International Journal of Earth, Energy and Environmental Sciences
ISSN: 2517-942X
Vol:10, No:11, 2016

Spatial and Temporal Variability of Fog Over the Indo-Gangetic Plains, India

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***Abstract*—**The aim of the paper is to analyze the characteristics of winter fog in terms of its trend and spatial-temporal variability over Indo-Gangetic plains. The study reveals that during last four and half decades (1971-2015), an alarming increasing trend in fog frequency has been observed during the winter months of December and January over the study area. The frequency of fog has increased by 118.4% during the peak winter months of December and January. It has also been observed that on an average central part of IGP has 66.29% fog days followed by west IGP with 41.94% fog days. Further, Empirical Orthogonal Function (EOF) decomposition and Mann-Kendall variation analysis are used to analyze the spatial and temporal patterns of winter fog. The findings have significant implications for the further research of fog over IGP and formulate robust strategies to adapt the fog variability and mitigate its effects. The decision by Delhi Government to implement odd-even scheme to restrict the use of private vehicles in order to reduce pollution and improve quality of air may result in increasing the alarming increasing trend of fog over Delhi and its surrounding areas regions of IGP.

***Keywords*—**Fog, climatology, spatial variability, temporal variability, empirical orthogonal function, visibility, Mann-Kendall test, variation point.

I. Introduction

THE influence of climate on our lives is all pervading as it is important factor in agriculture, commerce, industry, transport, tourism and many other important activities of daily life. Advance knowledge of information on climatology of meteorological parameters is of great demands from various users, planners, disaster management personals, tourism department etc. Reliable regional estimates of climate parameters are crucial for effective and efficient territorial management; thus there is a need to study these parameters and their changes over time, which includes temperature, humidity, rainfall and various other important meteorological events including fog.

Over 70% of damage caused by natural phenomena is related to meteorological disasters, among which severe drought, floods, hail storms and fog are the most common. Fog is a hazardous weather phenomenon worldwide. The economic loss due to disruption in normal traffic schedules and accidents can be comparable to many natural disasters [1]. In addition, fog can cause discharge between power lines and interrupt electricity service. In recent years, some costly or even catastrophic events in world have been caused by dense fog. Due to these known facts, it is unsurprising that much research has been carried out on fog all over the world. Fog studies through observations (Field observations and remote sensing), models, climatology, and statistical methods have resulted in many achievements [1]. As an example, the extent to which sea fog in the United Kingdom and United States has been studied is apparent in the review by Lewis et al [2].

Over India, the Indo-Gangetic Plains (IGP) in northern India experiences frequent fog episodes every winter (December–January) resulting from suitable meteorological and environmental conditions. Northern regions of India, Pakistan and Bangladesh experience severe fog conditions during winter season, which thoroughly disrupts human activities [3]. Visibility is reduced below 1000 m during fog, affecting public life. The negative impact of fog on human life has long been recognized. Every year, IGPs of India witness fog formation during the post-monsoon and winter months [4]. Several studies have attempted to examine various aspects of fog occurrence; however, these studies are limited to selective days over varied point locations [5]-[7].

Over recent decades, several authors have analyzed fog phenomenon in the northern part of India. Many researchers have studied various aspects of fog occurrence over Delhi and adjoining northern India during winter, however, there has not been any climatological study of the trend in fog formation over IGP India with ground base observation considering the latest data till 2015 [8], [9]. Over the Indo-Gangetic plains, the long duration of fog has been studied in detailed to know its climatic features. Presence of fog for more than 50% of the time during winter and an increase in fog frequency from 6.4 to 58% during the last four decades have also been reported in this region [10]. This alarming rise of fog events during the winter has been attributed to the rise in pollution levels and a gradual increasing trend in relative humidity. This alarming rise in fog frequency is another evidence of climate change which is a matter of serious concerned today for everyone all over the globe. Among the many disastrous consequences of climate change, an increase in frequency of fog occurrence over the IGP is also indeed an area of great concern for the inhabitant of this densely populated region of the world. The aim of this study is to analyze fog climatology, the trends of long-term changes of fog climatology and its spatial-temporal variability over the IGP, India using ground based observational data.

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International Journal of Earth, Energy and Environmental Sciences
ISSN: 2517-942X
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II. Study Area: IGP

The study is carried out over the IGP of India. The IGP is a fertile plain encompassing most of the northern and eastern India. It is bounded on the north by the Himalayas, southern edge of the plains is marked by Chota Nagpur plateau, and it has in its west Iranian plateau. The low elevated and sloping land of the river Indus and Ganges basin is very crucial for agriculture production and food security over this highly populated Indian region. IGP is among the most agriculturally productive region of the world. Characterized by favorable climate, fertile soils and abundant water supply, the IGP is considered as the "Bread basket" of South Asia, providing food and livelihood security for the hundreds of millions of inhabited.

In social and economic terms, the IGP is the most important region of India. Given the large domain the IGP covering approximately 20^0N to 32^0N and 60^0E to 100^0E, it is difficult to generalize the climate of the region. The four seasons over our study region are Winter, Pre-monsoon, Monsoon and Post monsoon. The key component that controls the climate of the IGP is the southwest monsoon. The monsoon brings significant rainfall over the IGP.

The IGP is an environmentally sensitive, socially significant and economically strategic domain of India. The IGP during winter season is influenced by the extra tropical systems like western disturbance and also due to its physiography, IGP is highly prone to prolonged wide spread dense fog. Climate changed have had marked effect over IGP. Thus, an attempt had been made to examine the changes in winter fog frequency from 1970-2015, in order to elucidate their spatial and temporal patterns, thereby facilitating attempts to formulate effective mitigation strategies. For our study, the IGP region is classified into three sectors, Western IGP comprising of Punjab, Haryana and Delhi, Central IGP consisting of Uttar Pradesh, North Madhya Pradesh, Bihar and adjoining areas, and Eastern IGP consisting of West Bengal and entire North eastern states of India. A map showing the areas of these sectors and locations of meteorological stations is presented in Fig. 1.

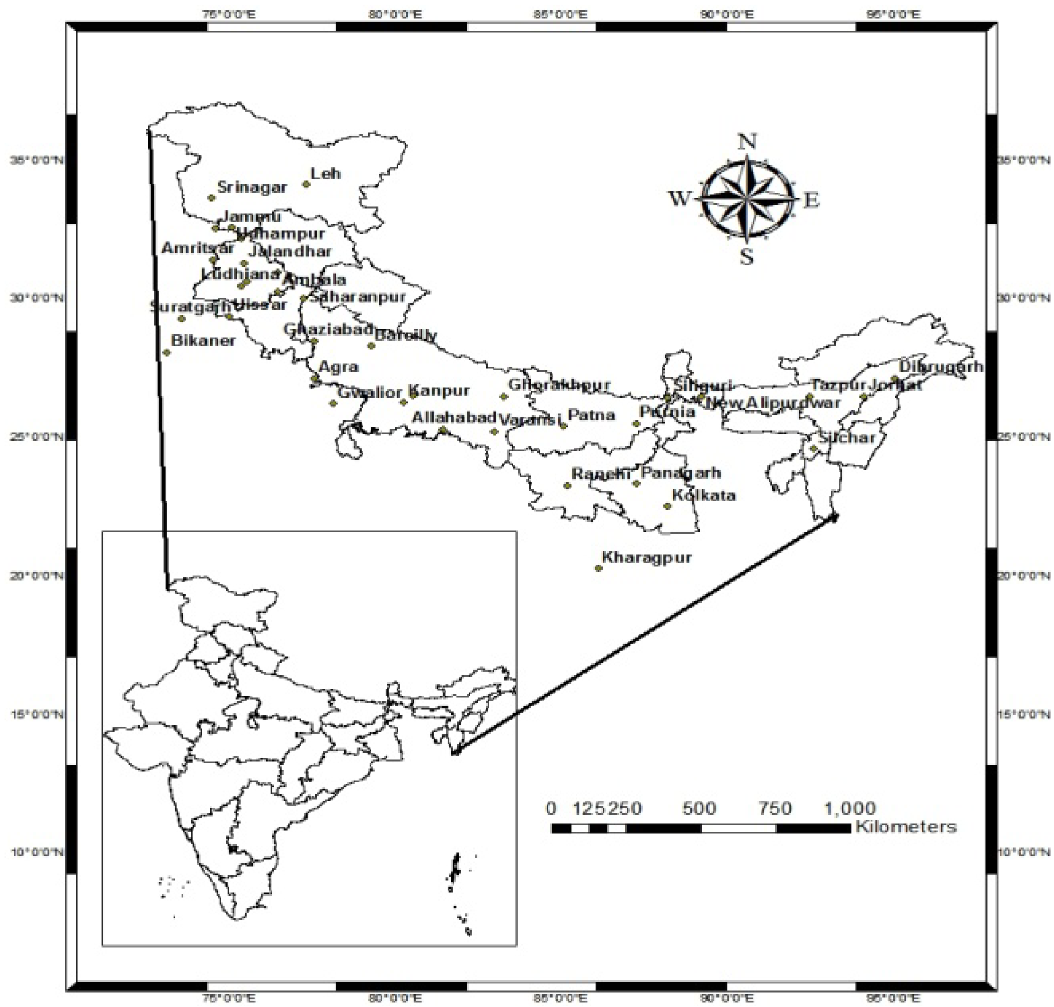

Fig. 1 Study area (IGP)

III. Data Sources and Methodology

A. Data Sources

The data for the 1971–2015 period during peak winter months i.e. December and January were retrieved from the current weather registers archived at various meteorological sections of Government of India all over the IGP. Fig. 1 shows the spatial distribution of the meteorological stations used in the present study. It is essential to indicate that locations of the meteorological stations are not the ideal. There are considerable spatial variations in certain areas. Most of the stations are located in flat areas with uneven distribution and few stations are located in mountainous areas. The observations made at all the stations have passed through a rigorous quality control procedure. Further, consistency checks and data gaps were filled according to standard procedures. We were very strict with data selection, only keeping the reliable data for further analysis.

