A Ground Observation Based Climatology of Winter Fog: Study over the Indo-Gangetic Plains, India

Sanjay Kumar Srivastava, Anu Rani Sharma, Kamna Sachdeva

Abstract**—**Every year, fog formation over the Indo-Gangetic Plains (IGPs) of Indian region during the winter months of December and January is believed to create numerous hazards, inconvenience, and economic loss to the inhabitants of this densely populated region of Indian subcontinent. The aim of the paper is to analyze the spatial and temporal variability of winter fog over IGPs. Long term ground observations of visibility and other meteorological parameters (1971-2010) have been analyzed to understand the formation of fog phenomena and its relevance during the peak winter months of January and December over IGP of India. In order to examine the temporal variability, time series and trend analysis were carried out by using the Mann-Kendall Statistical test. Trend analysis performed by using the Mann-Kendall test, accepts the alternate hypothesis with 95% confidence level indicating that there exists a trend. Kendall tau's statistics showed that there exists a positive correlation between time series and fog frequency. Further, the Theil and Sen's median slope estimate showed that the magnitude of trend is positive. Magnitude is higher during January compared to December for the entire IGP except in December when it is high over the western IGP. Decade wise time series analysis revealed that there has been continuous increase in fog days. The net overall increase of 99 % was observed over IGP in last four decades. Diurnal variability and average daily persistence were computed by using descriptive statistical techniques. Geo-statistical analysis of fog was carried out to understand the spatial variability of fog. Geo-statistical analysis of fog revealed that IGP is a high fog prone zone with fog occurrence frequency of more than 66% days during the study period. Diurnal variability indicates the peak occurrence of fog is between 06:00 and 10:00 local time and average daily fog persistence extends to 5 to 7 hours during the peak winter season. The results would offer a new perspective to take proactive measures in reducing the irreparable damage that could be caused due to changing trends of fog.

Keywords**—**Fog, climatology, Mann-Kendall test, trend analysis, spatial variability, temporal variability, visibility.

I. Introduction

DURING the peak winter months of December and January in last two years, more than 150 accidents took placed in different parts of Delhi and National capital region of India, claiming the life of 69 people. Recently on 22 December 2015, in a tragic accident, 17 cars piled up on Yamuna express way near New Delhi, causing injuries to more than dozen people besides damage to the vehicles. A closer look at the data revealed that most of the accidents in the month of December and January are due to poor visibility in fog. Hundreds of flights are cancelled, diverted or delayed for hours every year in December and January at various airports of India due to fog. Trains and road transportations are also disrupted, causing great inconvenience to the inhabitants of densely populated IGP. The effect of fog on human life was recognized in the early ages of mankind, but its impact has enhanced manifold during the recent decades due to the huge increase in social and economic activities. Over 70% of the damage caused by natural phenomena is related to meteorological disaster, among which severe droughts, floods, thunderstorms, hailstorms, and fog are the most common [1]. The total economic loss related to fog is comparable with that of tornados, hurricanes, or storms in the same situation [2]. Fog is defined as obscurity near the surface layer of the atmosphere which is due to the presence of suspended water droplets and is associated with the visibility lesser than 1000 meters. Extremely poor visibility in the dense fog is very dangerous for aircraft landing and takeoff, road driving, and navigation. Fog caused by air pollution is a severe health hazard; fog is a cause of corrosions to buildings and other infrastructure and facilities, a limiting factor in agriculture production, and so on. Some costly catastrophic events in the world have been caused by dense fog. There are numerous such events all over the world. With this scenario in the background, it is not surprising that much research has been carried out on fog all over the world. Previous studies on fog have focused on particular regions of frequent fog occurrence or on respective characteristics of radiation or advection fog [3], [4]. This might be because fog is one of the meteorological phenomena greatly influenced by geographical characteristics and because the fog formation occurs due to various different causes. Fog studies through observations both field and remote sensing, models, climatology, and statistical methods have resulted in many achievements [2]. Timely and accurate forecasts of reduced visibility are necessary for the agencies responsible for road safety, search and rescue operations and air traffic management. Nevertheless, fog forecasting by meteorological services is still a difficult issue. Our understanding of the physics still remains incomplete, as numerous complex process influences fog formation, development and dissipation [2].

