Evaluation of ambient air quality in Dehradun city during 2011–2014

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The variations in the ambient concentrations of particulate matter (SPM and PM₁₀) and gaseous pollutants (SO₂ and NO₂) at Clock tower (CT), Rajpur road (RR) and Inter State Bus Terminal (ISBT) station in Dehradun city, Uttarakhand, India are analysed for the period of 2011–2014. Mean concentrations are observed to be higher during pre-monsoon season as compared to the winter and monsoon. PM₁₀ and SPM concentrations with maximum values of 203 ± 23 and $429 \pm 49 \mu\text{g m}^{-3}$, respectively, during winter, are found to exceed the national standards by factors of 2 and 3. Winter-time elevated pollution in Dehradun is attributed to the lower ventilation coefficient (derived from Era interim model fields) and minimal precipitation. Nevertheless, the SO₂ and NO₂ levels are observed to be within the criteria notified by the Central Pollution Control Board (CPCB), India. Correlation analysis shows profound impacts of the meteorology and local dynamics on the observed variations in observed trace species. Additionally, the stronger inter-species correlation variations ($r = 0.79$ for SO₂ with NO₂, and $r = 0.89$ for PM₁₀ with SPM), which may suggest their origin from common sources. Analysis of ‘Air Quality Index (AQI)’ variations indicates unhealthy atmospheric conditions near the major city centers and bus station. More observations in the region are highly desirable to understand the dispersion of the enhanced pollution in the Dehradun valley.

Keywords. Air pollutants; statistical analysis; meteorological parameters; air quality index.

1. Introduction

Deleterious changes in atmospheric composition due to the introduction of contaminants are referred as the air pollution. The concentration of air pollutants depends not only on the quantities that are emitted from different emission sources but also on the subsequent chemical and dynamical

processes in the atmosphere. In fact, a thick blanket of pollution traps heat around the earth and therefore, plays a significant role in global warming and climate change (Ramanathan and Feng 2009). Presently, air pollution is deteriorating rapidly over much of the globe during past few decades (e.g., Akimoto 2003). Change in the regional vegetation cover, land use and many

developmental activities are increasingly affecting the local air quality as well as the weather patterns. A number of studies have reported the variations in criteria pollutants over mega cities in India (Aneja *et al.* 2001; Gurjar *et al.* 2008). With an increasing level of urban population (Sokhi and Kitwiroon 2008; UN-Habitat 2012), adverse environmental impacts (Wenzel *et al.* 2007; Gurjar *et al.* 2010) pose a serious threat to human health globally (Ravindra *et al.* 2016). Large consumption of fossil and bio-fuels are contributing to the alarming levels of pollutants especially in the megacities (Butler *et al.* 2008; Ravindra *et al.* 2016), and the outflux of the pollutant plumes (Molina and Molina 2004; Kanakidou *et al.* 2011) from the mega cities affects the environment at regional and global scales with associated political and potential socio-economic impacts (Krass 2007; Gurjar *et al.* 2016). In particular, some earlier investigations (Chauhan and Joshi 2008; Chauhan *et al.* 2010), concerning about the regional zone (Dehradun and adjacent locations) realized that transport vehicles and industrial emission are the major sources of air pollutants in this region. These investigations also revealed that the gaseous pollutants in this expanse generally are always well within the Indian air quality standards while the concentration of particulate matter exceeds the criteria (Chauhan and Joshi 2010; Awasthi *et al.* 2016; Deep *et al.* 2017). According to a recent report of World Health Organization (WHO) released in 2016, Dehradun is the 15th most polluted city in India; however, it is 31st most polluted city in the world. The report by WHO is based on the amount of fine particulate matter, i.e., PM_{2.5} present in the air in a particular region. Once considered a green city, the inclusion of Dehradun in the list of the most polluted cities in the world is alarming and is anticipated to affect the air quality and climate in the region.

