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Recent trends in tropospheric NO_2 over India observed by SCIAMACHY: Identification of hot spots

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ABSTRACT

Satellite remote sensing technology has a great potential to measure the properties of atmosphere and has shown marked advancements through the last decade, in monitoring nitrogen oxide species (NO_X) in troposphere. NO_2 in troposphere is one of the key factors which determine the air quality and has serious implications on human health and plant growth. It is also well known for its indirect contribution to climate change. The identification of spatial and temporal variations of NO_2 is necessary for any effective mitigation plan to curb its obnoxious abundance. Tropospheric NO_2 measurements provided by the satellite remote sensor "SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY" (SCIAMACHY) are utilized here to identify the regions across India where a concentration of NO_2 exceeds the permissible healthy level. A new approach based on empirical approximation is attempted to normalize the unit of satellite measurement with the unit of existing air quality standard. Trend analysis for all the regions are carried out by means of a non–linear regression method. The geospatial and statistical analysis of monthly tropospheric NO_2 data from the full operational period of SCIAMACHY (2002 August–2012 March) have resulted in the identification of 12 hot spot regions across India among which most of them exhibited a significant increasing trend. Some of the rural districts which were not previously implicated for NO_2 pollution risk are also recognized here. This study illustrates the possibility of the use of satellite measurements in air quality monitoring and management in regional spatial scale. The effects of seasonal climatic changes in India on the ambient NO_2 pollution level are also explained.

Keywords: *Air pollution in India, air quality, industrial emission, remote sensing of NO_2*

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1. Introduction

"The atmosphere is as intimate and personal as a breath of air". Quality of air and quality of life are inseparably interrelated. The technological developments and the rapid economic growth in India ensued in an increase of the vehicular and industrial emissions over the past two decades. Apart from rapid industrialization, urbanization has resulted in the emergence of industrial centers without corresponding growth in civic amenities and pollution control measures. Air quality monitoring carried out by the Central Pollution Control Board (CPCB) under the National Air Quality Monitoring Programme (NAMP) found some of the worst forms of air pollution in Indian cities (CPCB, 2010). Urban air pollution costs India almost US $ 1.3 billion a year (Nagdeve, 2002).

Recent studies shows that, among various air pollutants NO_X is a major concern over the last few years in India as the other pollutants like SO_2 and Pb are being well tackled by various emission control norms and policies (Mohan, 2010; CES, 2011). NO_2 in troposphere is one of the key factors which determine the air quality and has serious implications on human health and plant growth (Jeffrey et al., 2009; U.S. EPA, 2010; WHO, 2011). Photochemical smog, acid rain and nitrate aerosol are the detrimental effects associated with higher level of NO_2 concentration. It is also well known for its indirect contribution to climate change by producing tropospheric ozone which affects the global greenhouse gas budget through their effect on the atmosphere and abundance of OH radicals (Kleinman, 1994; Bovensmann et al., 1999; Khlystova et al., 2009).

A detailed inventory carried out by Garg et al. (2001) revealed, the various emission sources of NO_2 in India belong to industrial (50%), transportation (32%) and biomass burning sectors (10–20%). Total NO_2 emissions only from power plants is estimated to be 0.5 Gg per day and 0.185 Tg per year and is on a steep increasing trend to ensure the additional power demand (~100 000 MW) in India by the year 2012 (Motti and Sharma, 2001). Moreover due to the growing population, increasing urbanization and high energy consumption rate, the emissions from large emission point sources (LPS) are growing much faster than the national average.

It is necessary to identify the spatial and temporal variations of NO_2 for the effective mitigation of the ill effects caused by its obnoxious abundance. However in the large continental area like India the available ground level observations are insufficient for the proper reflection of the actual air quality and pollution dispersion. Large disparities exist in the geographical distribution of ground measurement stations, as many of them are situated in the city regions compared to the limited number of stations in rural area (CPCB and MOEF, 2011). The alternate method of satellite retrieval provides the best coverage across the nation uniformly in a comparable temporal frequencies (daily or once in few days). But its incapability (in current scenario) for addressing details in the finer spatial or temporal scale (i.e., local and diurnal changes) restricts its use only to track long–term variations in the atmosphere over a large region. For fine scale investigation ground measurements are the only reliable option.

Satellite data can aid in the detection, tracking and understanding of pollutant transport by providing observations over large spatial domains (Bogumil et al., 2003; Richter et al., 2005; Kim et al., 2006; Martin, 2008; Ghude et al., 2009) and vertical profiling (Rozanov et al., 2005). Satellites can be the only data source in rural and remote areas where there are no ground–based measurements. Individual satellite observations are mean values over an area of typically 10 to 50 km square (depends on the spatial resolution of the satellite), and are representative for this area. This in contrast to surface measurements of short–lived species like NO/NO_2, which can be influenced by very local factors (a single nearby road, a factory, etc.) give a better spatial average estimate. Satellites typically measure a tropospheric column, which is related to the total amount/mass of air pollution in the atmosphere. This has a more direct relation with the amount of pollution released at the surface (emissions) than the concentrations measured with the surface network (Veefkind et. al., 2007).