Over the Indian region every year, widespread fog forms across IGPs during winter months [5]. The IGP are the low elevation, generally gradual sloping surfaces of the Indus and Ganges river basin, which is highly prone to the prolonged dense widespread fog during winter season. The typical meteorological, topographic and increasing pollution conditions over this area are perhaps the most common contributory factor for the fog formation. This fog is generally

Sanjay Kumar Srivastava is with the Department of Natural Resources, TERI University and Indian Air Force, New Delhi, India (e-mail: sk_khush@yahoo.co.in).

Anu Rani Sharma and Kamna Sachdeva are with the Department of Natural Resources, TERI University, India.

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considered as radiation fog. Meteorologically, the radiation fog is a very low stratus cloud, which even touches the ground. The basic requirement for the radiation fog to form is high relative humidity, clear skies and light winds. High concentration of aerosol contents in the lower atmosphere over the study area enhances the formation and persistence of the fog by additional condensation nuclei. Fog has remarkable spatial and temporal heterogeneity and variability over this region of India. Several studies have attempted to examine and understand the mechanism behind this spatial and temporal variability. However, these studies could not fully explain the complexity involved in the mechanism of fog variability. Over the last decades, various authors have studied the fog phenomenon in Northern part of India [6]–[10]. However, still our understanding of the mechanism remains incomplete, as numerous complex process influence formation, development and dissipation. Due to this, our ability to accurately forecast fog over IGP is extremely limited. Timely and accurate forecast of fog are necessary for the agencies responsible for road, rail, and air transportation, search and rescue operations, industrial and agriculture production, citizen's health and welfare.

The existing system of fog forecasting over the Indian region is mainly by using traditional synoptic methods. However, now some numerical methods are also being used to improve the fog forecast. However, no significant progress has been made to develop and implement any objective methods or models for the fog forecasting over Indian regions. Conventional methods of the forecasting fog phenomena have been of immense help to the users, but it has its own inherent limitations in predicting the exact characteristics of fog which includes its time of onset, cessation, and the expected lowest visibility in fog. Research is ongoing in several institutions to improve the accuracy of fog forecasts. However, deficiencies in the existing fog forecast system is noticeable during every winter season when lots of inconvenience is caused to the society due to delay in flights, trains, and other modes of transportation besides loss of life due to accidents and huge economic setback. This could be mainly because of the fact that the still huge amount of research is needed to understand the complexity of fog mechanism over the IGP as this is the region which is highly prone to the prolonged dense fog during the winter season every year. The impact of fog is recognized as the challenging threat to societies and economies across the IGP. Fog events which are in the IGP are probably the fastest in formation, largest in areas and durations and severe in intensity, compared to the other fog areas of the world. In the present study, an attempt has been made to examine the climatological characteristic of fog using ground based observations of meteorological parameters. An attempt is also made in this paper to analyze the spatial and temporal variability of winter fog over the IGP.

A.Study Area: IGPs

The study is carried out over the IGP of India. The northern Indian river plains is a 255-million-hectare fertile plain encompassing most of the northern and eastern India. The region is named after the Indus and Ganga rivers, and encompasses a large number of urban areas like Amritsar, Ludhiana, Chandigarh, Delhi, Agra, Kanpur, Lucknow, Allahabad, Patna, Kolkata, and so on. The IGP is bounded on the north by the Himalayas, southern edge of the plains is marked by Chota Nagpur plateau, and it has Iranian plateau in its west. The IGP are the low elevation and generally sloping surfaces of the Indus and Ganges river basin and is critical for agriculture production and food security in the south Asian region. IGP are among the most agriculturally productive regions of the world. Characterized by favorable climate, fertile soils, and abundant water supply, the IGP are considered as the "Bread basket" of South Asia, providing food and livelihood security for the hundreds of millions of inhabitants. In social and economic terms, the IGP are the most important region of India (Fig. 1).

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. However, four broad seasons are: Winter (December-March), Pre monsoon (April-May), Monsoon (June-September) and Post monsoon (October-November). The key component that controls the climate of the IGP is the southwest monsoon. The monsoon brings significant rainfall over the IGP. The IGP are an environmentally sensitive, socially significant, and economically strategic domain of India. The IGP during the winter season are influenced by the extra tropical systems like western disturbance and also due to its physiography, the IGP are highly prone to prolonged wide spread dense fog. With around 900 million inhabitants, the IGP are densely populated and majority of the inhabitants are poor and battle extreme winter's fog every year. For our study, the IGP region is classified into three regions, western IGP comprising of Punjab, Haryana and adjoining south-west Uttar Pradesh, central IGP consisting of Uttar Pradesh, North Madhya Pradesh, Bihar and adjoining areas, eastern IGP consisting of West Bengal and entire Northeastern states of India.

