Patterns and Sources of PM₁₀ in the Ecologically Sensitive Himalayan Region in Himachal Pradesh, India

Raman Kumar¹, Jui-Huan Lee², Ruei-Hao Shie³, Chia-Pin Chio¹, Chang-Chuan Chan^{1*}

¹ Institute of Occupational Medicine and Industrial Hygiene, College of Public Health, National Taiwan University, Taipei 10055, Taiwan

² Institute of Environmental Health, College of Public Health, National Taiwan University, Taipei 10055, Taiwan

³ Industrial Technology Research Institute, Hsinchu 31040, Taiwan

ABSTRACT

In this study, we aimed to comprehensively investigate particulate matter less than 10 µm in aerodynamic diameter (PM₁₀) at industrial, residential, and ecologically sensitive sites in the western Himalayan region. To achieve this goal, PM₁₀ data from 20 stations across the state of Himachal Pradesh were used to characterize the spatial and temporal patterns. To determine the potential sources of pollution, we created a bivariate polar plot based on wind speed and direction. Our findings showed that only the PM₁₀ concentrations at the ecologically sensitive sites ($59.02 \pm 34.77 \mu\text{g m}^{-3}$) were below the National Ambient Air Quality Standard of $60 \mu\text{g m}^{-3}$. The concentrations at both the industrial ($115.9 \pm 47.82 \mu\text{g m}^{-3}$) and residential ($87.16 \pm 35.83 \mu\text{g m}^{-3}$) sites exceeded the standard, with the highest concentrations occurring during the winter and the lowest occurring during the monsoon season of the same year. The emission sources both within and outside of the Himachal Pradesh for each site were determined based on the bivariate polar plot, and industrial and vehicular emission, biomass and solid waste burning, dust from a nearby unpaved road, and long-range transported pollution were identified as contributors to the deterioration of air quality in this state. Moreover, the monsoon season significantly affected air quality. We conclude that local industrial and traffic pollution and long-range-transported emissions increased the PM₁₀ concentration in Himachal Pradesh, resulting in its exceedance of the limit indicated in the World Health Organization (WHO) guidelines.

Keywords: Himachal Pradesh; Air pollution; Spatial and temporal variation; Ecologically sensitive; Bivariate polar plot.

INTRODUCTION

PM₁₀ (particulate matter aerodynamic diameter less than 10 µm) is one of the major criteria pollutant affecting human health and air quality on a global scale (Pande *et al.*, 2018a). Rapid industrialization and urbanization in India have resulted in highly polluted cities and a large proportion of the Indian population is exposed to high levels of particulate pollutants (Dey *et al.*, 2012; Greenstone *et al.*, 2015). According to World Health Organization (WHO), 37 cities in India have been identified as having the highest pollution levels of PM₁₀ among the top 100 cities in the world, and more than 100 cities under the national ambient monitoring program exceeded the limit indicated in the WHO guidelines of $20 \mu\text{g m}^{-3}$ (Guttikunda and Mohan, 2014; Venkataraman *et al.*, 2018).

Most of the air pollution research in India has been focused on big cities and Indo-Gangetic Plain (IGP). However, some

findings have shown that the Himalayan region, which is supposed to be a pollution-free region because of its distance from Indian megacities, is experiencing an increase in the air pollution level (Gautam *et al.*, 2009; Panwar *et al.*, 2013). Especially, it has been reported that PM concentrations could even exceed the standards values set by the WHO during a specific season, which poses a serious threat to public health.

Increasing efforts have been spent to investigate air pollution in a different region of Himalaya. For example, in the northern and eastern Himalayan region, it has been suggested that the complex hilly terrain can trap pollutants emitted from the IGP region thus elevate the pollutant concentration (Ojha *et al.*, 2012). Moreover, it was reported that the sources of pollution in both Darjeeling (eastern Himalaya) (Chatterjee *et al.*, 2010) and Kothi and Mohal (western Himalaya) (Kuniyal *et al.*, 2015) would vary temporally where the long-range transport became the major sources in the summer season whereas the emission from anthropogenic activities such as biomass burning dominates the winter season. However, studies abound mostly examined the air pollution in the Himalayan region based on few stations in the residential or ecological area, while the impact from the local industry (i.e., the industrial area) is lacking.