Since NO_2 measurements are the most matured tropospheric satellite product, the data from Global Ozone Monitoring Experiment (GOME I & II) and SCIAMACHY (SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY) have been well explored by many researchers to address various problems starting from emission source inventory and global spatial distribution to temporal trend analysis and surface air quality (Leue et al., 2001; Richter and Burrows, 2002; He et al., 2007; Shi et al., 2008; Cheng et al., 2012; Meena et al., 2013).

In this context, with growing emissions in India, it is appropriate to identify the areas where the concentration of NO_2 exceeds a healthy level (approximate maximum permissible level) by making use of available satellite measurements. Since the existing air quality standards are decided on the basis of ground station measurements and there is no such established standard for the new space based remote sensing platform, here we used an approximation of maximum permissible level value (explained in Section 2.2) which represents the ambient air quality standard for NO_2 prescribed by Central Pollution Control Board of India (CPCB, 2009). The major objectives of this study are (i) to identify the regions across India where NO_2 concentration exceeds a maximum permissible level, using SCIAMACHY data and (ii) to find out the existing trend in each such identified regions using a non–linear regression curve fitting method. Analysis of the variations of NO_2 concentrations with respect to seasonal climatic changes is described in the Supporting Material (SM).

2. Materials and Methods

2.1. Tropospheric NO_2 from SCIAMACHY

The datasets used in this study (SCIAMACHY Tropospheric NO_2, version 2.0, 2002–2012) are downloaded from TEMIS (Tropospheric Emission Monitoring Internet Service) website. The details of the algorithm used for the NO_2 retrieval can be found in Eskes and Boersma (2003), van der A and Eskes (2006).

Comparison of the SCIAMACHY columns with measurements from the German DOAS and FTS (Fourier Transform Spectrometer) validation network shows very good agreement with the exception of high latitudes in summer, where a systematic underestimation is apparent in polluted sites, where the difference in sensitivity of the measurement systems to tropospheric absorptions plays a role (Lambert et. al. 2004; Richter et al., 2004; Heue et al., 2005). SCIAMACHY NO_2 Vertical Column Densities (VCDs) have also been validated by comparing with airborne in situ measurements in eastern North America (Martin et al., 2006) and Northern Italy (Petritoli et al., 2004). The detailed mapping of the trend and seasonal changes of tropospheric NO_2 over China with GOME and SCIAMACHY is found to be successful in differentiating the regions of higher surface emissions and proved in comparison with the ground truth estimation (van der A et al., 2006; Cheng et al., 2012). The studies which have been conducted in India at Delhi and Pune to compare the satellite derived measurements with ground level spectroscopic observations (IR analyzer NO_X) showed a good agreement and proved the efficiency of satellite method to detect the seasonal variations occurred at the surface level (Ghude et al., 2008).

2.2. Methodology

Identification of hot spots. Global data set of monthly mean tropospheric NO_2 column (ESRI Grid format) for the period 2002 August to 2012 March from SCIAMACHY sensor are served as the database for this study. The geographical region of Indian sub–continent is extracted with a georeferenced vector layer of Indian boundary. A classification rule is applied to segregate the annual mean pixel values which are above the limiting value (approximately equal to CPCB Annual standard of NO_2 for ecologically sensitive areas, 30 $\mu g/m^3$). In the same way, the annual pixel means greater than or equal to 40 $\mu g/m^3$ (CPCB annual standard 40 $\mu g/m^3$ prescribed for industrial and rural areas) are also identified. Here 30 $\mu g/m^3$ is used as a judging rule for the identification of hot spots as it represents all possible threats of NO_2 pollution.

A conversion formula is applied to convert the unit of CPCB standard ($\mu g/m^3$) to its equivalent in satellite measurement unit (molecules/cm^2). The definition of molar mass is used for converting microgram (μg) to number of molecules, [i.e. One Molar mass of NO_2 (46.0055 g) contains Avogadro number (6.023×10^{23}) of molecules]. To find the number of molecules in unit volume (cm^2 to cm^3) a hypothetical condition is assumed in which each measurement corresponds to a height (100 m) of the planetary boundary layer and within which NO_2 molecules are mixed homogeneously. The height of 100 m is an estimated height from the comparison of surface measured values of NO_2 (mean) from eleven CPCB stations located at Delhi and the SCIAMACHY pixels overlaying the same geographical region.