In order to have a continuous monitoring of air quality in India, the Government of India has enacted the AIR (Prevention and Control of Pollution) Act in 1981 and the Environment (Protection) Act in 1986. The Central Pollution Control Board (CPCB) under the AIR (Prevention and Control of Pollution) Act initiated a national ambient air quality monitoring system in the year 1986 to collect the air pollution data with a wide network of monitoring stations throughout the country (CPCB 2003, 2012, 2015). There is also a national meteorological service in India namely the India Meteorological Department (IMD) which

was established in 1875 to take meteorological observations with an aim to conduct and promote the research in meteorology, seismology and other allied subjects in the country. Since the issues related to air quality, weather and climate, vegetation and human health are closely interrelated therefore, the air pollution data and meteorological data collected by CPCB and IMD, respectively, provide a database for research with diverse scientific objectives. Apart from the influence of local emissions, air pollutants can get transported from sources at distant regions to the Himalayan foothills (e.g., Solanki *et al.* 2013; Sarangi *et al.* 2014; Srivastava *et al.* 2014; Ojha *et al.* 2017). It is usually detected with remote sensing devices such as Lidar, and such events are quite common during summer and forming the elevated layers in the lower troposphere, which finally settles down in the foothill of Himalayas and might contribute to the local sources at occasions, and leading to sudden rise in the levels of particulate pollutants.

In the present paper, we analyze the variations in ambient air quality of Dehradun city in Uttarakhand during 2011 period utilizing CPCB observations and meteorological data from IMD in Dehradun. The organization of this paper is as follows. A brief description of the study sites and local meteorology is presented in sections 2.1 and 2.2. A detailed statistical analysis of air pollutants is performed in section 3 followed by the results and discussion (section 3). A summary and conclusions are presented in the section 4.

2. Material and methodology

2.1 Description of study sites

Dehradun (30°19'N, 78°04'E, 410–600 amsl), the capital city of Uttarakhand state of India, is located in a valley in southwestern part of Uttarakhand. In fact, Himalayas on its north and Shiwalik on the south provides it the shape of a valley. After its inception as the capital city of Uttarakhand, the environmental conditions worsen gradually, mainly due to the increasing number of anthropogenic activities. The major causes of anthropogenic environmental pollution in the city are industrialization, deforestation, urbanization, large-scale construction, unplanned development, rapid population growth, and increasing number of vehicles, etc. As per census 2011, population of Dehradun increased by more than 30% as

Figure 1. Location of the study sites in Dehradun city of Uttarakhand state, India.

compared to that during 2000. In order to study the air quality in Dehradun, we have selected three different sites as shown in figure 1. These three different sites with highest expected pollution levels are Clock tower (CT), Rajpur road (RR) and Inter-State Bus Terminal (ISBT).

2.2 Observations of pollutants and local meteorological parameters

Particulate matter (PM) consists of a mixture of solid and liquid particles suspended in the air (NAAQMS 2009). Suspended particles with aerodynamic diameter of less than $10\text{ }\mu\text{m}$ are commonly known as PM_{10} and particles with diameter less than $2.5\text{ }\mu\text{m}$ are however known as $\text{PM}_{2.5}$ or respirable suspended particulate matter (RSPM). The major gaseous pollutants include sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO) and ozone (O_3). The dominant source of insertion of above mentioned pollutants in the atmosphere is fossil fuels and can be anthropogenic as well as natural. Meteorological conditions also play an important role and further determine the fate of the air pollutants after subsumed into the atmosphere.

The climate of the region is classified under humid sub-tropical type. The summers in Dehradun are moderately hot while the winters are very cold.

The temperature may rise up to about 41°C in summers, though the average temperature remains around $35\text{--}36^\circ\text{C}$. There are about 1–2 days of heat waves when the maximum temperature of a day rises to $4\text{--}6^\circ\text{C}$ above the normal values. Though, the winters are not bitterly cold on most of the days, the temperatures may however fall to $1\text{--}2^\circ\text{C}$ for a few days in winters when the cold winds from the nearby Himalayan mountains makes the winters severe. The winters in Dehradun are also marked by mist and fog on few days especially during nights and early in the mornings. Dehradun is one of the rainiest capital cities of India. Due to altitudinal variations and local topography, the rainfall and temperature variations within the city are quite considerable. Especially during the past two decades, landscape of the city has changed drastically and deforestation at very fast pace changes its microclimate. Figure 2 depicts the observed variations in rainfall (mm), maximum temperature ($^\circ\text{C}$) and relative humidity (%) in Dehradun during the study period. The highest rainfall observed on is in the months of July and August, whereas the highest temperatures are observed in the month of May every year. Humidity during all seasons is almost above 30% and most of the time about 90% during monsoon months.