* Corresponding author.

E-mail address: ccchan@ntu.edu.tw

In this study, we aimed to carry out a comprehensive investigation of air pollution (PM_{10}) among residential, ecologically sensitive, and industrial areas in the Western Himalayan region. To achieve this goal, we analyzed air quality data collected from 20 stations in Himachal Pradesh (India) over 5 years. Besides examining the spatial and temporal trend of PM_{10} , we distinguished the local or regional PM_{10} emissions using both air quality monitoring data and data on meteorological factors such as wind speed and direction.

METHODS AND MATERIALS

Study Area

Himachal Pradesh is a Himalayan state located in the northwest region of India. It is located between $30^{\circ}22'40''$ – $33^{\circ}12'40''$ N and $75^{\circ}47'55''$ – $79^{\circ}04'20''$ E, with elevation ranging from approximately 350 m to 6,816 m above the sea. The state has 12 districts and covers a geographical area of 55,673 km². According to the 2011 Indian census, the state has a population of 6.864 million people, among which 90% of people live in rural areas. The state has four agro-climatic zones with low hills, high hills, alpine zones, and cold deserts. The low hill zones are located between 1,000 and 2,000 m, where the temperature ranges between 5°C and 38°C, whereas the high hill zones are located between 2,000 and 3,500 m, with an average rainfall of 280 cm and the temperature ranging between 5°C and 25°C; the alpine zones are located at 3,500 m, where the temperature ranges between 10°C and 29°C, the average rainfall is 138 cm, and the average snowfall is 150 cm. The fourth zone is called a cold desert, with 3–5 m of snow cover, and the temperature remains as low as –40°C (Aggarwal and Chandel, 2010).

Shimla is the state capital that served as the summer capital of India during the pre-independence years. Himachal Pradesh is a popular tourist destination that attracts millions of tourists every year. In addition to tourism, the state is rapidly becoming industrialized, and industrialization has gained momentum because of policy initiatives by the state government in 2003. The state has four primary industrial areas in Solan, Una, Sirmour, and Kangra districts. Solan and Sirmour districts have the largest industrial areas: Baddi, Barotiwala, and Nalagarh (BBN) and Parwanoo in district Solan, and Gondpur and Kala-Amb in district Sirmour. The primary industries in these districts are pharmaceuticals, mining (stone crushing), cement plants, food processing, mini steel plants, and textiles.

Air Quality and Meteorological Data

Measurement of PM_{10} were obtained from 20 stations across different altitudes located in Himachal Pradesh (Fig. 1), operated by the HPSPCB (Himachal Pradesh State Pollution Control Board; <https://hppcb.nic.in>). According to HPSPCB and Central Pollution Control Board (CPCB) guideline (CPCB, 2003), these stations can be further categorized into industrial, residential, and ecologically sensitive sites (Table 1). To describe the temporal variations, monthly averaged PM_{10} data were analyzed during 2011–2015. Seasons in Himachal Pradesh are defined as follows: Winter occurs from December to February, summer occurs from March to May, monsoon occurs from June to September, and post-monsoon occurs from October to November. PM_{10} data were measured by using gravimetric method, details can be found in CPCB's guideline (CPCB, 2011).

Air quality is influenced not only by emission sources but

Fig. 1. Geological map and location of selected monitoring stations in Himachal Pradesh, India.

Table 1. Geological and social characteristics of monitoring sites in Himachal Pradesh, India.