B. Methodology

The information extracted from fog climatology can serve as a basis for the development of forecast decision support and guidance tools. After assuring the raw data quality, we calculated the means, standard deviation, variance, range, minimum and maximum statistics using descriptive statistical techniques. To have a better understanding of hidden decadal characteristics and periods of significant change, the data were divided into four and half decades (1971-1980, 1981-1990, 1991-2000, 2001-2010 and 2011-2015). The time series and trend analysis were conducted using Mann-Kendall method and regression analysis [11]-[13]. Then, we used EOF decomposition and geo-statistical analysis method to analyze spatial and temporal patterns associated with winter fog frequency. Eigenvectors obtained from EOF decomposition are then multiplied by trend vectors in the matrix of the winter fog frequency series to obtain eigenvector fields, thus describing the spatial trends in winter fog over IGP. Finally, we once again use the Mann-Kendall (M-K) method to identify variation points in the winter fog series for each sectors of IGP, thereby comprehensively describing the temporal and spatial patterns of winter fog over IGP [14].

C. Empirical Orthogonal Function Decomposition

EOF decomposition was first established by K. Pearson in 1902 [15]. It decomposes elements of a set of space-time data into two functions, one dependent only on time and another dependent only on space, to analyze the spatial structure of element fields [16]. Thus, EOF decomposition is commonly used to analyze spatial and temporal variations in meteorological elements. In contrast, principal component analysis (PCA) is mainly used to find a few independent vectors in a dataset to reduce its dimensionality, thereby simplifying data handling and interpretation. However, the operational steps are basically the same, when the original variables are anomaly data or standardized anomaly data [17]. EOF decomposition and several variants thereof have been widely applied for analyzing spatial changes in meteorological elements. Notably, EOF decomposition has been used to analyze drought occurrence in both time and space in Korea. A data-interpolating EOF has been used to analyze distributions of sea surface temperatures in a study demonstrating that decomposition can be highly effective, even when very high proportions of data are missing [18].

D. Trend and Spatial Trend Analysis

Regression analysis is applied to analyze the co-relationship of two variables, which determines relative direction and intensity. In this study, regression analysis is used to get the linear regression of fog frequency and time, and the equation is as:

$$F = aT + b,$$

where F is the fog frequency, T is the time, and a and b are coefficient parameters. If the unit of T is the year, usually a is the changing trend of annual winter fog frequency.

In order to examine temporal variations, time-series analyses using the M-K statistical test were carried out over the study region. The M-K test is the most common test used for trend analysis of hydro-meteorological data. M-K test is a non-parametric test and does not require the data to be normally distributed also it has low sensitivity to sudden break in homogeneous time series. The limitation of the M-K test is that in the case of positive autocorrelation present in the series, it shows a positive trend even when the trend is not present [19]. Hamed and Rao suggested a modified M-K, which calculates the autocorrelation between the ranks of the data after removing the apparent trend due to positive autocorrelation [20]. The magnitude of the trend was estimated using Theil and Sen's median slope estimator, which gives a robust estimate of trend as it is not influenced by outliers [21]. Theil and Sen's median slope estimator is extremely useful in assessing the practical significance of trend [22].

E. M-K Variation Analysis

The M-K test can also be used for variation diagnosis. Originally published in 1945, it was initially only used to detect trends in sequences [23]. However, subsequent modifications have enabled its use for detecting variation points in various trends and it has been applied in reversed sequence to detect variation points in trends in climate data time series [24], [25]. Since then, the method has been widely used to diagnose variation points in hydrological and meteorological data sequences [26], [27]. Notably, the MK method has been used to determine whether there were positive or negative trends in seven meteorological variables (and if so their significance) recorded at 12 weather stations in Serbia during 1980–2010 [28]. A modified form of the method has also been used to test scaling effects and four variants have been applied to determine trends in selected stream flow Statistics from Indiana [29], [30]. In addition, a procedure for calculating exact distributions of the M-K trend test statistic for persistent data with an arbitrary correlation structure has been presented and the test has been used to detect directions and magnitudes of changes in monotonic trends in annual and seasonal precipitation over time in annual precipitation in Madhya Pradesh, India [31]. Here, we applied the M-K test to detect trends variation points in the time series of the data obtained stations over IGP.

IV. Results and Discussions

A. Descriptive Statistics

On monthly basis, the mean frequency of fog over all the station under study over the IGP, based on last forty five year data from 1971 to 2015, shows that the average poor visibility days, range with highest value of 15.58 days in January and lowest value of 1.42 days in April (Table I). The reason of poor visibility varies from season to season. Radiation fog occurs several times during the winter months (December–February) every year over the IGP [32]. Seasonal variation of fog shows that there is prominence of fog over IGP [33]. The most favourable month for fog occurrence over Patna (one of the station over IGP) has been December followed by January [34]. The results of the descriptive statistical analysis of fog data (1971-2015) at various locations in IGP for the peak winter months of January and December are shown in Table II. It is evident from the statistical data of mean, standard deviation, variance, range, maximum and minimum fog frequency that the frequency of fog is at its peak during the month of January (~16 days), followed by December (~13 days) over IGP. Fog frequency is maximum over Purina (central IGP) with 47.9 days during the peak winter months of January and December. It is followed by Saharanpur, Ghaziabad (both in central IGP) with 46.1 and 45.5 days, respectively. The range i.e. difference between minimum and maximum fog frequency over a station is lowest with 28 days and highest with 54 days based on the data of last forty five years. Maximum and minimum frequency of fog days along with wide range for individual stations clearly indicates that during the last four and half decade there has been significant increase the fog days during the peak winter months over the study area. Further, the coefficient of variance also indicates that the occurrence of fog over the IGP is highly variable, fluctuating and it lacks consistency.

TABLE I
MONTHLY FOG STATISTICS OVER IGP

Months	Mean	Standard Error	Standard Deviation	Variance
Jan	15.58	1.25	6.78	45.95
Feb	7.39	0.92	4.94	24.39
Mar	2.69	0.43	2.29	5.25
Apr	1.42	0.16	0.85	0.73
May	1.96	0.22	1.19	1.43
Jun	3.25	0.95	5.14	23.38
Jul	2.29	0.19	1.03	1.07
Aug	2.31	0.21	1.09	1.18
Sep	2.41	0.28	1.49	2.24
Oct	4.26	0.68	3.66	13.42
Nov	7.82	1.19	6.38	40.75
Dec	13.27	1.47	7.92	62.67

TABLE II
FOG STATISTICS OVER IGP STATIONS (JAN & DEC)

Station	Mean	Standard deviation	Variance	Minimum	Maximum	Range
Jalandhar	39.7	14.1	198.4	9	55	46
Ambala	32.0	14.3	205.6	6	55	49
Amritsar	23.8	12.5	156.6	3	50	47
Bhatinda	37.7	13.4	180.6	8	62	54
Ludhiana	30.7	15.4	236.8	6	54	48
Ghaziabad	45.5	11.1	122.7	12	62	50
Sharanpur	46.1	12.0	144.1	16	62	46
Bareilly	41.2	11.5	131.6	19	60	41
Kanpur	38.2	12.8	163.7	14	57	43
Allahabad	32.4	14.8	219.2	6	57	51
Jorhat	44.6	5.9	35.3	31	55	24
Gorakhpur	39.4	12.9	164.9	16	62	46
Purnia	47.9	7.1	51.3	28	6	33
Chandigarh	15.0	10.1	103.5	1	43	42
Jammu	8.7	7.1	51.3	0	29	29
Pathankot	11.3	10.9	118.5	0	37	37
Hissar	28.8	15.9	255.9	5	57	52
Suratgarh	30.13	14.9	220.9	7	59	52
Siliguri	20.14	9.4	89.3	5	38	33
Tezpur	16.4	10.7	114.7	3	46	43
Dibrugarh	26.02	8.23	67.9	9	49	40
Srinagar	10.56	6.5	42.7	0	28	28
NewAlipurdwar	13.2	10.5	110.3	2	36	34
Kharagpur	11.1	10.0	100.2	1	37	36
Shilong	11.42	6.5	42.5	2	30	28
Panagarh	17.38	11.1	124.6	4	44	40
Kolkatta	31.2	3.9	131.3	15	57	42