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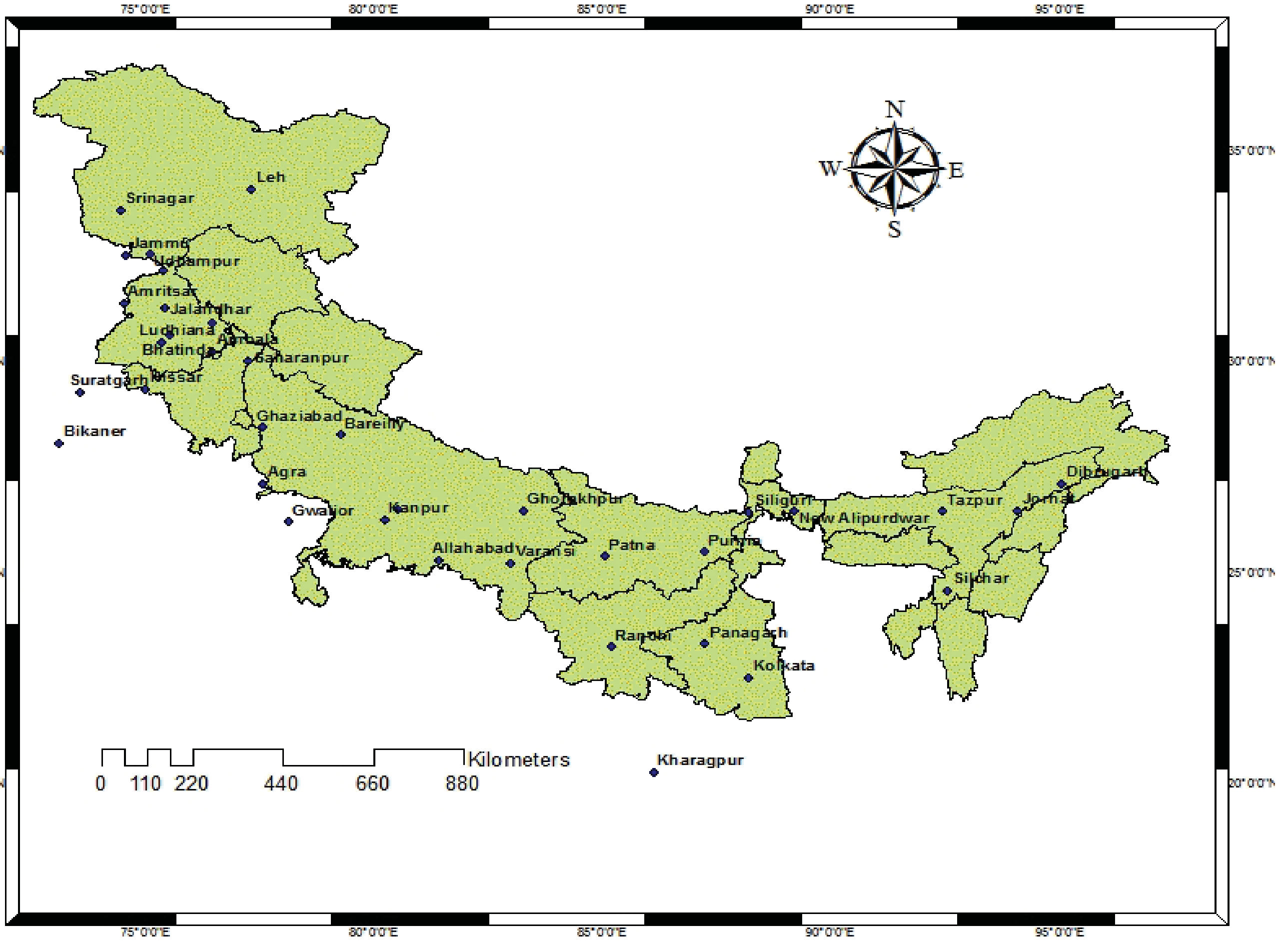


Fig. 1 IGPs (Study Area)