Even though the data represents the total tropospheric column density (height ~10–13 km), most of the NO_2 molecules are occupied in the boundary layer (up to 1–2 km), with a rapid drop–off at higher altitudes (Boersma et al., 2009) and with a lesser life time which is in the order of hours (Liang et al., 1998). Drop off is particularly sharp for NO_2 because of the decrease of the NO_2/NO ratio with decreasing temperature (Martin et al., 2004). It is also reported that on an average a <8% free tropospheric contribution to the tropospheric column in summer and <2% in winter, small enough to be neglected (Boersma et al., 2009). Considering these facts and the tropical meteorological condition of Indian atmosphere owing more sunlight and high humidity [as reported by Beirle et al. (2003), the average lifetime of NO_X in the boundary layer depends on meteorological conditions, photolysis, and length of night, temperature, OH and H_2O concentrations], the assumption of 100 m will introduce minimum errors. A possibility to make use of satellite data for air quality management, seen by European legislation considers ±25% uncertainty as acceptable in lower and upper threshold values of NO_2 (Dentener and Borowiak, 2006; Veefkind et al., 2007). It is to be noted that both the measurement techniques are entirely different and the specified national air quality standard is based on the surface measurements. The establishment of new standards for monitoring air quality from space platforms is necessary to harness the advantage of this promising technology in controlling air pollution and may be expected to arise in the near future.

For initiating any effective action plans of air quality management at administrative level, it is better to attach hot spot regions with any existing administrative boundary. The district level boundaries have been chosen here in consideration with the spatial resolution (0.25°~30 km) of the data. The districts whose at least 50% or more area is covered under the annual mean pixels which are above the limiting value ($>393\times10^{13}$ molecules/cm^2 ~30 µg/m^3) are identified as hot spots. Considering the proximity of neighboring hotspot districts, they are clustered together for the convenience of the analysis, and categorized the cluster of districts as "hot spot regions" (Figure 1, see the SM, Table S1). The frequency of occurrences of >30 µg/m^3 ($>393\times10^{13}$ molecules/cm^2) and >40 µg/m^3 ($>524\times10^{13}$ molecules/cm^2) conditions in each hotspot districts are also ascertained and reported (see the SM, Table S2).

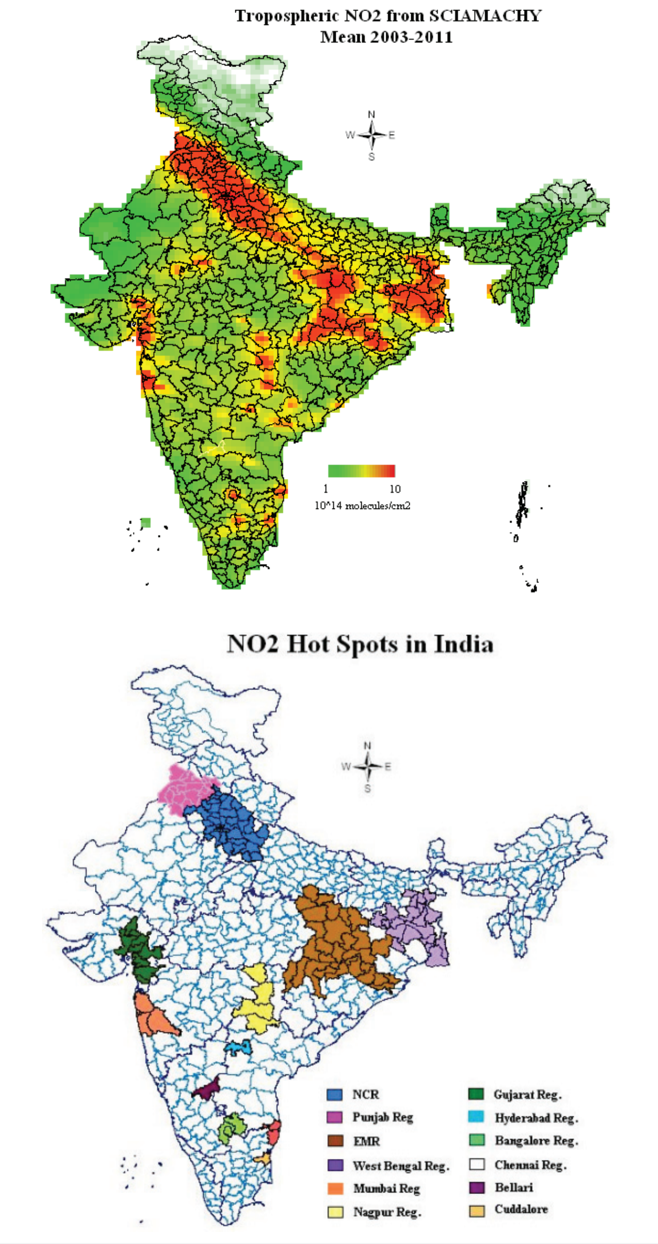

Figure 1. *Tropospheric NO_2 vertical column density from SCIAMACHY (mean 2003-2011) and identified hot spot regions in district level boundary map.*