City/Town	Area	Station	Station code	Population		Data use in this study (months)
				2001	2011	
Shimla	Ecologically Sensitive	Tekka Bench	S1	144955	169578	60
		Bus Station	S2			60
Manali	Ecologically Sensitive	Nehru Park	S3	6265	8096	54
		Regional Office Manali	S4			49
Baddi	Industrial	DIC Baddi	I2	22601	29991	60
	Industrial	AHC Barotiwala	I1			60
	Residential	Housing Board	R1			60
Nalagarh	Industrial	M.C. Office Nalagarh	I3	9443	10708	60
Parwanoo	Industrial	Sec. I	I4	8609	8758	60
	Residential	Sec. IV	R2			60
Kala-Amb	Industrial	Kala-Amb	I5		1076	60
	Residential	Trilokpur	R3		1935	60
Paonta-Sahib	Residential	Paonta-Sahib	R4	19090	25183	58
	Industrial	Gondpur	I6			60
Una	Residential	Una	R5	15900	18722	52
	Industrial	Mehatpur	I7		9218	56
Damtal	Residential	Old Road	R6	3715	3682	60
		Regional Office	R7			60
Sundernagar	Residential	Regional Office	R8	23986	24344	57
		M.C. Office	R9			37

also by meteorological factors. Meteorological factors strongly influence the dispersion and dilution of pollutants and can disperse accumulated pollutants emitted from local sources (Chuang *et al.*, 2018). Therefore, meteorological factors must be considered when evaluating environmental toxicity to understand pollution emission sources and effective control strategies. To examine the impact of wind speed and direction on air quality in monitoring stations in Himachal Pradesh, gridded archived meteorological data over three years (2012–2014) using the Global Data Assimilation System (GDAS) at 1°C and 3 hourlies averaged, were obtained from U.S. National Ocean and Atmospheric Administration (NOAA) website (<https://ready.arl.noaa.gov/index.php>). The collected meteorological data were then analyzed with PM₁₀ data taken by HPSPCB with the frequency of twice a week to examine the influence of wind speed and direction on air quality.

Data Analysis

We conducted descriptive analysis by using the openair package in R software (Carslaw and Ropkins, 2012), and we compared spatial variations in the pooled data between stations in Himachal Pradesh during 2011–2015 by using one-way analysis of variance (ANOVA). We used a bivariate polar plot to determine the potential sources of pollution. The bivariate polar plot represents a graphical technique that can be used to identify potential sources of air pollution, and these plots are presented in a polar coordinate to visualize the potential sources with a color index. According to Carslaw and Beevers (2013) description of the construction of a bivariate polar plot, the wind speed, wind direction, and concentration data were partitioned in “bins,” and the mean concentration was calculated for each bin. We calculated the u and v components of wind as follows:

$$u = \bar{u} \cdot \sin\left(\frac{2\pi}{\theta}\right), v = \bar{u} \cdot \cos\left(\frac{2\pi}{\theta}\right) \quad (1)$$

where $\bar{u}$ is the mean hourly wind speed, and θ is the mean wind direction in degrees, with 90° from the east. This calculation provides the u and v components and the concentration (C) surface. The generalized additive model provides a flexible framework for filtering a surface, which can be expressed as shown in Eq. (2):

$$\sqrt{C_i} = \beta_0 + s(u_i, v_i) + \epsilon_i \quad (2)$$

where C_i is the i^{th} pollutant concentration, β_0 is the overall mean of the response, $s(u_i, v_i)$ is the isotropic smooth function of the i^{th} value of covariate u and v , and ϵ_i is the i^{th} residual.

The features of a bivariate polar plot can be identified and grouped using the k -means clustering method (Carslaw and Beevers, 2013). The basic k -means algorithm for k clustering is obtained by minimizing:

$$\sum_{k=1}^k \sum_{x_i \in C_k} \|x_i - \mu_k\|^2 \quad (3)$$

where $\|x_i - \mu_k\|^2$ is a chosen distance measure and μ_k is the mean of cluster C_k .

The distance measure is defined as the Euclidean distance:

$$d_{x,y} = \sqrt{\sum_{j=1}^J (x_j - y_j)^2} \quad (4)$$

where x and y are two J -dimensional vectors that have been

standardized by subtracting the mean and dividing it by the standard deviation. In the current case, J is of length three (i.e., the wind components u and v and the concentration C), each of which is standardized. Details of the k -means clustering method have been provided in a previous study (Carslaw and Beevers, 2013).