B. Spatial Variability

1. Spatial Distribution: Hot Spots of Fog

Fig. 2 depicts the spatial distribution of average number of foggy days during the peak winter months of December and January, averaged across the forty five year study period. The fog data collected from various meteorological stations were analyzed to determine the hot spots of fog over IGP. The hot spot analysis was carried out using Getis-OrdGi* algorithm. The hot spot analyses classified the fog prone zone into three clusters. Cluster A referred as High Fog Zone (HFZ), it pertains to the area where the average foggy days are above 63%. It covers mainly the plains of river Indus and Ganges i.e. Punjab, Haryana, Delhi, Uttar Pradesh, Bihar and some parts of North east India. Cluster B is referred as Moderate Fog Zone (MFZ), it pertains to the area where the average foggy days are between 34% to 63%. It covers western parts of Punjab, South Uttar Pradesh, North Madhya Pradesh, Jharkhand, West Bengal and Parts of North east India. Cluster C is referred as Low Fog Zone (LFZ), it pertains to the area where the average foggy days are less than 34%. It covers Jammu Kashmir, Himanchal Pradesh, and North-east India. The reason for high fog over HFZ includes availability of very high moisture content along with anthropogenic aerosols due to rapid industrialization. The IGP has also been classified into west, central and east IGP to study the spatial and temporal variability of fog based on geographical locations.

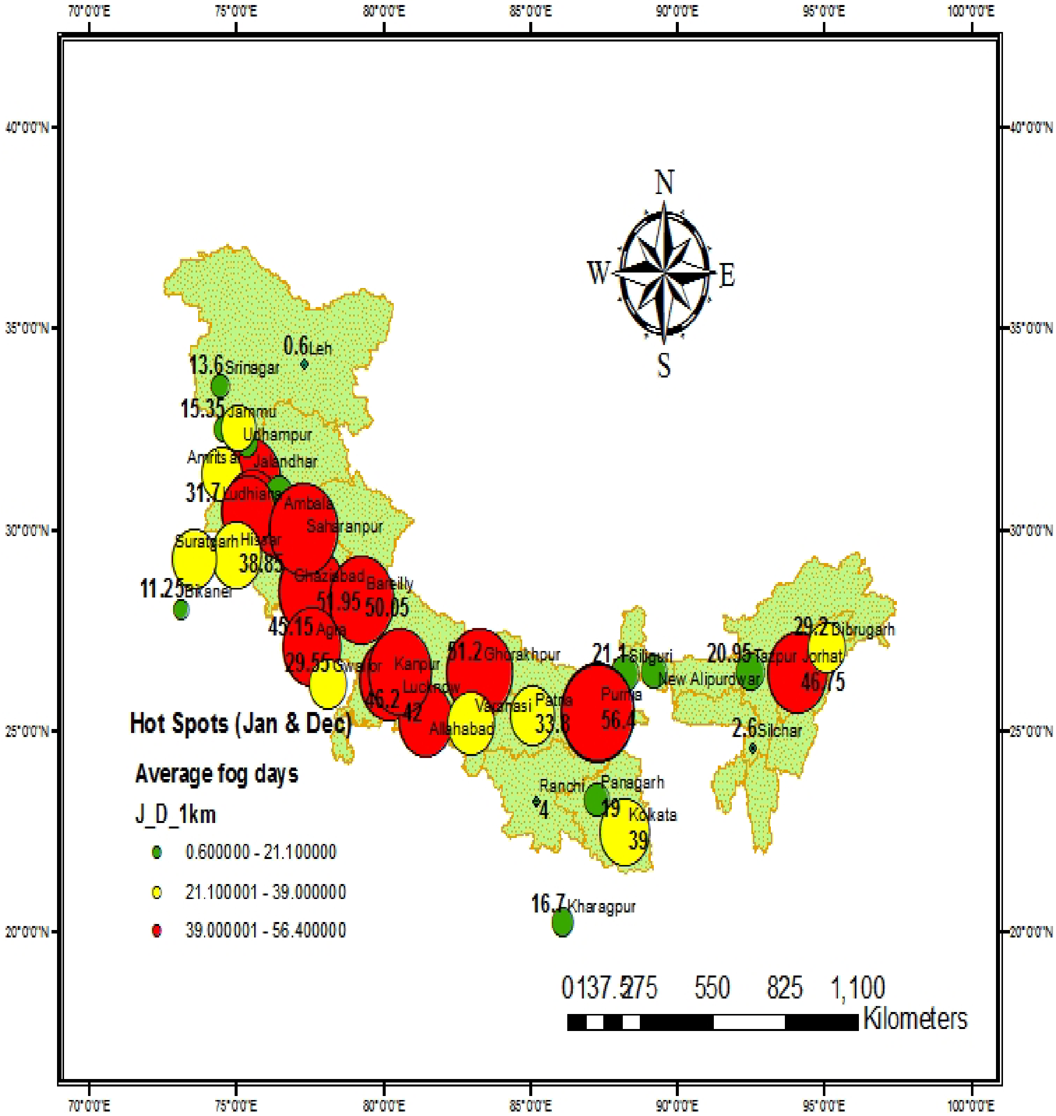

Fig. 2 Hot spots (IGP)

2. EOF Decomposition

The fog data analyzed herein originated from various stations of IGP during the period 1971-2015. EOF was used to calculate the eigen values. Eigen values for the covariance matrix of winter fog matrix and their contributions to variance both specific and cumulative, obtained by EOF are also shown in Table III. The fog frequency field rapidly converged; the first principal component (PC) accounted for more than half (50.11%) of the variance in winter fog. The first four components (all of which had Eigen values more than one) explain for 76.19% of the variation. Thus, the first four PCs and eigenvectors described the spatial distribution of winter fog over IGP quite well.

The vector corresponding to the largest eigenvalue is eigenvector 1, with progressively small eigenvalues associated with subsequent eigenvectors. The first four eigenvectors obtained from the EOF decomposition of the winter fog over IGP are shown in Table IV. The first four eigenvectors obtained from the EOF analysis provide an approximate description of the fog values. If the values are consistently positive or negative, there is a consistent fog trend and the area with the largest absolute value is the center of the variable field. In contrast, if the eigenvalue fluctuates between positive and negative, the trend is non uniform. As shown in the Table IV and Fig. 6 (a), all components of eigenvector 1 are positive except the data from Srinagar and Shillong, indicating that fog frequency during peak winter months over IGP had high spatial consistency during the study period. The upward trend in winter indicates that the winter fog frequency over IGP has enhanced, and this consistent trend accounts for 50.11% of the variance. The overall consistency and enhanced representation by eigenvector 1 are the spatial features of fog pattern over IGP during the study period. The eigenvector 2, 3, and 4 values obtained from EOF decomposition of winter fog data are shown in Figs. 6 (b), (c), and (d) respectively. The positive trend indicates that winter fog over IGP has enhanced for all the four eigenvectors, and this consistent trend accounts to 76.19% of variance through first four eigenvectors.

TABLE III
EIGEN-VALUES & THEIR CONTRIBUTION TO VARIANCE

	Initial			Extraction sums of squared loadings		
Component	**Eigen values λ**	**Proportion of variation (%)**	**Cumulative proportion of variation (%)**	**Eigen values λ**	**Proportion of variation (%)**	**Cumulative proportion of variation (%)**
1	15.62	55.78	55.78	14.03	50.11	50.11
2	2.44	8.71	64.49	3.18	11.35	61.46
3	2.10	7.51	72.00	2.71	9.68	71.14
4	1.17	4.19	76.19	1.42	5.05	76.19
5	0.98	3.52	79.72			
6	0.88	3.17	82.89			
7	0.80	2.85	85.75			
8	0.57	2.03	87.78			
-	-	-	-			
28	0.01	0.22	100			