II. Dataset and Methodology

The data for the period (1971-2010) for 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. Further, consistency checks and data gaps were filled according to standard procedures. The information extracted from fog climatology can serve as a basis for the development of forecast decision support and guidance tools. Martin [16], showed how large amount of climatological data can be condensed into a small amount of relevant climatology information which is useful for the short term forecasting. The monthly mean frequency of fog along with the standard deviation and the coefficient of variation at various locations over the entire IGP during December to January were evaluated by using these descriptive statistical graphical tools. To have a better understanding of hidden decadal characteristics and significant period of change, data were divided into four decades (1971-1980, 1981-1990, 1991-2000, and 2001-2010). The analysis revealed a significant change in the fog trend over the years. Further, temporal variation was understood by using time series analyses over the study area during December and January months. The Mann-Kendall Statistical test (MK test) is the most common test used for trend analysis of hydro meteorological data [11], [12]. According to this test, the null hypothesis Ho assumes that there is no trend (the data are independent and randomly ordered) and this is tested against the alternative hypothesis Ha, which assumes that trend exists. There are two advantages of using this test. First, it is a non-parametric test and does not require the data to be normally distributed. Second, the test has low sensitivity to abrupt breaks due to inhomogeneous time series. The limitation of the MK test is that in the case of positive autocorrelation present in series, it shows a positive trend even when trend is not present [13]. A modified Mann-Kendall was suggested, which calculates the autocorrelation between the ranks of the data after removing the apparent trend due to positive autocorrelation. A positive (negative) value of Mann-Kendall statistics indicates an upward (downward) trend. Further, the magnitude of trend was estimated using the Theil and Sen's median slope estimator. This method gives a robust estimate of trend [14] as it is not influenced by outliers. The trends which have statistical significance might not have practical significance and vice versa [14], [15], hence the practical significance of trend was assessed by estimating the Theil and Sen's median slope. Diurnal variability and average daily persistence of fog over the entire IGP were evaluated and analyzed by using advanced descriptive and inferential statistical techniques.

III. Results and Discussion

A. Mean Monthly Frequency of Fog

Poor visibility is mostly observed during the post-monsoon and winter months. On a monthly basis, the mean frequency of poor visibility; i.e. when the visibility is less than 1 km, occurrence over the IGP for twelve months of the year based on data from 1971-2010 is illustrated in Fig. 2. It is revealed that frequency of visibility less than 1 km is at its peak in the month of January (~16 days) followed by December (~13 days). The mean, standard deviation, standard error, and coefficient of variation for visibility less than 1 km for all the twelve months of the year is presented in Table I. The occurrence of poor visibility less than 1 km over the IGP is highly variable during the winter season, while it is most consistent during the pre-monsoon season.

TABLE I
Fog Statistics over IGP

	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
Decade wise Change in Fog Frequency

Month	1971-80 (A)	1981-90 (B)	1991-2000 (C)	2001-2010 (D)	% Change A to B	% Change B to C	% Change C to D	% Change A to D
Dec(H)	10.9	13.9	19.8	21.7	27.5	42.4	9.6	99.1
Dec(M)	5.9	7.7	10.8	12.7	30.5	40.3	17.6	115.3
Dec (L)	3.0	3.5	5.4	8.5	16.7	54.3	57.4	183.4
Jan (H)	10.8	15.9	19.8	21.5	44.4	26.9	8.6	99.0
Jan (M)	5.0	8.7	12.1	16.8	74.0	39.1	39.2	362.8
Jan (L)	3.6	4.7	9.3	12.1	30.6	97.9	30.1	236.1

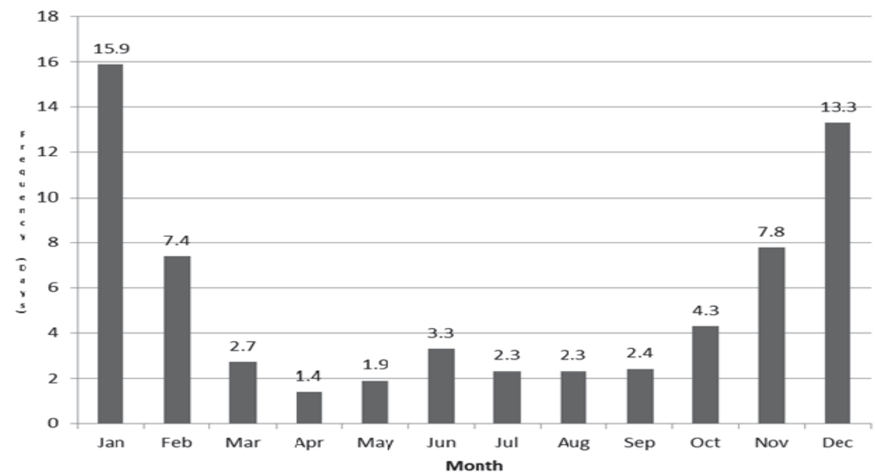


Fig. 2 Average Monthly Visibility (less than 1 km in days)