Figure 3 shows the seasonal variability in the wind speed and wind direction over Dehradun.

Figure 2. Variations in local meteorological parameters at Dehradun: precipitation (mm), temperature (°C) and relative humidity (%) during the study period (i.e., 2011–2014).

Figure 3. Variations in wind speed and direction over Dehradun for different seasons during 2012 and 2013.

Pre-monsoon and monsoon seasons are typically dominated by south westerlies and westerlies, with the magnitude between 0.5 and 3.5 m s^{-1} . However,

a branch of north-easterly ($0.5\text{--}2.5 \text{ ms}^{-1}$) is observed to prevail throughout the year. During pre-monsoon and winter, the transport from west

and north-west could enhance the pollution over to the Himalayan foothills and up to some extent over Dehradun.

2.3 Instrumentation and data analysis

The variations in the ambient concentrations of SO_2 , NO_2 , PM_{10} and SPM in Dehradun as measured by the CPCB for a period of four years 2011–2014 are analyzed. The measurements were carried out at three locations of the city as discussed in section 2.1.

The collection of the data of air pollutants was done with the help of a Respirable Dust Sampler (RDS) Envirotech (460) NL. This dust sampler was used to monitor particulate matter below $10\text{ }\mu\text{m}$ (PM_{10}) under ambient air quality monitoring, based on filtration–gravimetric method using a Whatman filter paper ($20.3 \times 25.4\text{ cm}$). The apparatus was kept at a height of 2 m above the ground level. The concentration of SPM and PM_{10} were determined using high efficiency filter paper method by passing air at high flow rate, which retains the particles. The gaseous pollutants such as sulphur dioxide (SO_2) and nitrogen dioxide (NO_2) were also monitored simultaneously in an attached impinger with the dust sampler. NO_2 and SO_2 were collected by bubbling in a specific absorbing solution (sodium hydroxide for NO_2 and sodium tetra-chloromercuate for SO_2) at an average flow rate of $0.1\text{--}0.5\text{ min}^{-1}$. The collected samples were then placed in iceboxes immediately after sampling and afterwards kept in a refrigerator prior to their analysis. Finally, all the samples were analyzed in the laboratory by CPCB. Modified methods of West and Gaeke (1956) and Jacobs and Hochheiser (1958) were followed for the analysis of different gaseous pollutants. However, there are also errors (instrumental and human) associated with the measurements and the sample analysis. The measurements are performed under the controlled conditions. The dataset of gaseous pollutants was collected four times during each day, while the dataset of particulate matter was acquired thrice in a day. This collection of data was performed from 6 am to 6 pm every day. The meteorological datasets were obtained from IMD (<http://amssdelhi.gov.in/Nigam/MCDDN/>). Using these datasets, in the present study, we have calculated the correlation between different meteorological parameters and the air pollutants. Seasonal cycle of the meteorological variables such as wind speed, mixing

depth, and ventilation coefficient, is generated from ERA-interim reanalysis datasets (<http://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/>) provided by the European Center for Medium Range Weather Forecasts (ECMWF) and utilized to understand the possible association with pollution dynamics over the region.

3. Results and discussion

Available datasets are subjected to statistical analysis and a monthly mean is obtained to understand the seasonal and year-to-year variations in pollutant concentrations in Dehradun as discussed in the sections.

3.1 Temporal variation of the pollutants

The variations in monthly average concentrations of the measured pollutants during 2011–2014 periods are shown in figure 4. The levels of pollutants are found to be minimum, in general, during monsoon months. However, as compared to the period 2011–2013, during 2014 the mean levels are relatively higher. In the year 2014, reductions in NO_2 and SO_2 during monsoon time are smaller, while larger effects were observed in previous three years (2011–2013). Monsoon is basically a variable synoptic scale phenomenon and possesses significant inter-annual variability, hence may contribute to such reductions from one year to the other. Weaker monsoon means, bringing less rain, and thus reducing the scavenging of the pollutants from atmosphere, which may result into the relatively larger concentrations of NO_2 and SO_2 , in the year 2014, as compared to the previous years. SPM and PM_{10} also show similar trends. However, they show maxima during spring and summer for all three sites. Monthly mean values of SO_2 and NO_2 further show a gradual increase from 2011 to 2014. In the year 2011, the highest levels of SO_2 were in the range of $25\text{--}30\text{ }\mu\text{g m}^{-3}$ during winter and summer, whereas the mean values approached $30\text{ }\mu\text{g m}^{-3}$ and remain above $25\text{ }\mu\text{g m}^{-3}$ throughout 2011–2014. The higher levels during winter time are attributed to the lower boundary layer heights confining the pollutants in to a shallower volume during winter. Similarly, the mean concentrations of PM_{10} indicate gradual increase and ranging between 200 and $300\text{ }\mu\text{g m}^{-3}$; however, the highest values are observed in the month of May 2012. For SPM, the highest values ($687\text{ }\mu\text{g m}^{-3}$)