RESULTS

Spatial Variations in PM_{10} Concentrations in Himachal Pradesh

The average PM_{10} concentration was significantly different among all the three categories (Table 2). The average PM_{10} concentration was higher in industrial sites ($115.9 \pm 47.82 \mu\text{g m}^{-3}$), followed by residential ($87.16 \pm 35.83 \mu\text{g m}^{-3}$) and ecologically sensitive sites ($59.02 \pm 34.77 \mu\text{g m}^{-3}$). The annual PM_{10} concentration in industrial and residential sites significantly exceeded the National Ambient Air Quality Standard (NAAQS) of $60 \mu\text{g m}^{-3}$. Among the seven industrial sites, the annual average PM_{10} concentration was three times higher in I5 and two times higher in I6 and I2. On the other hand, the concentrations in residential sites located near industrial areas, such as R1 and R4, were higher than those in the other residential sites. Residential sites closer to highways, such as R6 and R9, had higher PM_{10} concentrations than sites far from the highways. Similarly, among ecological sites, monitoring stations located on roadsides, such as S2 and S4, had higher PM_{10} concentrations than other monitoring sites, including S1 and S3 in Shimla and Manali, respectively. The posterior comparison also showed that the annual average PM_{10} concentrations in industrial and residential sites were significantly higher than those in ecologically sensitive sites.

Seasonal Variation of PM_{10}

PM_{10} concentrations showed seasonal variability across the monitoring stations (Fig. 2). However, the monsoon season had a significant effect on air quality because of the washout effect. For example, at industrial sites, PM_{10} concentrations in the summer ($125 \pm 50.1 \mu\text{g m}^{-3}$) and winter ($126.5 \pm 48.2 \mu\text{g m}^{-3}$) seasons were approximately two times higher than the NAAQS, and the concentrations only reduced

($102 \pm 43.7 \mu\text{g m}^{-3}$) in the monsoon season and then increased ($114.9 \pm 45.4 \mu\text{g m}^{-3}$) in the post-monsoon season. Similarly, at residential sites, the average PM_{10} concentration was higher ($91.8 \pm 36.6 \mu\text{g m}^{-3}$) in the summer season and decreased ($73.4 \pm 29.1 \mu\text{g m}^{-3}$) in the monsoon season. The PM_{10} concentration increased in the post-monsoon ($88.3 \pm 32.8 \mu\text{g m}^{-3}$) and winter ($101 \pm 39.1 \mu\text{g m}^{-3}$) seasons. Finally, at ecologically sensitive sites, the average PM_{10} concentration was the highest during the summer season ($66.9 \pm 33.7 \mu\text{g m}^{-3}$), whereas it was the lowest in the monsoon season ($50.4 \pm 28.2 \mu\text{g m}^{-3}$).

Bivariate Polar Plot and PM_{10} Clustering

We observed that west and northeasterly winds were prominent in Himachal Pradesh. Wind originating from the west and northeast directions was increasingly prominent in industrial areas, which included Shimla and Sundernagar stations (Fig. 3). However, the northeasterly wind was observed at Damtal, whereas the western-southern wind was observed at Manali. The bivariate polar plot, which calculates the mean concentration of wind speed and direction bins, was constructed to demonstrate the potential PM concentration sources in all monitoring sites during 2012–2014. PM_{10} concentration sources, from local to long-range transport through air mass movements from outside regions, were evaluated. Emission sources were local in industrial areas, as indicated by the high PM_{10} concentration at low wind speed (Fig. 4(a)). However, the high PM_{10} concentration at Paonta-Sahib and Kala-Amb stations was observed when the wind originated from the northwest direction. A similar trend was observed at the Parwanoo, Barotiwala, and Nalagarh stations, where the PM_{10} concentration levels increased when the wind originated from the northwest direction. Local emissions were observed at the Damtal, Una, and Sundernagar residential areas (Fig. 4(b)). However, high PM_{10} concentrations were observed when the wind originated from the southwest direction at the Sundernagar station. In ecologically sensitive areas, high PM_{10} concentrations were observed when the wind originated from the west direction at Shimla and the south direction at Manali (Fig. 4(c)).