TABLE IV
EIGENVECTORS OBTAINED BY EOF DECOMPOSITION

Station	1	2	3	4
Jalandhar	0.88	0.03	0.02	0.27
Ambala	0.91	0.08	0.06	0.15
Amritsar	0.88	0.19	-0.24	0.11
Bhatinda	0.64	0.09	-0.04	0.40
Ludhiana	0.95	0.12	0.12	-0.03
Ghaziabad	0.83	0.06	0.13	0.11
Sharanpur	0.83	0.07	0.13	0.29
Bareilly	0.89	0.02	-0.02	0.08
Kanpur	0.87	0.11	0.09	0.11
Allahabad	0.90	0.09	0.18	0.09
Jorhat	0.16	-0.15	0.61	-0.41
Gorakhpur	0.81	0.30	0.23	0.07
Purnia	0.38	0.69	0.15	0.14
Chandigarh	0.89	0.13	0.17	0.03
Jammu	0.73	0.11	0.20	-0.05
Pathankot	0.77	0.43	0.16	0.07
Hissar	0.95	0.07	0.05	0.08
Suratgarh	0.84	0.05	0.18	0.09
Siliguri	0.37	0.19	0.19	0.78
Tezpur	0.21	0.39	0.76	0.26
Dibrugarh	-0.04	-0.08	0.86	0.14
Srinagar	0.11	-0.74	-0.59	-0.01
NewAlipurdwar	0.58	0.47	0.46	0.25
Kharagpur	0.77	0.19	0.10	-0.02
Shilong	-0.65	-0.40	-0.17	0.30
Panagarh	0.57	0.72	0.14	0.07
Kolkatta	0.64	0.32	0.48	-0.16

The Geo-statistical analysis module of ARCGIS 10 was used to undertake a semi-variogram analysis of the first four eigenvectors. Thereafter, kriging interpolation technique was used to draw a map of each eigen vector field. The azimuth angles of eigenvector 1, 2, 3 and 4 are 4.51°, 25.57°, 2.3°, and 13.58°. All the eigenvectors have a small Nugget values, indicating that fog measurement error is small. Indeed, the nugget of eigenvector 3 is zero, indicating that the measurement error for winter fog in the eigenvector field can be ignored. The partial sill of eigenvector 1 is significantly lower than that of the other eigenvectors indicating smaller scale variations.

C. Temporal Variability

Time series analysis of fog data for the period of forty five year i.e. 1971-2015 is depicted in Fig. 3. It is evident from the figure that there has been generally increasing trend in fog frequency in last forty five years over IGP. Frequency of fog over Patna, which is one of the stations in IGP, has increased significantly during winter months [34]. Studies on fog over IGP of India during last decade have shown that there has been significant increase in occurrence and persistence of fog during winter over IGP.

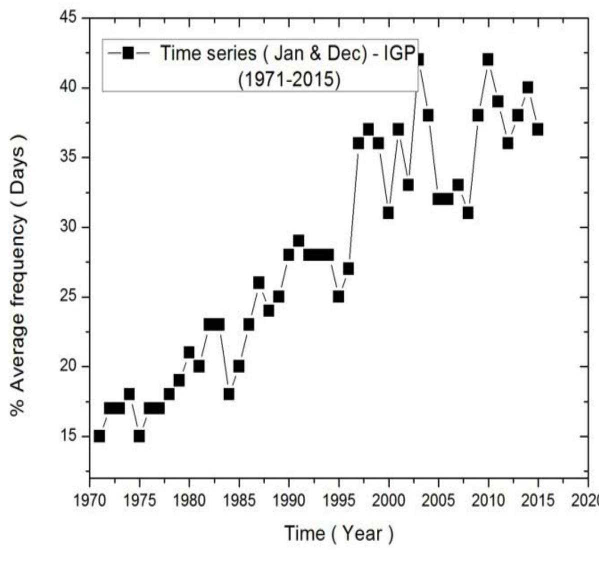

Fig. 3 Time series 1971-2015 (IGP)

In the present study, to have a better appreciation of fog characteristics and its trend, forty five years of data were divided into four and half decades (1971-1980, 1981-1990, 1991-2000, 2001-2010, 2011-2015). Fig. 5 (a) illustrates the decadal winter mean frequency of fog over the study area. It can be seen that during the decade 1971-80, the average fog days were just 28.06%, whereas it has significantly increased to 61.29% in the present decade 2010-2015. There has been alarming increase in foggy days by 118.39% in last four and half decades (Fig. 5 (b)). It is also observed that there has been increase of 9.57% in number of foggy days in just last five years. It was observed that there was a significant increase of 32.18% and 32.16% in foggy days during the decade 1981-1990 and 1991-2000 respectively compare to its previous decade. Fig. 5 (c) shows that there are 66.29% foggy days over central sector of IGP, followed by 41.94% and 33.06% foggy days over west IGP and east IGP respectively. Similarly, Fig. 5 (d) shows that there are 68.27% of foggy days over the cluster A (HFZ), followed by 48.03% and 21.79% foggy days over cluster B (MFZ) and cluster C (Low fog prone zone) respectively.

Interestingly, an air quality policy of the Delhi State Government was adopted in 2001, resulting in a reduction in the concentration of soot and water soluble particles observed in winter season. Fortunately, these aerosol components are anthropogenic and can be controlled by these air pollution control policies. Delhi and the National Capital Region have shown good improvement since 2001, achieved in part by the introduction of compressed natural gas fuelled vehicles. However, although this may reduce the occurrence of fog in the longer term, the data show that there has been little effect from this policy to date. Further, trend analysis was carried out in order to evaluate uncertain pattern of fog in the past and to predict its future pattern. Trend analysis was performed using the number of foggy days for the month of December and January during the period 1971-2015. The result is illustrated in Fig. 4. Trend analysis was performed using non-parametric M-K test on time series of fog. The null hypothesis was stated that fog data series was independent, whereas the alternate hypothesis, stated existence of trend. As the p values are lesser than the significant level (0.5), M-K test at 95% confidence level rejected the null hypothesis and accepted the alternate hypothesis that there exists a trend for almost all the station over the IGP. Stations with a mean frequency larger than 3% display a positive trend at the 99 % significance level. During January, highest M-K statistics value of 429 was observed over Ludhiana, followed by Jalandhar and Ghaziabad city with values 402 and 384 respectively. Kendall's tau correlation value 0.59 over Ludhiana was highest over the region and it is followed by Jalandhar and Ghaziabad with values 0.58 and 0.56 respectively. This reveals that there exists a strong correlation between time in years and fog frequency over the station with high values i.e. as the time progress the fog frequency also tend to increase accordingly.

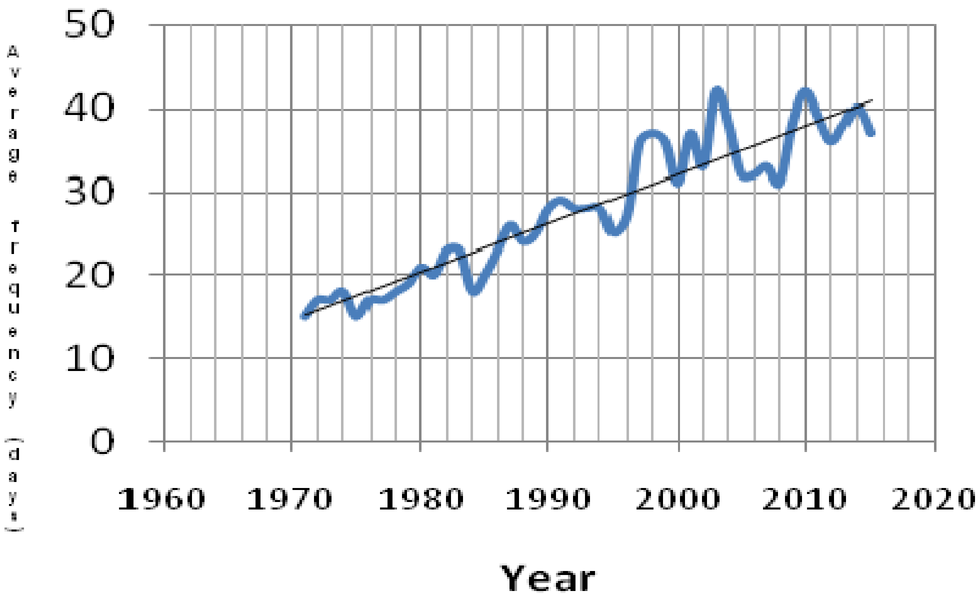

Fig. 4 Trend Analysis (IGP)

Kendall's tau statistics is a measure of correlation and therefore it measures the strength of relationship between the two variables, time and fog frequency (Fig. 7). In our case, it showed that there exists a stronger positive correlation over almost all the stations during January compared to December. Almost similar trend in spatial variability was observed for both the peak winter months. Further, the magnitude of trend was estimated using the Theil and Sen's median slope estimator (Fig. 8) [21]. This method gives a robust estimate of trend as it is not influenced by outliers or extreme values [11]. It was observed that magnitude of the trend is higher over most of the regions of IGP during January excepts over Punjab which has higher magnitude in December.