Figure 4. Variations in the monthly average concentrations of SO_2 , NO_2 , PM_{10} and SPM in Dehradun during 2011–2014.

are observed in the month of December 2012. Seasonal variations in wind speed, mixing depth and ventilation coefficient obtained from ECMWF ERA-interim-forecasts are used with 3 hr resolution and shown in figure 5 during the study period. Meteorological field data was obtained with ~ 13 km ($0.125^\circ \times 0.125^\circ$) of interpolation grid. Average mixing depth is seen to be highest during pre-monsoon, while it is lower during the summer monsoon (in August) and winter (in January). Lack of rain combined with lower ventilation is suggested to be driving the observed winter time maxima in Dehradun. Variations in other meteorological parameters as well as in the emissions also contribute to the observed variations (Ojha *et al.* 2012; Dumka *et al.* 2017; Tiwari *et al.* 2017 and references therein).

3.2 Inter-seasonal and inter-annual variability of air pollutants

In order to study the seasonal variations of the pollutants, the analysis at various time scales is carried out based on the prevailing meteorological conditions over the year using standard

classification of IMD. It classifies the meteorological seasons over India as: winter (January–February), pre-monsoon (March–May), southwest monsoon (June–September) and post-monsoon (October–December) (IMD 2015). The seasonal variation of particulate matter and gaseous pollutants are presented in figure 6(a–d) and the respective statistics as mentioned in table 1, which indicate that at the three study sites, there are significant seasonal variations in the concentrations of gaseous and particulate pollutant. PM_{10} levels were observed to be highest during winter season, except in the year 2012 where it was maximum in the pre-monsoon. In the year 2011, the highest seasonal average of $162 \mu\text{g m}^{-3}$ was recorded in the winter while lowest ($99 \mu\text{g m}^{-3}$) were observed in the monsoon. However, in the year 2012, the maximum $192 \mu\text{g m}^{-3}$ was recorded in the pre-monsoon and the lowest $127 \mu\text{g m}^{-3}$ in the monsoon. In the year 2013, highest $156 \mu\text{g m}^{-3}$ was recorded in the winter season and lowest $115 \mu\text{g m}^{-3}$ in the monsoon season. In the year 2014, the corresponding highest and lowest values were 154 and $131 \mu\text{g m}^{-3}$, respectively. Based on the year-long measurements over Guwahati,

Figure 5. Average seasonal cycle (a) wind speed (b) mixing depth and (c) ventilation coefficient in Dehradun obtained from model fields (ECMWF ERA-interim-forecasts) for the study.

Figure 6. Seasonal variations of air pollutants observation sites in Dehradun during 2011–2014 period.

Tiwari *et al.* (2017) have also shown the high mass concentration of PM (PM_{2.5} and PM₁₀) during the winter months.

Similarly, the maximum concentration of SPM was observed during winter in 2013 and 2014, while it was maximum during pre-monsoon in the year 2011 and 2012. In the year 2011, the highest seasonal average of 429 $\mu\text{g m}^{-3}$ was recorded in the winter and lowest of 218 $\mu\text{g m}^{-3}$ was in the monsoon. In the year 2012, maximum value of 463 $\mu\text{g m}^{-3}$ was recorded in the pre-monsoon and a minimum of 276 $\mu\text{g m}^{-3}$ in the monsoon.

Table 1. Annual statistics of pollutants in selected sites of Dehradun city in India during 2011–2014.