Moreover, primary emission sources were identified using the k -means clustering. Primary emission sources in

Table 2. Comparison of PM_{10} among three categories of monitoring sites across Himachal Pradesh, India during 2011–2015.

Categories					
Industrial		Residential		Ecologically Sensitive	
Site code	Mean $\pm$ SD	Site code	Mean $\pm$ SD	Site code	Mean $\pm$ SD
I1	101.6 ± 22.1	R1	113.8 ± 38.5	S1	45.8 ± 13.4
I2	134.8 ± 52.4	R2	59.3 ± 15.4	S2	66.6 ± 25
I3	98.7 ± 24.1	R3	86.1 ± 19.1	S3	48.9 ± 40.2
I4	83.5 ± 22.6	R4	106.0 ± 34.7	S4	74.5 ± 45.8
I5	169.3 ± 53.9	R5	72.0 ± 19.8		
I6	141.6 ± 38.7	R6	99 ± 38.6		
I7	76.7 ± 19.4	R7	82.5 ± 52.5		
		R8	73.8 ± 22		
		R9	93.4 ± 21.6		
Total	115.9 ± 47.8		87.16 ± 35.8		59.02 ± 34.8
	IS > ES		RS > ES		
t-test	p value < 0.05		p value < 0.05

Fig. 2. Seasonal variation of PM₁₀ in all three categories of monitoring sites in Himachal Pradesh, India during 2011–2015.

Fig. 3. Windrose showing the wind speed and direction; (a) Damtal (b) Manali, and (c) Shimla, during 2012–2014.

all the industrial stations were observed to originate from industrial, residential, and road sectors, and some minor emission sources were observed to originate from outside regions. Similarly, in residential stations, the highest PM₁₀ concentration was observed from local sources. For example, in Fig. 5(a), at Damtal station three clusters were assumed and categorized based on emission sources: emission from industries wherein primary emission from mining and other industrial sector ($149.13 \pm 81.67 \mu\text{g m}^{-3}$); the residential group primary emission from household and other anthropogenic activities ($116.11 \pm 54.28 \mu\text{g m}^{-3}$); and emission from long-range transport ($83.41 \pm 36.03 \mu\text{g m}^{-3}$).

We observed significant emissions that originated from the west direction during the summer and monsoon seasons in Shimla (Fig. 5(b)). This emission was assumed to originate from long-range transport. Moreover, three clusters were assumed and categorized based on emission sources: emissions from long-range transport; the residential group wherein the

primary emission was assumed to originate from household and other anthropogenic activities; and emissions from road sectors (vehicle emissions and road dust are categorized under the road sector). After clustering the three groups, the average PM₁₀ concentration was $42.24 \pm 17.32 \mu\text{g m}^{-3}$ for long-range transport, $48.24 \pm 18.38 \mu\text{g m}^{-3}$ for the road sector in Shimla, and $49 \pm 20 \mu\text{g m}^{-3}$ for the residential sector in Shimla.

DISCUSSION

In this study, we found the annual PM₁₀ concentrations were the highest in industrial sites followed by residential and the ecologically sensitive sites. This result is consistent with the general notion that the industrial sites are more polluted due to industrial and vehicular activities. Notably, our findings showed that except the ecologically sensitive sites, the annual PM₁₀ concentrations in the western Himalaya

Fig. 4. Bivariate polar plot for all monitoring sites. The color scale shows concentration of PM_{10} ($\mu\text{g m}^{-3}$) and radial scale shows the wind speed. Name of each site mentioned on each polar plot. (a) Bivariate plot for all industrial sites. (b) Bivariate polar plot for residential sites (c) Bivariate polar plot for ecologically sensitive sites.