D. Variation Diagnosis

The M-K method was used to discriminate variation points in the trend of winter fog series recorded at each station during 1971-2015. The results summarized in Table V show the variation points occurred in the trends of winter fog sequence recorded over west, central and east IGP. The timing of variation points has spatial characteristics. Fig. 7 shows that during the period 1971-80, the first variation occurred in early 1970s over central IGP, which was followed by west and east IGP. The frequency of variation was high over central and east IGP compare to west IGP. It was observed that frequency of variation was high over all the three sectors of IGP during the two decades 1981-90 and 1991-2000. After 2000, the frequency of fog variation over west and central IGP declined. However, there was an increasing trend over all the three sectors of IGP. Another important inference from the study was that till 1985, the frequency of fog over east IGP was more than west IGP. After 1985 the reverse pattern was observed and thereafter, frequency was throughout higher over West IGP. The most probable cause for this reversal could be the significant increase in aerosols due to rapid industrialization and increase in moisture content due to increase in irrigation network over west IGP during the last one and half decade of nineteenth century and early twentieth century.

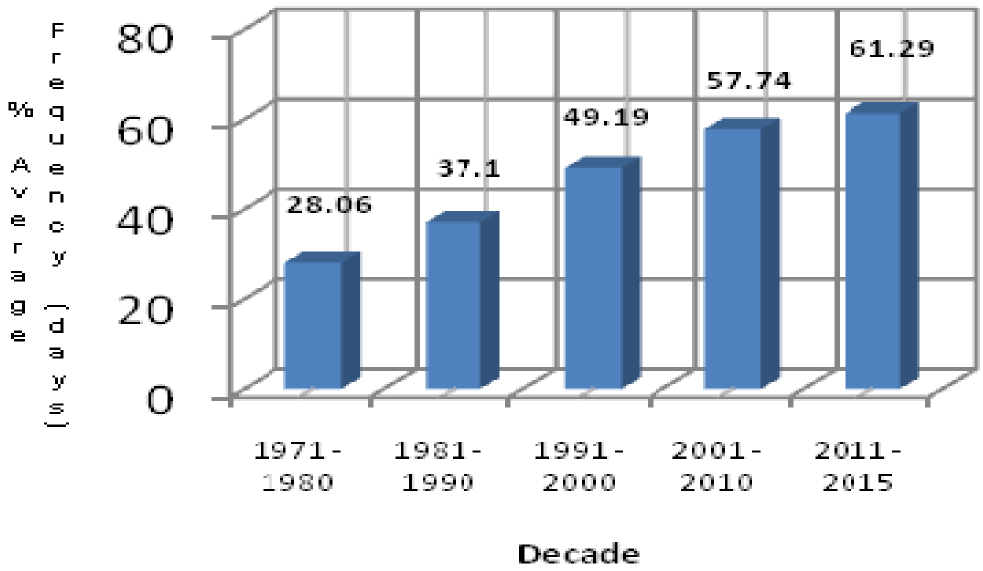

Fig. 5 (a) Fog frequency decade-wise (%)

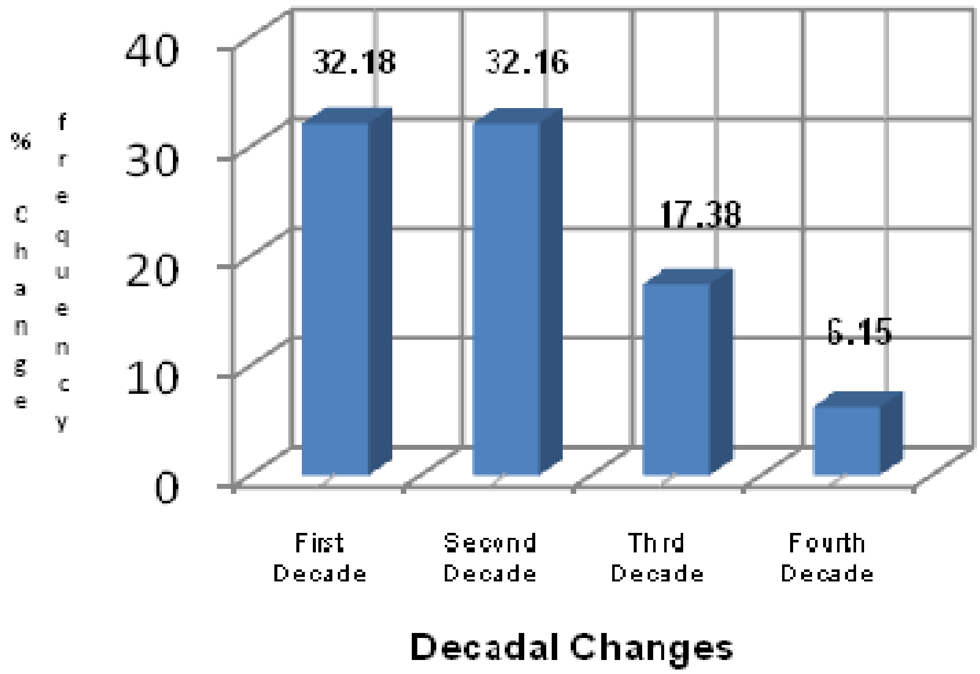

Fig. 5 (b) Fog frequency decadal change (%)

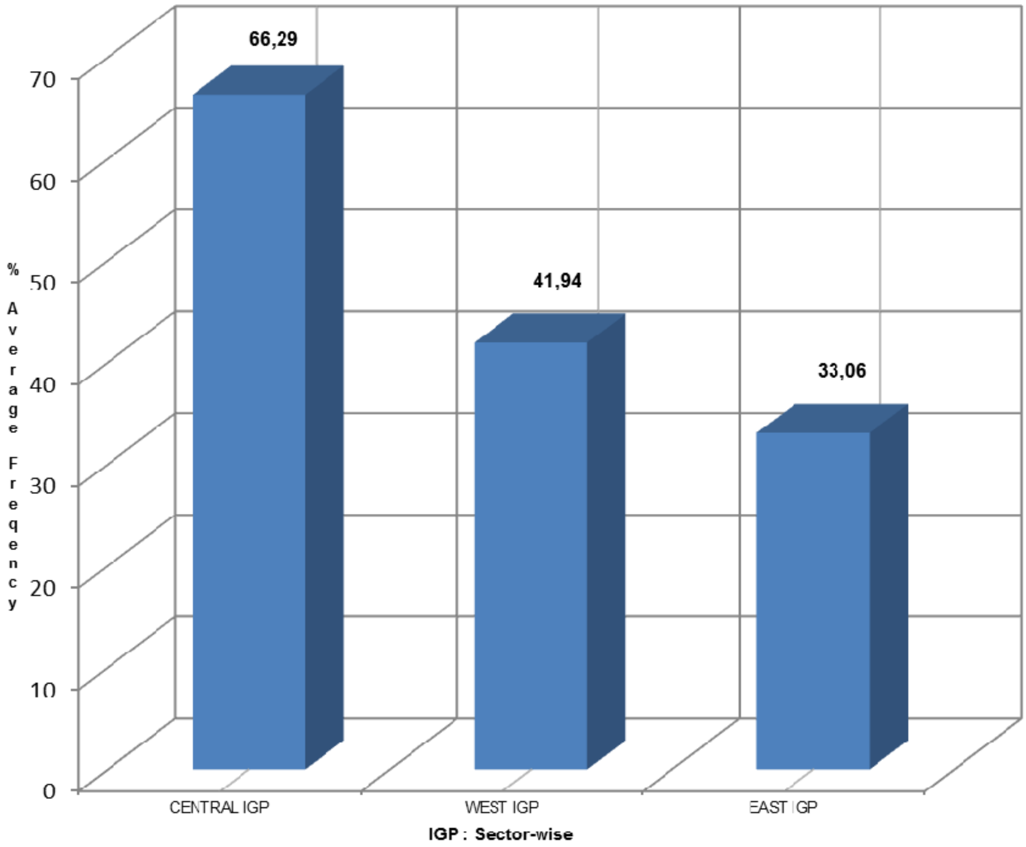

Fig. 5 (c) Fog frequency sector-wise (%)

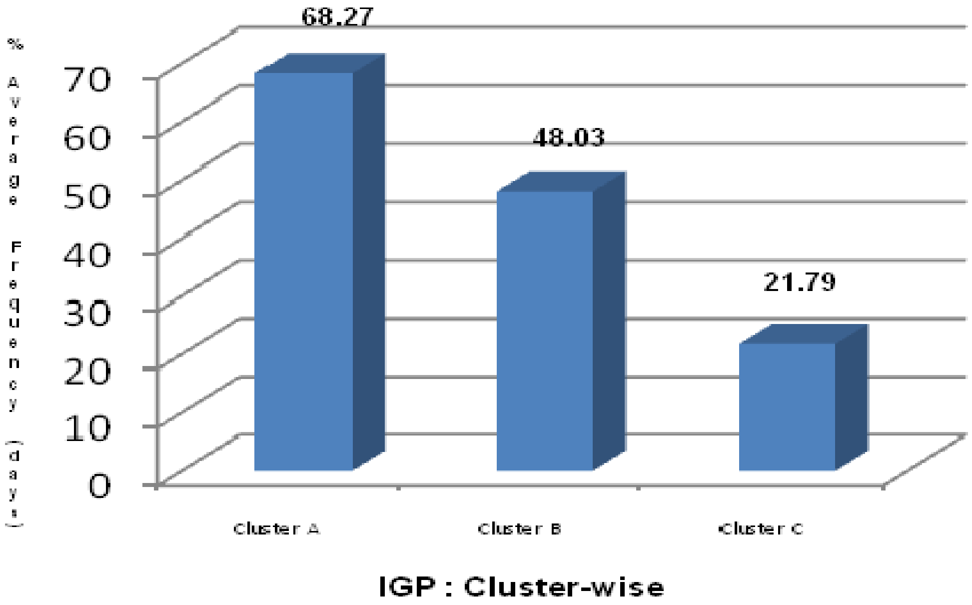

Fig. 5 (d) Fog frequency cluster change (%)

