in Visakhapatnam is not only due to the industries but also due to traffic.

Against this background, the present study focuses on analysing the mass concentrations of PM and gaseous pollutants. The objectives of the study are to examine the present levels of PM concentrations and their causative factors.

MATERIALS AND METHODS

The real time hourly mass concentrations of PM₂.₅, PM₁₀, CO, NO₂ and SO₂ are recorded by National Air Quality Index of Central Pollution Control Board compiled for each city under the Ministry of Environment, Forests and Climate Change, India. The instruments measuring the mass concentrations are located in the central point of the city. The mass concentrations of PM₂.₅ and PM₁₀ are measured using beta attenuation method. The gas pollutants NO₂, SO₂ and CO are measured using the gas phase chemiluminescence method, ultraviolet fluorescence method and NDIR spectroscopy respectively. The data are publicly accessible and data used in this paper were obtained from the website (https://app.cpcbccr.com/).

The hourly mean variations of PM₂.₅, PM₁₀, NO₂, SO₂ and CO in each season (Summer: March, April and May, Rainy: June, July, August and September, Autumn: October and November, Winter: December, January and February) during March 2018 - February 2019 at the present location were measured.

RESULTS AND DISCUSSION

The annual mean PM₂.₅, PM₁₀ and the gaseous pollutants NO₂, SO₂ and CO concentrations in Visakhapatnam are 103.5±14.4, 49.3±8.6, 29.1±111.5, 55.1±3 and 35.7±8 μg/m³, respectively for the year 2018-2019. Both PM₂.₅ and PM₁₀ levels have exceeded the annual mean limit, posing a high health risk (Balakrishnan et al. 2013, CPCB 2009). Based on the annual average values, the worse air quality may be attributable to some specific feature of local/regional emission sources mixed with meteorological influences. The mean values of concentrations of PMs and air pollutants for different seasons are listed in Table 1.

Seasonal Variations

The hourly data were used to examine diurnal variability of PM₂.₅ and PM₁₀ concentrations and major air pollutants in each season. The seasonal variability of PM₂.₅ (Fig. 1) and PM₁₀ (Fig. 2) is lowest in summer and highest in winter. The higher concentrations of PM₂.₅ and PM₁₀ were observed during winter (178.5, 150.7 μg/m³ respectively) and autumn (111.05, 115.6 μg/m³ respectively) than summer and rainy seasons (Latha & Badarinath 2005). The PM concentrations are high during daytime than night time. The peak value was observed at 11:00 a.m. and falls to lowest in afternoon hours at 1:00 p.m. It is evident from NO₂ (Fig. 3) observations, that the increase in PM after 4:00 p.m. and before 11:00 a.m. is because of vehicle emissions as a result of transportation in rush hours. The heavy-duty vehicle traffic is more during the morning and night hours. As traffic-related emissions are less from 12:00 p.m. to 3:00 p.m., there is a significant decrease in NO₂ and PM concentrations in all seasons. The emissions from heavy-duty vehicles are more than those of light weight vehicles. The decreasing boundary layer heights also contribute to an increase in PM concentrations after 4:00 p.m. In all the seasons during night time, the high PM₂.₅ levels

| Table 1: Mean values of PMs and gaseous pollutants for different seasons in Visakhapatnam. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                 | Summer          | Rainy           | Winter          | Autumn          | Annual Mean     |
| PM₂.₅           | 58.24±10        | 66.46±6.2       | 178.57±41.8     | 111.05±22.5     | 103.58±55.1     |
| PM₁₀            | 84.74±10.8      | 95.10±5.8       | 150.77±37.8     | 115.68±20.9     | 111.57±29.1     |
| NO₂             | 42.37±10.7      | 49.49±9.29      | 61.48±25.8      | 43.97±15.3      | 49.33±8.6       |
| SO₂             | 16.74±8.19      | 12.96±2.07      | 17.23±6.2       | 10.78±2.5       | 14.43±3         |
| CO              | 28.79±9.5       | 32.84±8.8       | 46.98±11.2      | 33.75±5.16      | 35.59±7.9       |
CONCENTRATIONS OF PM$_{2.5}$ AND PM$_{10}$ DURING THE FOUR SEASONS

are due to accumulation of emissions from automobiles and secondary PM formation.