Trend analysis. The monthly values of NO_2 confined to each of the above identified hot spot regions are analyzed to find out their trend. A non–linear regression model suggested by van der A et al. (2006, 2008) and used by many others (Zhang et al., 2007; Ghude et al., 2008; Sheel et al., 2010) is employed here to estimate the trend value. The monthly values of NO_2 are found seasonally dependant and this model accounts for the seasonal component as well as the annual component.

$$Y_t = A + (1/12)\, B\, X_t + C\, \mathrm{Sin}(\omega X_t + \Phi) + R_t \qquad (1)$$

Here Y_t represents the monthly mean NO_2 column of month t, X_t is the number of months after August 2002 (starting month), R_t is the remainder (residual unexplained by the fit function) and A, B, C and Φ are the fit parameters. Parameter A is a constant resulting from the fit, and B is the annual trend of NO_2 concentration. The seasonal component contains an amplitude C, a frequency ω and a phase shift Φ. The frequency ω was fixed to a period of one year (i.e., $2\Pi/12$), since this was the minimum periodicity found in the observations. This model is fitted by least square method for the analysis. A linear trend B is taken as statistically significant with 95% confidence level if $|B/\sigma B|>2$, where σB is the uncertainty in B.

3. Results and Discussion

3.1. Identification of hot spots

National level NO_2 emission inventories are conducted by various agencies (Garg et al., 2001; Motti and Sharma, 2001) in India previously, for the identification of emission hot spots, which are based on the estimation of emissions from energy consumption details. But they fail to reflect the exact dispersion of released pollutants in the atmosphere and hence it is impossible to get an idea about the location of the most affected place. The wide coverage and holistic nature of the satellite remote sensing method provides the unique advantage to identify the imaginary boundaries up to which the air pollutants disperse and exist in higher concentration more frequently. It is possible to spot out the most affected districts, which would have been not otherwise possible with conventional ground measurements network. A district level assessment of the NO_2 pollution status followed by the initiatives and planning to curb the level in affected region may be an advantage for the public health and environmental sustainability. Moreover, districts in India have well established administrative and institutional mechanisms that would be useful for implementing mitigation measures.

In this study twelve hot spot regions are identified and named under the state or main city. National Capital Region (NCR) and Eastern Mining Region (EMR) are the big clusters of districts from various states. Details of all the hot spot regions are identified and portrayed in Figure 1 (list of districts are available in Table S1 in the SM).

Most of the industrial and urban areas across the country, along with neighboring districts are listed under this hot spot region category. These are in agreement with the ground based NO_2 emission inventories reported by others (Garg et al., 2001; Sahu et al., 2012). From Figure 1, it is observed that the numbers of districts which are surrounded the main cities or industrial pockets are more in the northern part. This can be explained by the higher rate of emissions of NO_2 from the closely located industrial areas, power plants and heavy traffic network and its dispersion to the nearby areas. The geographical extent and magnitude of the effects of NO_X (NO_X=NO+NO_2) and its oxidation products depend on its lifetime in the atmosphere (Neuman et al., 2006). The regional atmospheric conditions in these areas, owing to the dry nature (low humidity compared to the southern peninsula), enhances the atmospheric life time of NO_2 and hence facilitates dispersion to the adjacent districts.

The pollutant dispersion extends up to some of the rural neighboring districts (i.e., Rewari, Panchkula, Kaithal, Muzaffarnagar, Saharanpur etc.) in the NCR and indicates the air quality threats to the rural regions which are not previously concerned. The sources of emissions in NCR are the heavy traffic network and dense industrial clusters and Large emission Point Sources (LPS) including thermal power plants, fossil fuel extraction plants and industries of steel, cement, sugar, and paper as reported by Ghude et al. (2008).

The Punjab region covers all the districts in Punjab except the two districts (Gurdaspur and Hoshiarpur) irrespective of the distribution of LPS and traffic volume in each district. The EMR includes the districts from the five neighboring states. Most of the mining processes and associated industries exist along with many of the major power plants and refineries in this region and cause (Garg et al., 2001; Lu and Streets, 2012; Sahu et al., 2012) high emissions and spread of NO_2 to the nearby districts. The districts like Kaushambi, Palamu, Jashpur show higher pollution levels, even though their emissions are less. West Bengal region located at the east coast of India also include rural areas like Barddhaman, Puruliya, Bankura which clearly indicates the spread of NO_2 over these rural regions.