Fig. 4. PM₁₀ clustering for Damtal and Shimla stations. (a) Cluster analysis for Damtal station. (i) Showing three clusters for Damtal, and (ii) levels of PM₁₀ by the three clusters of emission sources. (b) Cluster for Shimla station. (1) PM₁₀ clustering for Shimla, and (2) levels of PM₁₀ by the three clusters of emission sources.

were all higher than the NAAQS of $60 \mu\text{g m}^{-3}$. Especially, the concentration in residential sites was approximately 50% higher than the NAAQS, while that in industrial sites was even two times higher than the NAAQS. We noted that the NAAQS is much looser than the WHO standard of $20 \mu\text{g m}^{-3}$. If the WHO standard is considered in our case, all sites including ecologically sensitive sites, exceeding the threshold. These findings are unexpected, as it is usually assumed that the Himalayan region, at least the residential sites, should be less polluted thus below the NAAQS or WHO standard. However, these observations are in line with previous studies showing the deteriorating air quality in the Himalayan region (Thakur, 2016). Exposure to PM₁₀ is linked to cardiovascular and respiratory diseases and premature mortality (Pande *et al.*, 2018b). Therefore, the high concentration of PM₁₀ in the residential and industrial sites as well as the ecologically sensitive sites, can seriously affect the health of the local community.

We observed the decline of the PM₁₀ concentration in the monsoon season across the monitoring sites. The PM₁₀ concentration aggravated during the summer season; this may be linked to high anthropogenic activities, such as tourism influx, and long dry weather periods. Moreover, clear and sunny days during the summer season present unstable atmospheric conditions and maximize the dispersion of generated pollutants through vertical mixing in the atmosphere (Chandra *et al.*, 2014), and these pollutants may be carried to high altitudes. Upslope breezes have been identified as an efficient method for humid air to be transported from the

northern edge of Ganges Plains up to 6,000 m in the central upper Himalayas (Decesari *et al.*, 2010). High PM₁₀ concentration levels in lower altitude sites during the winter season may be caused by the combined effect of source strength and lower boundary layer height (Sharma *et al.*, 2014a), compared with high altitude areas, wherein low temperatures lead to reduced re-suspension of loose sediments, soil, and roadside dust (Kaushal *et al.*, 2018).

We noted various sources that influence air quality across the monitoring sites in Himachal Pradesh. A bivariate polar plot was used to determine the sources responsible for the PM₁₀ concentration, from local sources to long-range transport from outside regions. Traffic, industrial emissions, and biomass burning have been identified as local emission sources, and long-range transport from outside regions has been identified as the secondary source of air pollution in Himachal Pradesh. Sharma *et al.* (2014b) measured ambient trace gases, black carbon, and PM_{2.5} at five locations in Himachal Pradesh over a short duration and revealed that air quality was primarily influenced by local activities, such as tourism, agriculture, biomass burning, and vehicular emission. However, long-range transport was identified as the secondary aerosol source in Himachal Pradesh. In industrial areas, emission sources responsible for the PM₁₀ mass concentration may be local industrial activities, vehicular emissions, and residential activities. However, many slums and bricks kilns in BBN industrial may have a significant influence on air quality. Outside regions and agriculture sectors may also have some influence on air quality because these stations are

closer to big urban settlements and agricultural fields. High PM₁₀ concentrations from the west direction at Nalagarh station may be linked to a coal power plant situated in a neighboring state, Punjab, and two cement plants located close to this site from the western and northwest directions. Coal power plants were also identified as a prominent contributor to reducing air quality in India (Guttikunda and Jawahar, 2014).

Increasing PM₁₀ level in the industrial sites as well as residential and ecologically sensitive sites, may cause hazardous conditions and serious public health concern. However, both deteriorating air condition and loose NAAQS standard show that the awareness of the impact of air pollution on public health is still lacking. That is, further researches such as the source apportionment on PM₁₀ should be done to raise the concern of both government and public.