B. Classification of Fog Prone Areas over IGP

Based on the ground observations of fog as reported by various meteorological stations all along the IGP, the fog prone areas are classified into three major zones. The classification is done on the basis of average number of fog days taken together for the month of December and January, considering the period of last forty years from 1971-2010. The region is classified as high fog prone zone, if the average frequency of fog occurrence over that region is more than two-third of the period, if the average frequency of fog occurrence is between one-third to two-third period, the region is classified as moderate fog prone zone and when the average frequency is less than one-third of the period, it is classified as low fog prone zone.

C. Spatial Variability of Fog (Hot Spot Analysis)

The classified data of the entire three fog prone zone were subjected to hot spot analysis. Fig. 3 illustrates the spatial variability of fog occurrence during the month of December and January considered together over the entire IGP. It reveals that widespread fog forms over Punjab, Haryana, Delhi, Uttar Pradesh and Bihar region and scattered fog forms over Northeast India, generally south of Brahmaputra River. Further, it is observed that the central region of IGP is high fog prone zone with the average fog frequency on more than two-third occasions, whereas west and south Punjab, north Madhya Pradesh, Orissa, parts of West Bengal and Northeast India with the average fog frequency from one third to two third occasions is a moderate fog prone zone. Hilly region of Jammu & Kashmir, Himachal Pradesh, Uttaranchal and Northeast India is a low fog prone zone with average fog frequency on less than one third occasions. Figs. 4 (a) and (b) illustrate the fog frequency in January and December over the study area. The analysis of results reveals that there was an increase in the number of fog days in January compared to December over the entire Punjab, South and East Uttar Pradesh, Bihar, West Bengal, and Northeast India. However, a decrease was observed over the central and west Uttar Pradesh. Significant increase up to 17 percentages over Punjab, 21 percentages over West Bengal, and 18 percentages over Northeast India was observed, whereas a small increase of the order of 0 to 6 percentages was seen over the rest part of the Indo Gangetic plains.

D. Time Series Analysis

After mean frequency analysis, time series analysis was carried out in order to estimate uncertain pattern of fog in the past. Time series analysis was performed on the fog data together for the month of December and January during the period from 1971-2010. The result is illustrated in Figs. 5 (a) and (b). It is observed that there is overall increase in fog frequency during the last forty years over the IGP. Further, it is also seen that the annual variability has increased after 1997 and has been much more significant in the last decade. Fig. 6 shows the time series analysis of fog frequency considered independently for the month of December and January during the last forty years. Fog frequency and inter annual variability is generally higher during January compare to December. However, turnaround points are almost same during both months. Once again, it is observed that difference in fog frequency is between January and December and it is prominent after middle of the last decade of the previous century. However, it is much more significant during the last decade.