The variation pattern of SO$_2$ (Fig. 4) is similar in different seasons and exhibited unique high SO$_2$ levels in summer. During summer, the major contributing factors for SO$_2$ may be coal stocked in Port and used in thermal power plant and other industries and vehicle exhaust. It is well known that wind flows from south-west direction during summer and rainy seasons where all the industries are located while the airflow is from northeast direction during the remaining part of the year. The wind direction could be obstructing the pollutants to go into the atmosphere during winter.

The variations in CO concentrations (Fig. 5) peaks during morning and evening traffic hours and valley in afternoon shows a clear link to the boundary layer height evolution.

**Pearson Correlation Coefficients**

Correlation method is used to gauge the extent and nature of the relationship between each of the impacting (independent) variables considered in the present study and PM levels. The results are presented in Table 2. The Pearson correlation coefficients between PMs and NO$_2$ and SO$_2$, as observed (Table 2) were either high or moderate in different seasons (PM$_{2.5}$ with NO$_2$: $r = 0.89 - 0.59$; PM$_{10}$ with NO$_2$: $r = 0.89 - 0.79$; PM$_{2.5}$ with SO$_2$: $r = 0.85 - 0.47$; PM$_{10}$ with SO$_2$: $r = 0.39 - 0.79$, PM$_{2.5}$ with CO: $r = 0.71 - 0.43$; PM$_{10}$ with CO: $r = 0.70 - 0.33$). The correlation between PM$_{2.5}$ and CO is higher than the correlation between PM$_{10}$ and CO.

It may be observed that all the three independent variables exhibited the theoretically expected positive relationship with PM levels indicating that NO$_2$, SO$_2$ and CO contribute
to the pollution levels recorded in Visakhapatnam city. The positive impact is visible through all the four seasons of the year. It could be further observed that the magnitude of the correlation coefficients varies across variables and seasons. In the summer season, all the three variables recorded high correlation with PM$_{2.5}$ and PM$_{10}$ levels excepting CO on PM$_{2.5}$ with moderate correlation. During rainy season NO$_2$ recorded high correlation while SO$_2$ and CO exhibited weak to moderate correlation. All the variables evinced a high correlation with PM$_{2.5}$ and PM$_{10}$ levels in the winter season. In autumn NO$_2$ and SO$_2$ registered high correlation while CO recorded weak correlation with PM levels. All the coefficients are statistically significant across all the variables and seasons. It may be concluded that the three variables considered in the study are significantly correlated with PM levels with varied magnitude across seasons and even variables.

The exact magnitude of the impact of each of the independent variable on pollution levels could be further discerned through the following equation.

$$ Y = a + bX_1 + cX_2 + dX_3 + U \quad \text{ ...(1)} $$

Where $Y = \text{PM}_{2.5}$ and $\text{PM}_{10}$ levels taken independently, $X_1 = \text{NO}_2$ mean levels, $X_2 = \text{SO}_2$ mean levels, $X_3 = \text{CO}$ mean levels, $U = \text{error term}$ and $a$, $b$ and $c$ are the estimated coefficients of the three independent variables.

The variables are theoretically expected to possess a linear relationship with PM levels and hence multiple linear regression method is adopted to estimate the coefficient values of the variables.

The regression results are presented in Tables 3-6 by season. It could be discerned (Table 3) that the considered variables explained 79 per cent of the variation in PM$_{2.5}$ level in summer season in Visakhapatnam city as observed from adjusted $r^2$. Both NO$_2$ and SO$_2$ registered expected signs. The coefficients of both NO$_2$ and SO$_2$ are significant at 5 and 1 per cent respectively. Further, one unit change in NO$_2$ is likely to cause 0.43 unit change in PM$_{2.5}$. Similarly, a unit change in SO$_2$ may impact PM$_{2.5}$ by 0.74 units. It may, therefore, be inferred that NO$_2$ and SO$_2$ significantly impact PM$_{2.5}$ during the summer season in Visakhapatnam city.