CONCLUSION

The PM₁₀ concentrations exceeded the WHO standards across the monitoring stations, particularly at industrial sites, which exhibited increasing levels of pollution. The concentrations increased during the winter, summer, and post-monsoon season, and although they decreased during the monsoon season, they still exceeded the NAAQS, especially at industrial and residential sites, thereby necessitating control measures for emission sources. We created a bivariate polar plot to evaluate the effect of wind speed and direction on air quality. Although the observed high concentrations were caused by long-range-transported emissions to Himachal Pradesh, local sources play an increasing role in air pollution in the state, which must be addressed by implementing air pollution control strategies. Moreover, considering the devastating effects of air pollution on the environment and human health, authorities must adopt control measures not only for ecologically sensitive sites but industrial and residential areas. In addition to policy initiatives for curbing air pollution, the population's participation is a crucial factor that can ensure the success of control strategies.

ACKNOWLEDGEMENTS

This work was financially supported by the Innovation and Policy Center for Population Health and Sustainable Environment (Population Health Research Center, PHRC), College of Public Health, National Taiwan University, from The Featured Areas Research Center Program within the framework of the Higher Education Sprout Project by the Ministry of Education (MOE) in Taiwan. Furthermore, the authors warmly acknowledge the Himachal Pradesh State Pollution Control Board Shimla for generously providing the data for this study.

FUNDING

This study was supported by the Ministry of Science and Technology (Grant Numbers MOST 106-2118-M-002-006-MY2, MOST 106-2118-M-532-001-MY2, and MOST 107-3017-F-002-003) and Featured Areas Research Center Program within the framework of the Higher Education

Sprout Project by the Ministry of Education (MOE) in Taiwan (Grant Number NTU-107L9003).

REFERENCES

- Aggarwal, R.K. and Chandel, S.S. (2010). Emerging energy scenario in Western Himalayan state of Himachal Pradesh. *Energy Policy* 38: 2545–2551.
- Carslaw, D.C. and Beevers, S.D. (2013). Characterising and understanding emission sources using bivariate polar plots and k-means clustering. *Environ. Modell. Software* 40: 325–329.
- Carslaw, D.C. and Ropkins, K. (2012). *openair* — An R package for air quality data analysis. *Environ. Modell. Software* 27–28: 52–61.
- Chandra, S., Kulshrestha, M.J. and Singh, R. (2014). Temporal variation and concentration weighted trajectory analysis of lead in PM₁₀ aerosols at a site in Central Delhi, India. *Int. J. Atmos. Sci.* 2014: 323040.
- Chatterjee, A., Adak, A., Singh, A.K., Srivastava, M.K., Ghosh, S.K., Tiwari, S., Devara, P.C.S. and Raha, S. (2010). Aerosol chemistry over a high altitude station at northeastern Himalayas, India. *PLoS One* 5: e11122.
- Chuang, H.C., Shie, R.H., Chio, C.P., Yuan, T.H., Lee, J.H. and Chan, C.C. (2018). Cluster analysis of fine particulate matter (PM_{2.5}) emissions and its bioreactivity in the vicinity of a petrochemical complex. *Environ. Pollut.* 236: 591–597.
- CPCB (Central Pollution Control Board) (2012). *National Ambient Air Quality Status & Trends - 2012*. Central Pollution Control Board, Ministry of Environment & Forests, New Delhi, India.
- Decesari, S., Facchini, M.C., Carbone, C., Giulianelli, L., Rinaldi, M., Finessi, E., Fuzzi, S., Marinoni, A., Cristofanelli, P., Duchi, R., Bonasoni, P., Vuillermoz, E., Cozic, J., Jaffrezo, J.L. and Laj, P. (2010). Chemical composition of PM₁₀ and PM₁ at the high-altitude Himalayan station Nepal Climate Observatory-Pyramid (NCO-P) (5079 m a.s.l.). *Atmos. Chem. Phys.* 10: 4583–4596.
- Dey, S., Di Girolamo, L., van Donkelaar, A., Tripathi, S.N., Gupta, T. and Mohan, M. (2012). Variability of outdoor fine particulate (PM_{2.5}) concentration in the Indian Subcontinent: A remote sensing approach. *Remote Sens. Environ.* 127: 153–161.
- Gautam, R., Hsu, N.C., Lau, K.M., Tsay, S.C. and Kafatos, M. (2009). Enhanced pre-monsoon warming over the Himalayan-Gangetic region from 1979 to 2007. *Geophys. Res. Lett.* 36: L07704.
- Greenstone, M., Nilekani, J., Pande, R., Ryan, N., Sudarshan, A. and Sugathan, A. (2015). Lower pollution, longer lives: Life expectancy gains if India reduced particulate matter pollution. *Econ. Polit. Weekly* 50: 40–46.
- Guttikunda, S.K. and Jawahar, P. (2014). Atmospheric emissions and pollution from the coal-fired thermal power plants in India. *Atmos. Environ.* 92: 449–460.
- Guttikunda, S.K. and Mohan, D. (2014). Re-fueling road transport for better air quality in India. *Energy Policy* 68: 556–561.