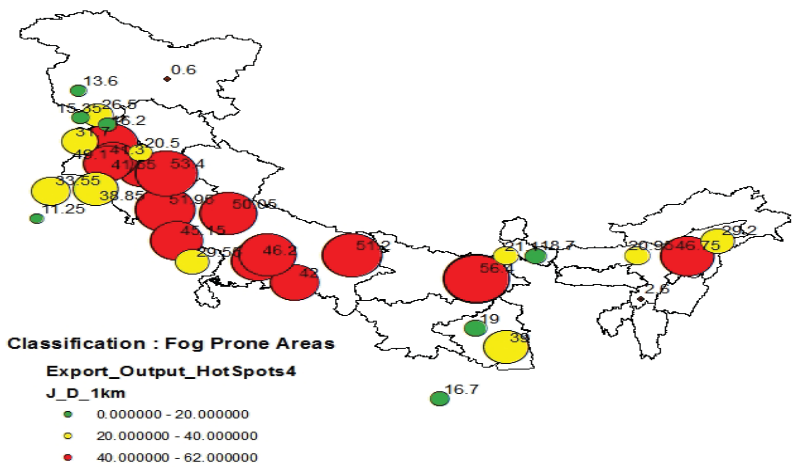
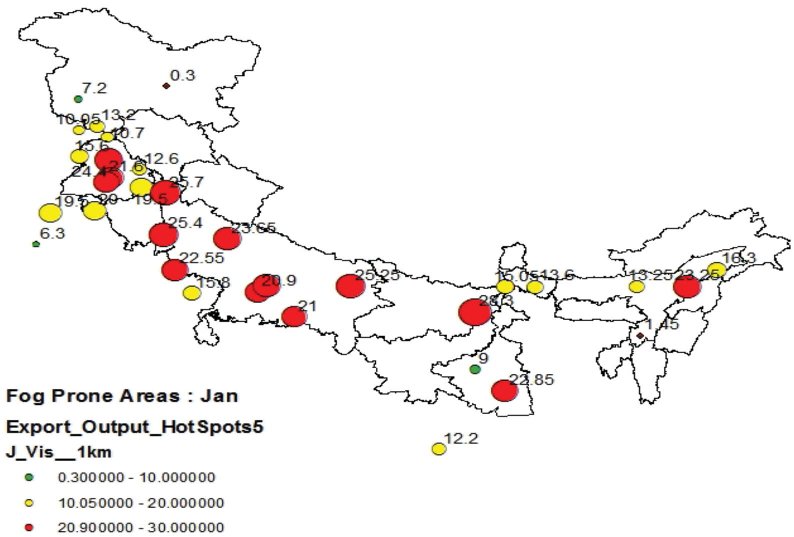


Fig. 3 Fog Classification (Hot spot Analysis)



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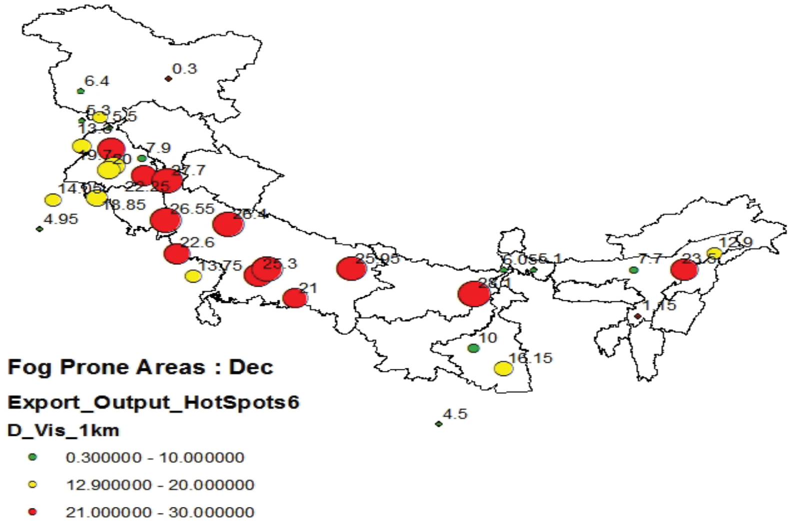

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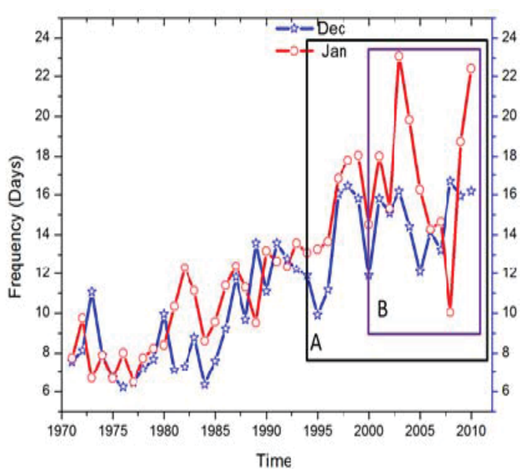
Fig. 4 (a) Fog Classification in January (Hot spot Analysis), (b) Fog Classification in December (Hot spot Analysis)



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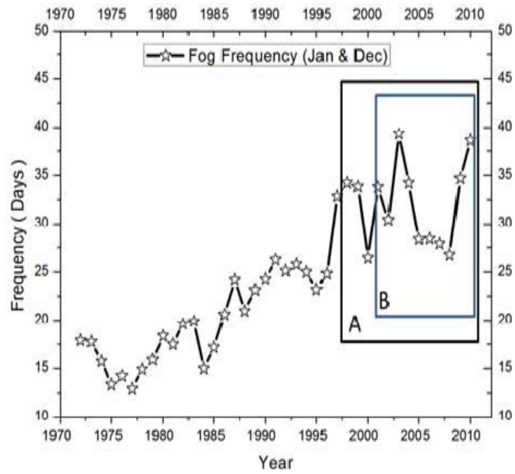