E. Diurnal Temporal Variability

To ascertain the diurnal temporal variability of fog period during peak winter months of January and December over IGP, the fog data were examined and analyzed. The results are illustrated in Fig. 8 (a). It is observed that average fog frequency is more than 80% i.e. on more than 80% occasion between 0600 and 0900 hrs, the visibility is poor due to fog during the peak winter months of January and December over IGP. The percentage drops rapidly after 0900 hrs to less than 20% by 1200 hr indicating a rapid improvement in visibility after 0900 hr. The average fog frequency percentage reaches its least value close to 10% by 1500 hrs. It remains below 20% from 1200 hrs till around mid night. In fact, on most of the days, the increase in percentage value or drop in visibility starts after sunset and it continues till sunrise next day. To understand the fog frequency characteristics sector wise, over western, central and eastern IGP, the data were subjected to further analysis. The most favourable areas for fog formation lies over central and west IGP sectors covering Punjab, Delhi, Haryana, Uttar Pradesh, where more than 18% of the days, fog is reported. The fog events which prolong longer into daytime has a stronger effect on the diurnally averaged aerosol radiation forcing then those events which are confined to the early morning hours. Further, Fig 8 (b) shows that over the western IGP sector, the peak average fog frequency percentage remains around 70-80% between 0300 and 0900 hrs. The peak value is approximately 40% over western IGP between 0600 and 0900 hrs, whereas, over east IGP the peak percentage is 30-40% at 0600 hrs. This concludes that fog occurrence is much higher and for longer duration over central IGP which constitutes plains of Uttar Pradesh, Bihar and Jharkhand.