Sites	Min	Max	Average	SD	SE
PM ₁₀ concentrations ($\mu\text{g m}^{-3}$)					
CT	78	310	162	49	7.4
RR	67	283	144	37	5.5
ISBT	70	303	167	50	7.5
SO ₂ concentrations ($\mu\text{g m}^{-3}$)					
CT	16	31	25	2.5	0.3
RR	18	28	24	2.3	0.3
ISBT	19	28	24	2.1	0.3
SPM concentrations ($\mu\text{g m}^{-3}$)					
CT	129	1579	352	143	8.2
RR	66	1603	334	142	9.4
ISBT	94	1794	387	163	11.2
NO ₂ concentrations ($\mu\text{g m}^{-3}$)					
CT	19	31	27	2.6	0.4
RR	20	30	26	2.8	0.4
ISBT	21	30	27	2.7	0.4

In the year 2013 and 2014, the corresponding highest values were 408 $\mu\text{g m}^{-3}$ for both years in the winter and lowest values observed were 237 and 316 $\mu\text{g m}^{-3}$ in the monsoon, respectively.

The gaseous pollutant SO₂ was found maximum 24 $\mu\text{g m}^{-3}$ during pre-monsoon and minimum 20 $\mu\text{g m}^{-3}$ in the post-monsoon in the year 2011. Similar trend was observed in the year 2012 with seasonal maximum and minimum are 26 and 24 $\mu\text{g m}^{-3}$, respectively. But a slight change was observed in the trend in 2013, where highest seasonal average recorded was 25 $\mu\text{g m}^{-3}$ in the pre-monsoon and the lowest recorded was 24 $\mu\text{g m}^{-3}$ in the monsoon. Again in the year 2014, the highest seasonal average 26 $\mu\text{g m}^{-3}$ was recorded in the pre-monsoon and lowest 25 $\mu\text{g m}^{-3}$ during the post-monsoon. However, the other gaseous pollutant NO₂ has shown somewhat different pattern. The maximum average of 26 and 28 $\mu\text{g m}^{-3}$ was recorded in the year 2011 and 2013, respectively during winter, while it was maximum 27 and 29 $\mu\text{g m}^{-3}$ in the year 2012 and 2014 in pre-monsoon season. On the other hand, minimum values were observed during monsoon season except in the year 2011. These values observed were 27, 24 and 27 $\mu\text{g m}^{-3}$ in the year 2012, 2013 and 2014, respectively and 19 $\mu\text{g m}^{-3}$ in the year 2011. A comparison of the concentration of these pollutants with observation at different sites in India is given in table 2.

The measured concentrations of PM₁₀ and SPM were found relatively high at ISBT and CT as compared to RR due to the higher traffic emissions

Table 2. Comparison of air pollutants in different sites in India.

Comparison of air pollutants of different sites ($\mu\text{g m}^{-3}$)							References
Sites	Years	Seasons	SO ₂	NO ₂	PM ₁₀	SPM	
Mizoram (Aizawl)	2012–2013	Winter	4	22	217	260	Rai and Chutia (2014)
		Pre-Monsoon	5	23	225	272	
		Monsoon	1	10	59	100	
		Post-Monsoon					
Andhra Pradesh (Visakhapatnam)	2012–2013	Winter	78	72	135		Srinivas and Purushotham (2013)
		Pre-Monsoon	41	48	169		
		Monsoon	61	59	100		
		Post-Monsoon	42	41	104		
Agra	2011		3	6	282	360	Mishra <i>et al.</i> (2014)
	2012		5	8	275	405	
	2013		5	7	320	490	
Dehradun (CT)	2011		23	24	171	397	
	2012		26	28	177	368	
	2013		24	27	138	298

Figure 7. (a) Backward air trajectories ending at 06 UTC with 200 m (AGL), (b) times series of NO₂, and SO₂ and (c) location of fire during selected days in the northern India.

Table 3. Correlation coefficient between air pollutants and meteorological parameters using Pearson's product-moment method for (a) site CT, (b) site RR and (c) site ISBT.