- Kaushal, D., Kumar, A., Yadav, S., Tandon, A. and Attri, A.K. (2018). Wintertime carbonaceous aerosols over Dhauladhar region of North-Western Himalayas. *Environ. Sci. Pollut. Res.* 25: 8044–8056.
- Kuniyal, J.C., Sharma, M., Chand, K. and Mathela, C.S. (2015). Water soluble ionic components in particulate matter (PM₁₀) during high pollution episode days at Mohal and Kothi in the north-western Himalaya, India. *Aerosol Air Qual. Res.* 15: 529–543.
- Ojha, N., Naja, M., Singh, K.P., Sarangi, T., Kumar, R., Lal, S., Lawrence, M.G., Butler, T.M. and Chandola, H.C. (2012). Variabilities in ozone at a semi-urban site in the Indo-Gangetic Plain region: Association with the meteorology and regional processes. *J. Geophys. Res.* 117: D20301.
- Pande, P., Dey, S., Chowdhury, S., Choudhary, P., Ghosh, S., Srivastava, P. and Sengupta, B. (2018a). Seasonal transition in PM₁₀ exposure and associated all-cause mortality risks in India. *Environ. Sci. Technol.* 52: 8756–8763.
- Pande, P., Dey, S., Chowdhury, S., Choudhary, P., Ghosh, S., Srivastava, P. and Sengupta, B. (2018b). Seasonal transition in PM₁₀ exposure and associated all-cause mortality risks in India. *Environ. Sci. Technol.* 52: 8756–8763.
- Panwar, T.S., Hooda, R.K., Lihavainen, H., Hyvarinen, A.P., Sharma, V.P. and Viisanen, Y. (2013). Atmospheric aerosols at a regional background Himalayan site—Mukteshwar, India. *Environ. Monit. Assess.* 185: 4753–4764.
- Sharma, S.K., Mandal, T.K., Saxena, M., Rashmi, Sharma, A., Datta, A. and Saud, T. (2014a). Variation of OC, EC, WSIC and trace metals of PM₁₀ in Delhi, India. *J. Atmos. Sol. Terr. Phys.* 113: 10–22.
- Sharma, S.K., Mandal, T.K., Sharma, C., Kuniyal, J.C., Joshi, R., Dhyani, P.P., Rohtash, Sen, A., Ghayas, H., Gupta, N.C., Sharma, P., Saxena, M., Sharma, A., Arya, B.C. and Kumar, A. (2014b). Measurements of particulate (PM_{2.5}), BC and trace gases over the northwestern Himalayan region of India. *MAPAN* 29: 243–253.
- Venkataraman, C., Brauer, M., Tibrewal, K., Sadavarte, P., Ma, Q., Cohen, A., Chaliyakunnel, S., Frostad, J., Klimont, Z., Martin, R.V., Millet, D.B., Philip, S., Walker, K. and Wang, S. (2018). Source influence on emission pathways and ambient PM_{2.5} pollution over India (2015–2050). *Atmos. Chem. Phys.* 18: 8017–8039.

Received for review, March 4, 2019

Revised, September 7, 2019

Accepted, November 7, 2019