In South India it is observed that the hot spots are not as wide as in the northern part. It coincide with the main industrial and urban cities and included a very few neighboring districts. High humidity level and the presence of continuous land and sea breezes in the coastal area helps to reduce the life time of the pollutant in the atmosphere from days to hours and hence its spread is reduced over a large area. Also the distribution of LPS are found not much closer in south India compared to the close proximity and coexistence of various industries and power plants in North India (Garg et al., 2001; Ghude et al., 2008; Sahu et al., 2012; Lu and Streets, 2012).

The Mumbai and Pune are well known emission hot spots addressed in many previous studies (Ghude et al., 2008; CPCB, 2010) but the NO_2 air quality risk at the neighboring districts Raigarh and Thane are less discussed. Higher NO_X emissions from these regions are also reported by Garg et al. (2001), but their severity in concern with the permissible limit is not addressed before. A spread of NO_2 up to a few kilometers over the Arabian Sea in the Mumbai coast is also observed. The emission from ships as well as dispersed pollutant from land contribute to this high pollution level over the sea and which may lead to a possible ocean acidification or impact the marine ecosystem, which has to be explored for a better understanding.

The other districts in which permissible healthy level of NO_2 exceeded are Bellari , Cuddalore (which are the emerging industrial centers) Karimnagar and Adilabad (in Nagpur region). The NO_2 related health risks and the need of NO_2 pollution reduction in these districts were not recognized before. The frequencies of annual concentration exceeding the permissible levels of NO_2 [i.e., more than 30 $\mu g/m^3$ (>393×10^{13} molecules/cm^2) and more than 40 $\mu g/m^3$ (>524×10^{13} molecules/cm^2)] in all districts are reported in Table S2 (see the SM). It can be considered as an index of NO_2 air pollution status of these districts during 2003–2011 period.

3.2. Regional trend

The trend of NO_2 concentration at each hot spot region (identified above) for a period of 2002 August to 2012 March (complete operational period of SCIAMACHY) is estimated using the model described in Equation (1). This indicates the pace of increase in pollution level. The monthly mean NO_2 concentration values for all the twelve regions are fitted with this non–linear regression model by applying least square method. The plotted graphs are listed below in Figure 2. In these plots, fit–1 represents the simulated line with both seasonal and annual components of the model and fit–2 is with only annual component. The observed annual trend values for all the regions and its significance in 95% confidence level are listed in Table 1.

Increasing trends in NO_2 concentrations are observed in all regions, among which nine regions (NCR, Punjab Reg., EMR, Mumbai Reg., Nagpur Reg., Hyderabad Reg., Bangalore Reg., Chennai Reg., Bellari) are found with significant trend ($|B/\sigma B|>2$)) and other three (West Bengal Reg., Gujarat Reg., Cuddalore) with not significant ($|B/\sigma B|<2$)) trend values. Highest significant increasing trend is observed at EMR (7.27±1.27x10^{14} molecules/cm^2/year) followed by NCR (3.24±1.22x10^{14} molecules/cm^2/year) and Punjab Reg. (3.14±0.58x10^{14} molecules/cm^2/year). The trend in EMR accounts for the cumulative emissions from all the industrial and urban districts in that region as listed in Table1.

The increased energy consumption (petroleum and coal) from the industrial sectors and added capacity of power plant production contributed to enhance the level of NO_2 in EMR during this period. The contribution from transport sector is considerably hiked with the increased number of vehicles plying in this region (MORTH, 2011). Most of the districts with high NO_X emission (Garg et al., 2001; Lu and Streets, 2012; Sahu et al., 2012) in the country are falling under this hot spot region. To assess the status of pollution level, trend value to be compared with annual average concentration of starting month, and it is highest in EMR (108.36x10^{14} molecules/cm^2/year).

In NCR, the major cause of the higher trend can be attributed to industries including power pants holding a share more than 75% of NO_2 emissions and the vehicle exhaust accounting for more than 20% (CPCB, 2010). Even though the industries in Delhi region are re–located as per Supreme Court directives; the emission from transport sector continued to rise because of this higher vehicular population. Among all the metropolitan regions in India the highest number of vehicles registered (total number of vehicles registered in 2005 and 2009 are 41.86 and 63.02 million, respectively) in the national capital region during the study period and this exceeds the combined vehicle population reported for Chennai, Kolkata and Mumbai (MORTH, 2011).

A significant increasing trend in district Bellari bears the next higher trend value (2.22±0.67x10^{14} molecules/cm^2/year) owing to the increasing industrial and mining activities in this region. The tropospheric NO_2 level in Bellari (2003 annual mean 22.57x10^{14} molecules/cm^2) is lower compared to other metropolitan cities and industrial areas but this has been almost doubled (42.6x10^{14} molecules/cm^2) during this study period and hence showing a higher trend value. There is an increasing trend observed in West Bengal Region (2.14±0.67x10^{14} molecules/cm^2/year) owing to the growth of urban and industrial emission, but the trend is found not significant.