It is evident from Table 3 that the influence of the considered variables on PM$_{10}$ for the same season. The results show

<table>
<thead>
<tr>
<th>Pollutants</th>
<th>Summer</th>
<th>Rainy</th>
<th>Winter</th>
<th>Autumn</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO$_2$</td>
<td>0.767</td>
<td>0.889</td>
<td>0.793</td>
<td>0.891</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.804</td>
</tr>
<tr>
<td>SO$_2$</td>
<td>0.855</td>
<td>0.750</td>
<td>0.396</td>
<td>0.719</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.789</td>
</tr>
<tr>
<td>CO</td>
<td>0.429</td>
<td>0.701</td>
<td>0.347</td>
<td>0.638</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.337</td>
</tr>
</tbody>
</table>

Fig. 3: Diurnal variations of hourly NO$_2$ concentrations.
that adjusted is 0.83 explaining 83 per cent of the variation in PM\(_{10}\) by the considered variables. All the coefficients bear expected signs, however, NO\(_2\) and SO\(_2\) turned out to be significantly determining PM\(_{10}\) levels in the city. A unit change in NO\(_2\) causes 0.55 unit change in PM\(_{10}\); In the case of SO\(_2\) one unit change in SO\(_2\) leads to 0.40 unit change in PM\(_{10}\) level. Hence even in the case of PM\(_{10}\) only NO\(_2\) and SO\(_2\) are significant factors contributing to PM\(_{10}\) levels in summer in Visakhapatnam city.

Turning to the rainy season, as observed (Table 4), is low explaining 29 per cent of the variation in PM\(_{2.5}\) level. Of the variables, none is significant as impacting PM\(_{2.5}\). However, all the variables have only a tendency to determine PM\(_{2.5}\) positively. When it comes to PM\(_{10}\) the is high (0.65) and NO\(_2\) and CO are significant causative factors. Unexpectedly, CO impacts PM\(_{10}\) negatively albeit the magnitude of the variable is low (0.27). SO\(_2\) is not a significant determinant of PM\(_{10}\). Hence, NO\(_2\) is the only factor contributing to PM\(_{10}\) levels in rainy season in Visakhapatnam city.

For winter (Table 5), high for both PM\(_{2.5}\) and PM\(_{10}\) indicate that the considered variables could explain 94 per cent and 91 per cent of variation respectively in pollution levels. All the variables registered expected signs and significant at the 1 per cent level.

The magnitudes of coefficients of both NO\(_2\) and SO\(_2\) are high indicating that one unit change in them impact PM\(_{2.5}\) and PM\(_{10}\) by more than twice. However, CO is significantly contributing negatively to both PM\(_{2.5}\) and PM\(_{10}\). The negative sign could be due to a high correlation between NO\(_2\) and CO resulting in the biased estimate of CO.

In autumn (Table 6), PM\(_{2.5}\) is significantly impacted by all three variables. So is the case with PM\(_{10}\). values are high. NO\(_2\) and SO\(_2\) are significant, so is CO but the sign is negative. It may be inferred that NO\(_2\) and SO\(_2\) are significant factors impacting both PM\(_{2.5}\) and PM\(_{10}\) levels.

**CONCLUSIONS**

It is observed that the annual averaged PMs exceeded the WHO standards (10μg/m\(^3\)) in all seasons. The PM concen-
The variations in CO concentrations (Fig. 5) peaks during morning and evening traffic hours and valley in afternoon shows a clear link to the boundary layer height evolution.

Table 6: Regression analysis results for the autumn season.

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>Intercept</th>
<th>Independent variable</th>
<th>$\overline{R^2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM$_{2.5}$</td>
<td>62.21</td>
<td>$1.36^*$</td>
<td>2.48**</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(7.66)</td>
<td>(2.95)</td>
</tr>
<tr>
<td>PM$_{10}$</td>
<td>82.77</td>
<td>$1.11^*$</td>
<td>3.53**</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(5.59)</td>
<td>(3.76)</td>
</tr>
</tbody>
</table>

Note: Figures in brackets are ‘t’ values; *significant at 1% level, ** significant at 5% level
ACKNOWLEDGEMENTS

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