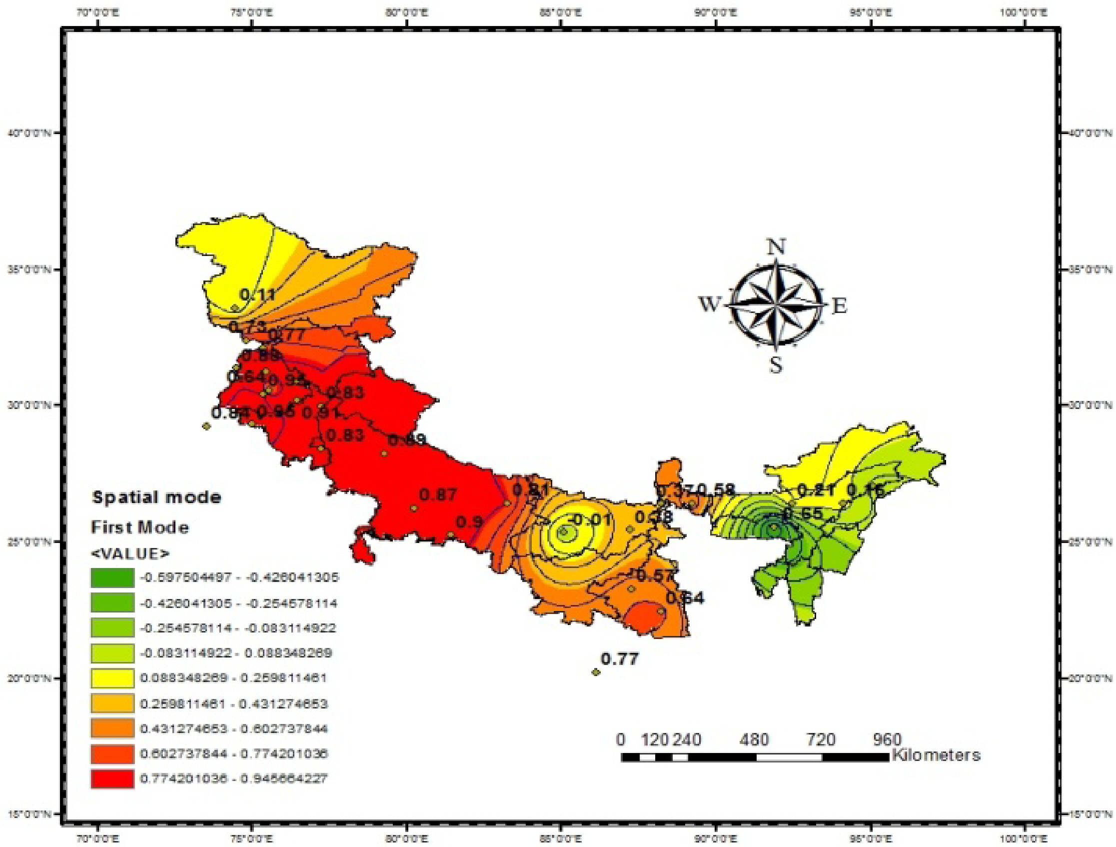

Fig. 6 (a) First mode

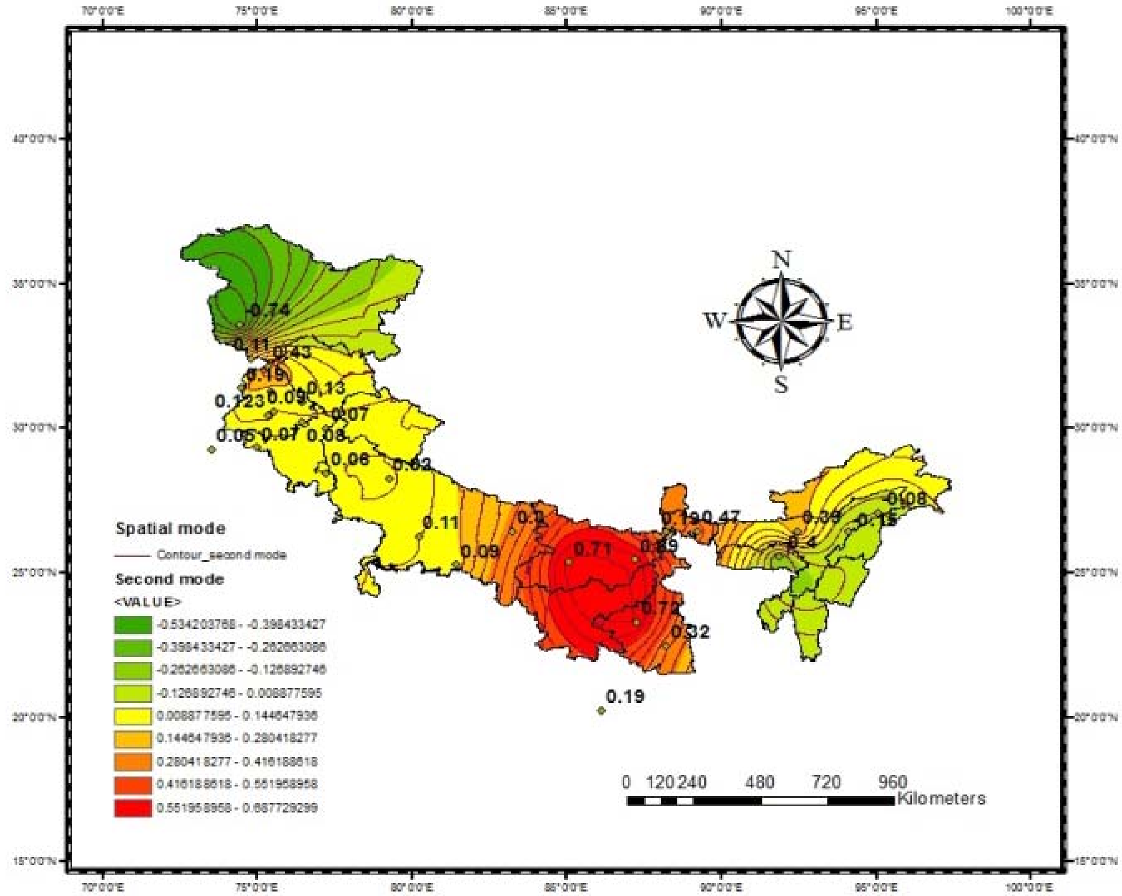

Fig. 6 (b) Second mode

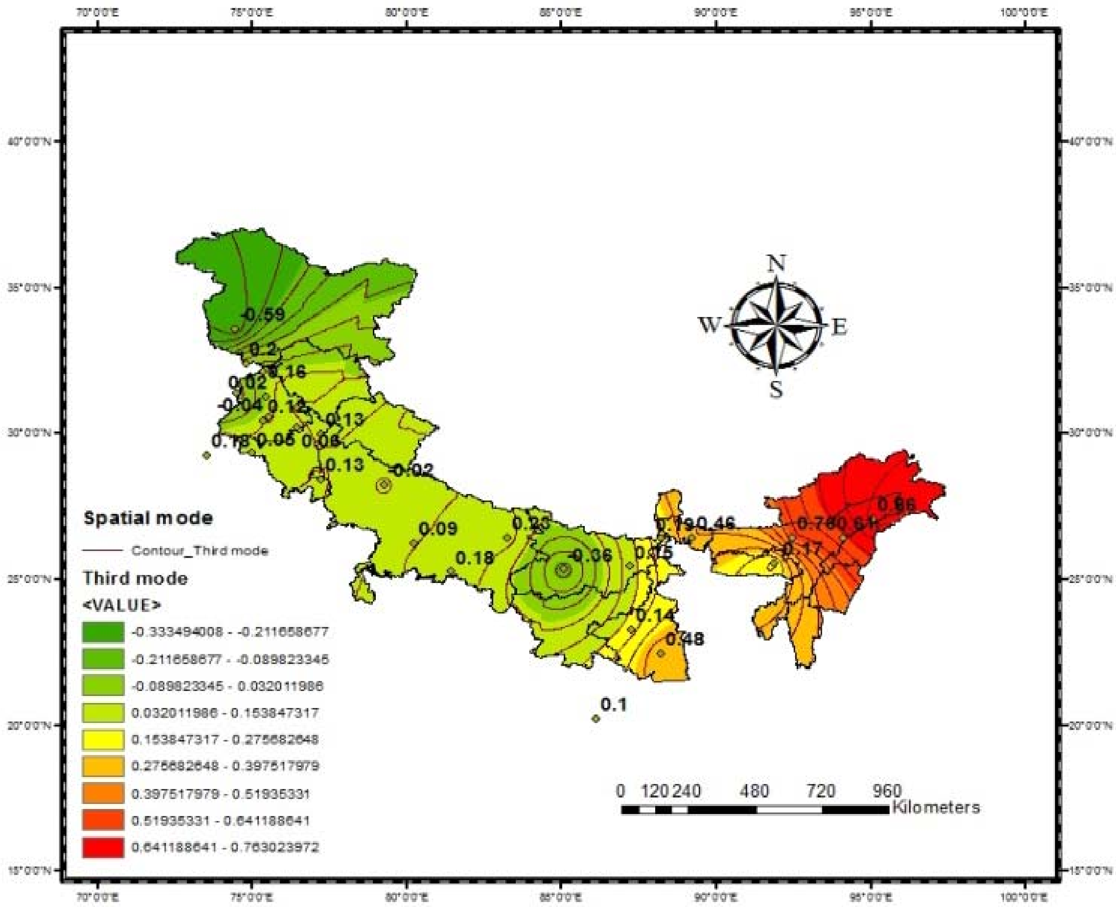

Fig. 6 (c) Third mode

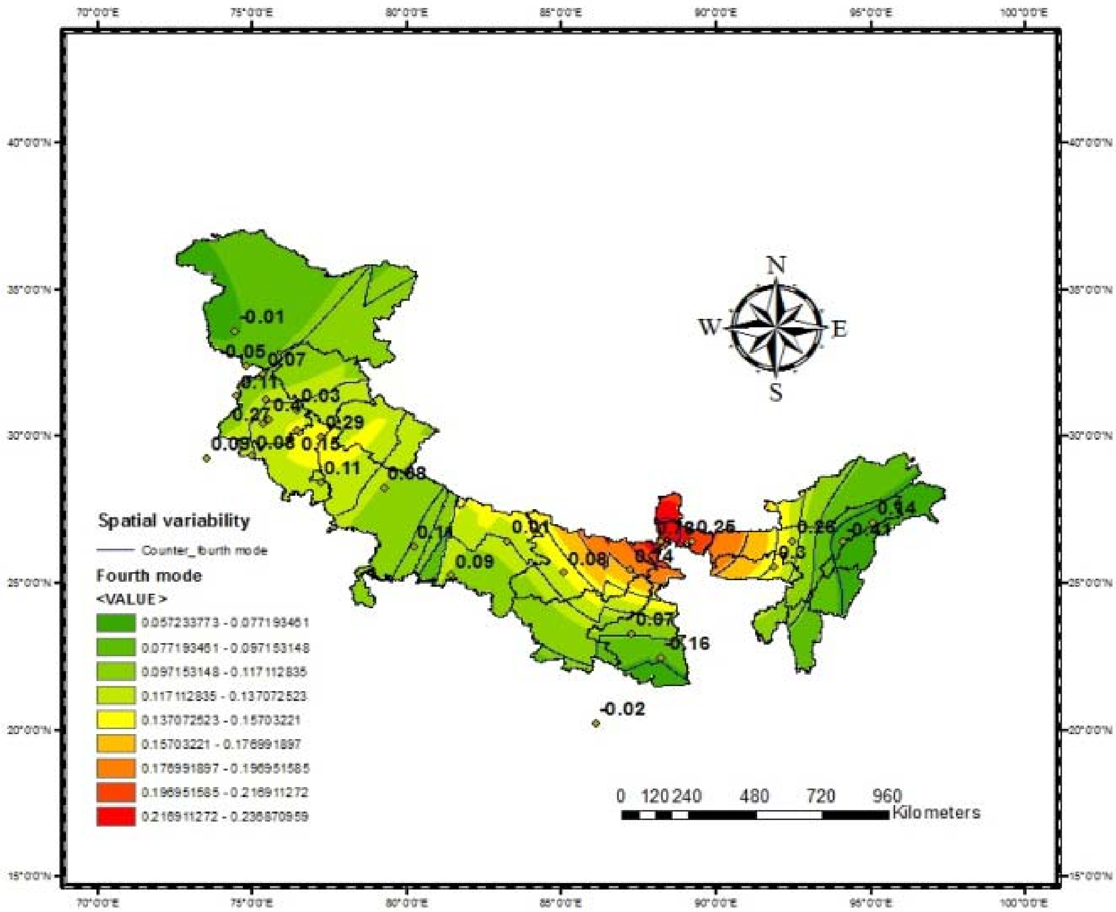

Fig. 6 (d) Fourth mode

V. Conclusions

The present work analyzed fog characteristics over IGP, Indian covering the period 1971-2015. The frequency of occurrence of fog over IGP has increased alarmingly in the peak winter months of January and December during the last four and half decades. The spatial and temporal patterns of winter fog over IGP was analyzed using long term ground based observational data by applying EOF decomposition. The main spatial patterns of winter fog over IGP during the study period were a consistent overall increase, which was strongest over central IGP followed by west IGP and weakest over east IGP. The consistent overall increase in fog frequency is accounted for 76.19% of the total variation. Variation points were detected in the winter fog frequency sequence recorded over IGP. However, their timing had clear spatial pattern, starting from central IGP and gradually followed by west and east IGP. During the two decades i.e. 1981-90 and 1991-2000, the variation point occurred frequently over all the three sectors of IGP. After 2000, the frequency of winter fog variation declined gradually. Our study reveals that over last four and half decades fog occurrence has drastically increased, despite some major efforts have been initiated by various governmental and nongovernmental organizations (NGOs) for example introducing an air quality policy (i.e. CNG vehicles) of the Delhi State Government adopted in 2001, resulting in a reduction in the concentration of soot and water soluble particles observed in winter season. In the recent past, major decision to implement odd- even scheme in Delhi to restrict the use of vehicles in order to improve the air quality may result in restricting the increasing trend of fog to some extent over Delhi region. One of the probable reasons for these increasing trends in fog over IGP is anthropogenic aerosols, which are higher during the winter period, because people all along the IGP, burn coal, wood, paraffin (kerosene), and plant leaves for cooking and to ward off the cold. Additionally, the rapid industrialization and increase in vehicle use are also major contributing factors in the release of anthropogenic aerosols. As the winter period is dominated by cold, relatively dry air and a low-level inversion with light winds and low minimum temperatures, anthropogenic pollutants are not able to disperse, contributing to enhanced, prolonged and frequent fog activity. An increase in winter fog frequency, as revealed by this study, may imply more blocking of sunlight at the surface and therefore may result in more cooling or severe winter conditions over and around Ghaziabad. The results of the study offer insight and a new perspective for planners and policy makers in guiding them to take proactive measures.