Hyderabad, Chennai, Bangalore, and Mumbai regions exhibited similar trends in NO_2 pollution level, even though the shares of contribution from various sectors differ in each region. Transport sector accounts for more than 60% of total city emission in Hyderabad, 68% in Chennai, and 67.3% in Bangalore. The statistics shows about 87% of increase in number of vehicles in Hyderabad, and 35% in both Chennai and Bangalore in 2009 compared to 2005 vehicular population (MORTH, 2011). In Mumbai region more than 80% of total NO_2 emissions from Mumbai City come from industrial sector and other fugitive emissions, and 95% of Pune city emission from vehicles (CPCB, 2010).

A significant rising trend is observed in Nagpur region (1.00±0.41x10^{14} molecules/cm^2) which is consistent with the enhanced capacity of thermal power plants amounting high coal consumption and economic development during this period (CEA, 2011). The emission of NO_2 is found increasing in Gujarat region but however the trend is not significant. The Cuddalore in Tamilnadu is also exhibited no significant increasing trend. Even though all South Indian hot spot regions showed an increasing annual trend, the trend values are smaller than North Indian regions of comparable economic growth. The hotter and humid atmosphere of South India enhances the photolysis of NO_2 and results in the low NO_2 amounts in the atmosphere.

By comparing the mean concentration of NO_2 for the whole period (2003–2011) the level of pollution in all the regions can be indexed. The order of hot spot regions in terms of descending pollution level is observed as EMR , NCR, West Bengal, Mumbai, Punjab, Nagpur, Gujarat, Chennai, Cuddalore, Hyderabad, Bangalore regions and Bellari, respectively.

Table 1. *Annual trend in 95% significance level and growth rate with respect to starting year 2003, for the hot spot regions*

Sl.No	Name of the hot spot region	2003 annual average NO_2 (10^{14} molecules/cm^2)	Annual trend in NO_2 (10^{14} molecules/cm^2/year)	Annual growth rate (% growth with respect to 2003)	Significance
1	National Capital Region	94.88	3.24±1.22	3.41±1.28	Yes
2	Punjab Region	51.27	3.14±0.58	6.13±1.13	Yes
3	Eastern Mining Region	108.36	7.27±1.27	6.71±1.17	Yes
4	West Bengal Region	63.47	2.14±1.14	3.37±1.80	No
5	Mumbai Region	58.73	1.36±0.51	2.31±0.88	Yes
6	Nagpur Region	53.43	1.00±0.41	1.87±0.77	Yes
7	Gujarat Region	48.03	0.91±0.89	1.89±1.85	No
8	Hyderabad Region	28.13	1.59±0.70	5.67±2.50	Yes
9	Bangalore Reg.	31.01	1.49±0.37	4.82±1.19	Yes
10	Chennai Region	36.3	1.52±0.43	4.20±1.19	Yes
11	Bellari	22.57	2.22±0.67	9.85±2.97	Yes
12	Cuddalore	43.25	0.57±1.29	1.32±2.97	No