Parameters	SO ₂	NO ₂	RSPM	SPM	Temp	RF	WD
(a) Site CT							
SO ₂	1	0.79	0.51	0.56	−0.13	−0.32	0.25
NO ₂		1.00	0.33	0.37	−0.27	−0.31	0.12
PM ₁₀			1.00	0.89	−0.09	−0.12	0.20
SPM				1.00	−0.12	−0.16	0.20
Temp.					1.00	0.17	0.16
RH						0.31	−0.41
RF						1.00	−0.13
WD							1.00
(b) Site RR							
SO ₂	1.00	0.86	0.46	0.42	0.03	−0.31	0.18
NO ₂		1.00	0.36	0.37	−0.09	−0.32	0.11
PM ₁₀			1.00	0.73	−0.09	−0.17	0.10
SPM				1.00	−0.10	−0.18	0.22
Temp.					1.00	0.14	0.20
RF						1.00	−0.14
WD							1.00
(c) Site ISBT							
SO ₂	1.00	0.86	0.38	0.35	0.004	−0.26	0.16
NO ₂		1.00	0.34	0.35	−0.15	−0.27	0.08
PM ₁₀			1.00	0.61	−0.11	−0.18	0.02
SPM				1.00	−0.06	−0.22	0.20
Temp.					1.00	0.20	0.31
RF						1.00	−0.02
WD							1.00

in its vicinity. Burning of wooden logs and other camp fire activities around the roads for warming are an additional source during the winter. The traffic emissions and wood burning-clubs with the moisture form dense smog (Geddes and Murphy 2012). The Rajpur road has relatively

lower concentrations of PM₁₀ and SPM in all the seasons indicating lesser effects of local emissions and a forest cover.

The annual statistical variability of air pollutants over the three selected study sites is presented in table 1. The statistical analysis includes different

Figure 8. Linear regression ($Y = AX + B$) of air pollutants at site CT.

values of pollutants (minimum, maximum and mean), standard deviation and standard error. The minimum, maximum and annual average concentration of PM_{10} was found to vary from 144 to $167 \mu\text{g m}^{-3}$ for all three sites. The minimum observed value of PM_{10} was found to be $133 \mu\text{g m}^{-3}$ in the year 2013 and maximum value of $145 \mu\text{g m}^{-3}$ in the year 2014. The highest annual concentration of PM_{10} was recorded at ISBT in the year 2014 and lowest was recorded at RR in the year 2011. Similarly, the maximum and minimum annual average concentration of SPM was found to vary from 352 to $387 \mu\text{g m}^{-3}$ for all three sites.

The minimum value of SPM was observed in the year 2013 and maximum was observed in the year 2014. At ISBT, the highest annual concentration of PM_{10} was recorded in the year 2014 and lowest at RR in the year 2011. During the period 2011–2014, the maximum and minimum annual average concentrations of SO_2 were found to vary from 21 to $25 \mu\text{g m}^{-3}$ for above sites.

3.3 Back air trajectory analysis

The highest values of particulate matter are observed on 17th May, 2012 over the study period

Table 4. AQI values and level of health concerns.

Sl. no.	AQI value	Level of health concern (AQI)
1	0–50	Good
2	50–100	Moderate
3	101–150	Unhealthy for sensitive group
4	151–200	Unhealthy
5	200–300	Very unhealthy
6	301–500	Hazardous

of 4 yrs. In order to understand the contribution from distant sources, a backward air mass trajectory analysis is carried out using HYSPLIT model (Stain *et al.* 2015). Figure 7(a) shows the air mass trajectory 200 m (AGL). It can be observed that most of the time on 17th May the air mass was from semi-arid dry regions in the west suggested to be transporting coarse mode particles above Dehradun. In general, during pre-monsoon the Himalayan foothills and adjacent plains encounter the episodes of enhanced dust (e.g., Kumar *et al.* 2014) contributing to higher levels of aerosols.

Northern Indian region experiences intense biomass burning every year during the pre-monsoon/

Table 5. AQI for all selected sites from 2011–2014 on yearly and monthly basis.

AQI on yearly basis												
Sites	2011			2012			2013			2014		
CT	300			295			240			264		
RR	239			296			238			258		
ISBT	239			287			281			313		
AQI on monthly basis												
Sites	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
CT	107	114	104	94	130	100	73	48	63	72	89	113
RR	95	106	91	97	104	88	56	55	60	73	79	88
ISBT	150	97	97	102	118	92	59	57	83	88	93	107

spring as documented in previous studies (e.g., Kumar *et al.* 2011; Ojha *et al.* (2014)). The observations of fire location biomass burning (retrieved from MODIS; <https://earthdata.nasa.gov/firms>) are shown in figure 7(c). Effects of biomass burning could also be transported to the observation sites in Dehradun as shown in the air trajectories contributing to the elevated values during May (pre-monsoon).