Timely measures can certainly help in reducing the irreparable loss or damage that may be caused by these alarming changing trends of fog over IGP, India in the years to come.

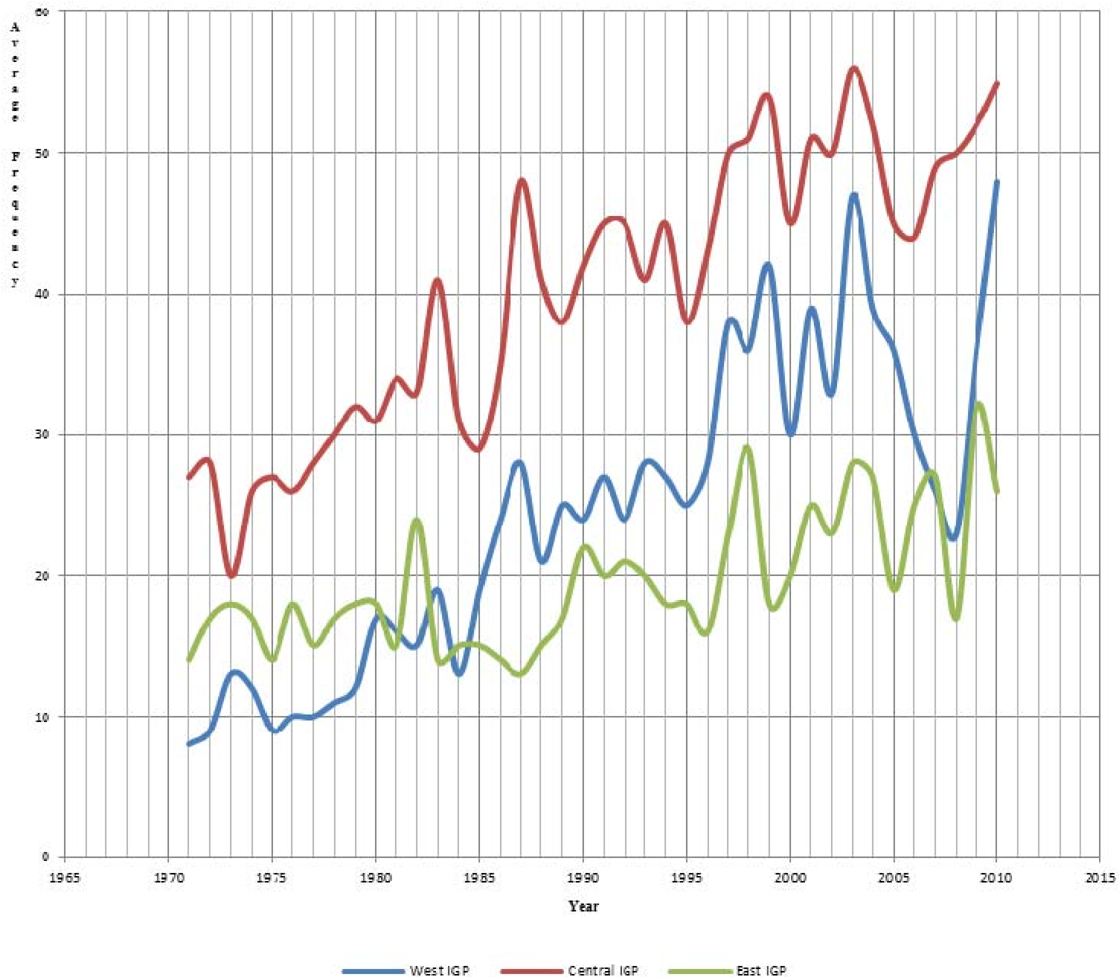

Fig. 7 Variation Points

TABLE V
VARIATION POINTS IN WINTER FOG TREND

	Variation points			
Sector	1971-80	1981-90	1991-2000	2001-2010
Central IGP	1972, 1973, 1976, 1979, 1980	1981- 83, 1985, 1987	1992-95, 1999, 2000	2001-2003, 2006
West IGP	1973, 1975, 1980	1982-84, 1987-90	1991-93, 1995, 1997-2000	2001-2003, 2008
East IGP	1973, 1975-77, 1980	1981-83, 1987, 1990	1991, 1992, 1996, 1998, 1999	2001-2003, 2005, 2007-2009

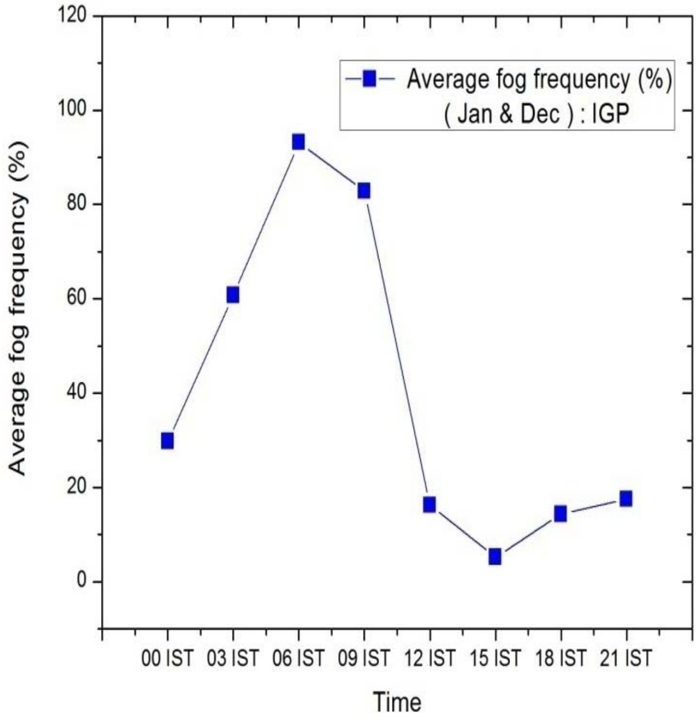

Fig. 8 (a) Diurnal fog frequency IGP (%)

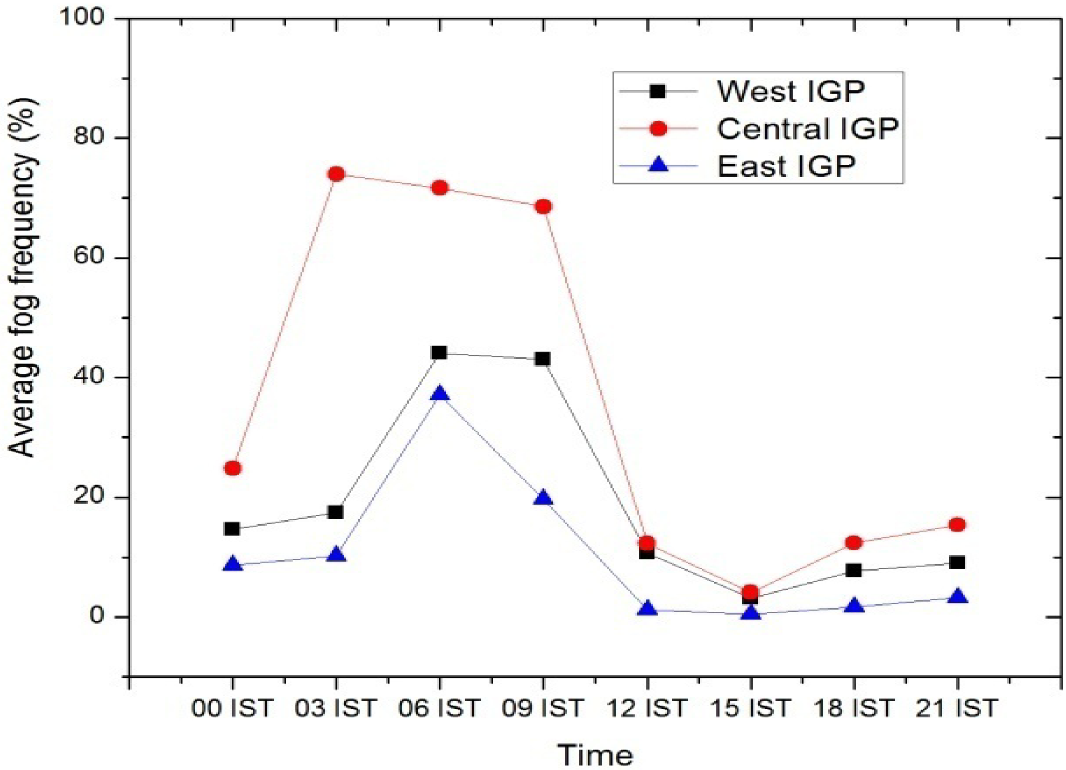

Fig. 8 (b) Diurnal fog frequency sector-wise (%)

ACKNOWLEDGMENTS

The authors extend sincere thanks to the staff of a government meteorological sections located across the study area, for providing the conventional and AWS meteorological data for the study.

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