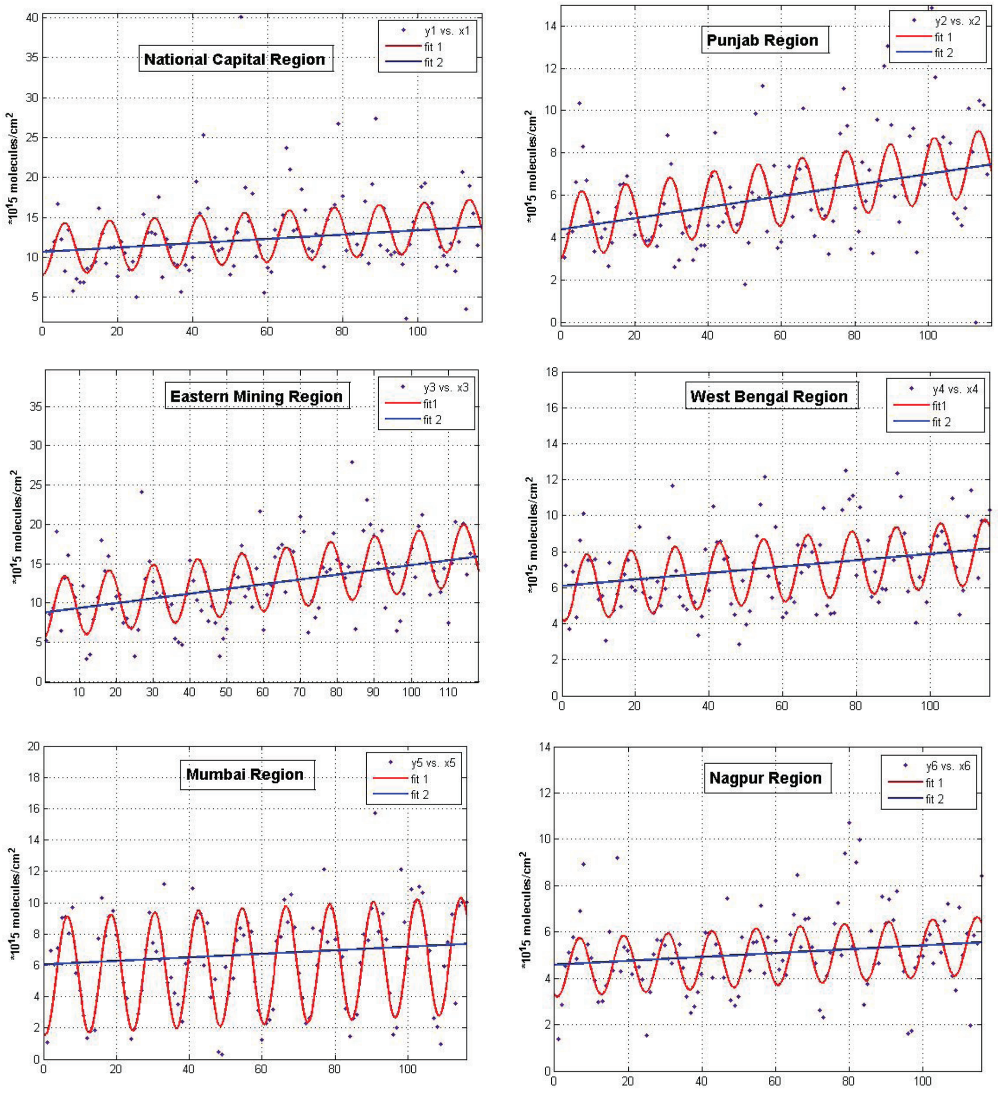

Figure 2. *Graphs showing regional trends in NO_2 concentration-curve fitting plots.*