3.4 Correlation analysis

The correlations between air pollutants and meteorological parameters are analyzed (table 3a–c) using statistical methods Pearson's and Spearman's rank.

We observed that SO₂ and NO₂ show a good level of agreement, ($r = 0.79$), while the correlation between SO₂ and PM₁₀ was 0.51, which is also a reasonably good positive correlation. The SO₂ and SPM were also positively correlated (0.57) in the CT area. Similar correlation was found between NO₂ and PM₁₀, which indicates that increase in one parameter is associated with increase in the other parameter. From table 3, it is clear that the meteorological parameters like temperature and rainfall show a negative correlation with air pollutants, while wind speed show a positive correlation with the above parameters. In the case of PM₁₀ and SPM, a good positive correlation (0.89) was observed in the CT area. This may be due to the fact that in the city area motor vehicles, the large scale constructions and burning of garbage are the common sources of SO₂, NO₂ and particulate matter (ENVIS 2016). Clock tower being located in center of the city shows stronger anthropogenic influences, in particular due to heavy traffic causing simultaneous enhancements in the PM₁₀ and SPM.

Figure 8 represents the linear regression analysis using the expression $Y = AX + B$, (here Y is response variable, X is predictor variable, the coefficient A is the slope of regression line and B is the intercept on the axis representing the concentration level of the response variable) for gaseous pollutant and particulate matter for all three selected sites. The high values of the A and B are for NO₂ *vs.* SO₂ at the site CT. However, for SO₂ *vs.* PM₁₀ and SPM, A has negative values. In case of PM₁₀ *vs.* SPM the values for A and B are positive and significantly high in all cases. Similarly, PM₁₀ is also having a positive intercept with NO₂ and SO₂ and negative intercept with SPM, indicating that the initial concentration of SPM relative to PM₁₀ is relatively higher. Observed positive correlation indicate the common sources of observed pollutants especially emissions from traffic. In addition, the simultaneous enhancement in the SO₂ and NO₂ levels indicate the influences from energy generation plants.

3.5 Air Quality Index

The variation in the Air Quality Index (AQI) is useful for an overall assessment of possible health effects, as compared to that deduced from the individual pollutants (e.g., NAAQMS 2009; CPCB 2012) (table 4). AQI is computed as

$$AQI = \left(\frac{V_o}{V_s} \right) \times 100$$

where V_o = observed values of air pollutants, V_s = standard values recommended for the NAAQS (CPCB).

The values of the AQI calculated on yearly and monthly basis are presented in the table 5. From the AQI values are found to be in the hazards and

very unhealthy range as per the Environmental Protection Agency (EPA) guidelines. Additionally, at the ISBT station it also crossed the upper limit of the AQI of hazardous range. According to Sharma *et al.* (2017), in 2011, the scenario has changed somewhat with an increment in the number of vehicles, i.e., 154,666 plus local transport modes and the levels of all the pollutants have increased manifold. The results indicate that substantial growth in the population, traffic and energy needs has led to unhealthy conditions, especially near the major city centers/bus station. It is described to initiate more observation in the areas away from the major stations to further understand the dispersion of the enhanced pollution in Doon valley.

4. Summary and conclusions

This study analyzes the variability in the concentration of SPM, PM₁₀, NO₂ and SO₂ made at three sites in the Dehradun city, during 2011–2014 periods. Winter time elevated pollution is attributed to lower ventilation, as seen in the Era-Interim model fields and lack of precipitation.

The PM₁₀ is found to vary between 150 and 195 $\mu\text{g m}^{-3}$, whereas SPM between 350 and 470 $\mu\text{g m}^{-3}$ during winter and summer. PM₁₀ and SPM levels are found to be higher at ISBT and CT due to stronger traffic emissions in the vicinity and camp fire activities around the roads for warming during the winter. Inter-species correlations suggested influences from common sources on the air quality at observing sites, such as traffic emissions, large-scale constructions, and burning of garbage. Additionally, simultaneous enhancements in SO₂ and NO₂ might be due to the influences from energy production plants. Variations in the AQI indicate considerable degradation of the air quality in the Doon valley due to enhanced traffic and energy needs for growing population, especially near the bus station. More observations would be desirable to further understand the dispersion of elevated pollution from Dehradun city and the implications towards human health, vegetation and climate.

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