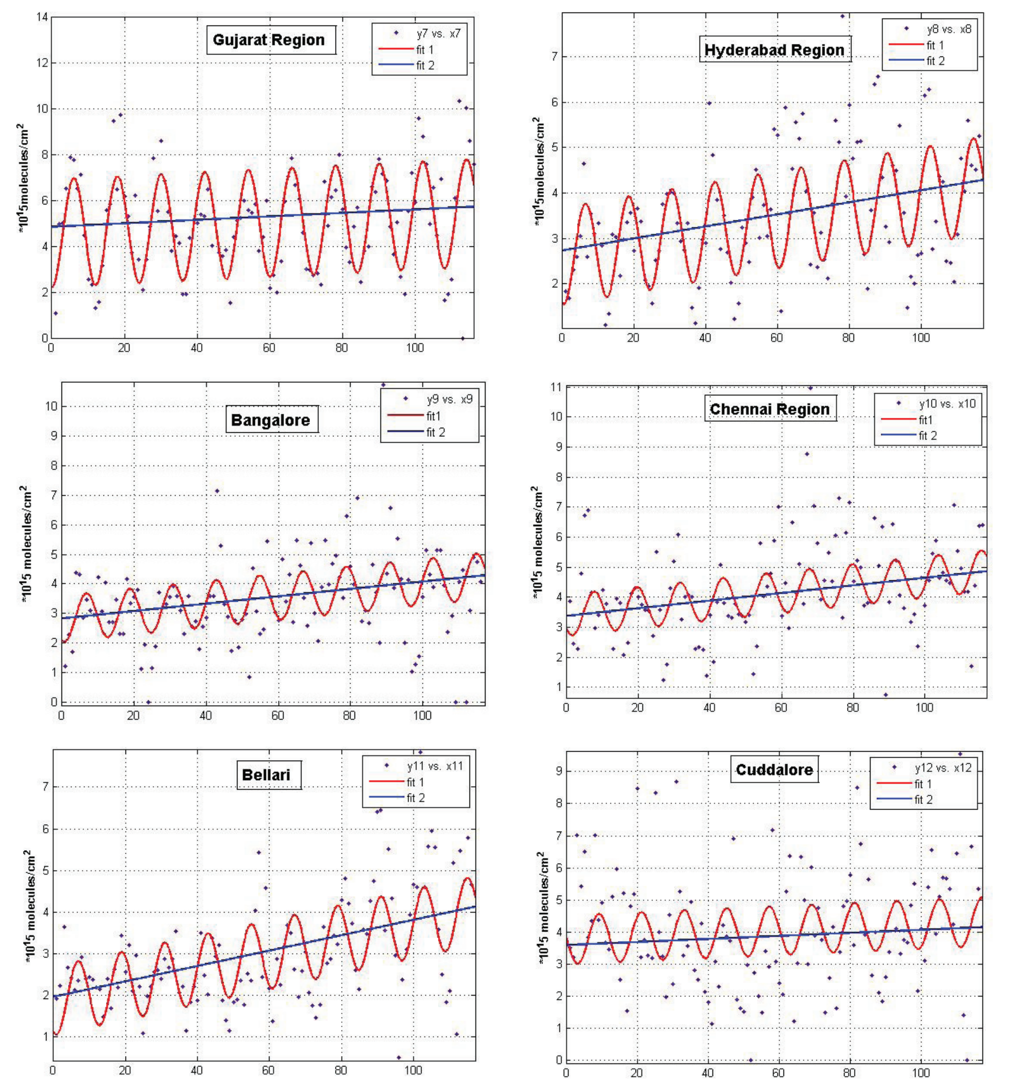

Figure 2. *Continued.*

4. Conclusions

By using a new approach for the use of satellite data in air quality estimation an attempt is made to identify the regions where the NO_2 pollution exceeds the maximum permissible limit in India. There are twelve hot spot regions (total 143 districts) identified across the country. All the districts which exceed the air quality standard of NO_2 prescribed by CPCB for the ecologically sensitive areas as well as industrial, residential, rural and other areas are listed along with the number of times of such occurrences. Thirteen districts including Delhi and Mumbai, have exceeded the NO_2 standard prescribed for industrial areas ($40\ \mu g/m^3$) in all the years from 2003 to 2011, while another nine more districts exceeded standard for ecologically sensitive areas ($30\ \mu g/m^3$). The frequency of exceeding the annual permissible level of NO_2 in these identified districts uncovered the actual air pollution hazard existing in these places.

All the identified hot spot regions except Bellari and Cuddalore, coincide with previously reported regions of high NO_2 emissions which shows the reliability of the new approach. Moreover, this study reveals the severity of the pollution level exist in these regions in a health and ecological point of view. Also it examined the extent of dispersion of NO_2 beyond the city or industrial centers and explored the risk of NO_2 pollution in the surrounding rural areas which were not previously known for the risk. It indicated the need of more pollution monitoring sites over rural regions.

The trend analysis of each region represents the tendency of collective emissions from all the districts come under that particular region and they showed an increasing trend in all the regions. There are some differences in statistics obtained from the previously reported studies, because of the cluster of districts considered here are not the same. But the general trend reported here for various regions are in agreement with the previously published results for the same locations.

Highest trend values and NO_2 concentrations are observed in EMR and NCR are similar to the other studies conducted for these regions. It is observed in the areas where a number of industries and power plants are closely located, the pollution level tend to exceed the permissible level. Hence it can be inferred that the industrial density (more number of emission points situated at shorter distance) is related to the air pollution risk and can be avoided with proper planning of the location of various industries.

This research listed out several districts (Table S1 & S2) which were not previously recognized for the NO_2 air pollution risk and hence unaware of the need of any control measures.

The findings of this research can be a wide guideline, in initiating and planning mitigation measures to avoid any harm to the public health as well as to prevent any environmental/ecological imbalances. This study also establishes the annual increasing trend of NO_2 concentration in the country which should be tackled in the future for a sustainable development.

The capability of satellite data in monitoring the air pollution in India is once again emphasized through this study. It also strongly recommends the need of new air quality guidelines based on space based measurement platforms for avoiding any discrepancy and use of this technology with confidence in country's related policy making. There is also an option for more detailed and fine scale (spatial and temporal) monitoring of air quality by the synergy of space based as well as ground based measurements which may provide an accurate and realistic picture of air pollution events possibly in three dimensions. There is a further scope for studying long–distance transport of nitrogen oxides and its impact on climate using the data provided from the satellites which will be the most reliable and efficient tool to address this problem. Continuous monitoring of air pollution is a necessity of growing world and this study reveals the potential of satellite technology and its applicability for this purpose.

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Supporting Material Available

List of districts with NO_2 level $>393\times10^{13}$ molecules/cm^2 ~30 microgram/m^3 under each hot spot (Table S1), Frequencies of annual NO_2 concentrations exceeding the standards in districts during 2003–2011 (Table S2), Analysis of seasonal variation of tropospheric NO_2 in Indian Subcontinent, Graph showing seasonal variation in tropospheric NO_2 in India (Figure S1), Trend in seasonal average of tropospheric NO_2 in India (Figure S2). This information is available free of charge via Internet at http://www.atmospolres.com.

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