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Fig. 5 (a) Time series Analysis (Dec & Jan), (b) Time series Analysis (winter season)

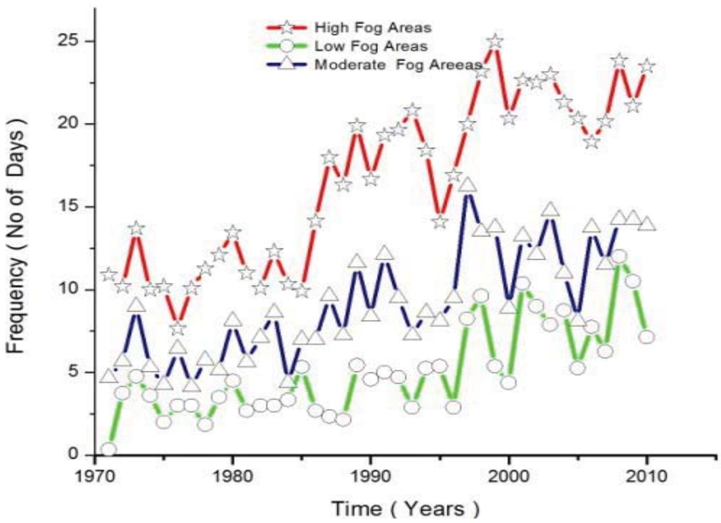


Fig. 6 Time series analysis -fog prone zone wise

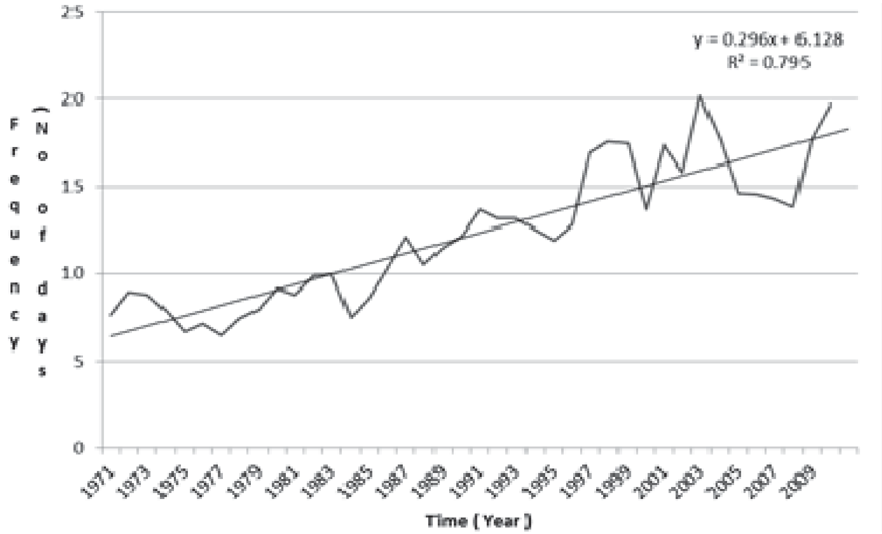


Fig. 7 Trend Analysis

E. Trend Analysis

After the time series analysis, trend analysis was carried out in order to estimate uncertain pattern of fog in the past and to predict its future pattern. Trend analysis was performed on the fog data together for the month of December and January during the period from 1971-2010. The result is illustrated in Fig. 7. Trend analysis was performed by using non-parametric Mann-Kendall test on time series of fog. The results are presented in Table III. 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), Mann-Kendall test at 95% confidence level rejected the null hypothesis and accepted the alternate hypothesis that there exists a trend for almost all over the IGP. Table III shows the Kendall statistics, Kendall's tau correlation, p-values, and Theil and Sen's median slope estimator. During the month of January, the highest Mann-Kendall statistics value of 429 was observed over Ludhiana, followed by Jalandhar and Ghaziabad 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. 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. 8). In our case, it showed that there exists a stronger positive correlation over almost all the stations during January compare to December. Almost similar trend in spatial variability was observed for both peak winter months. Further, the magnitude of trend was estimated by using the Theil and Sen's median slope estimator (Fig. 9). 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 the month of December.

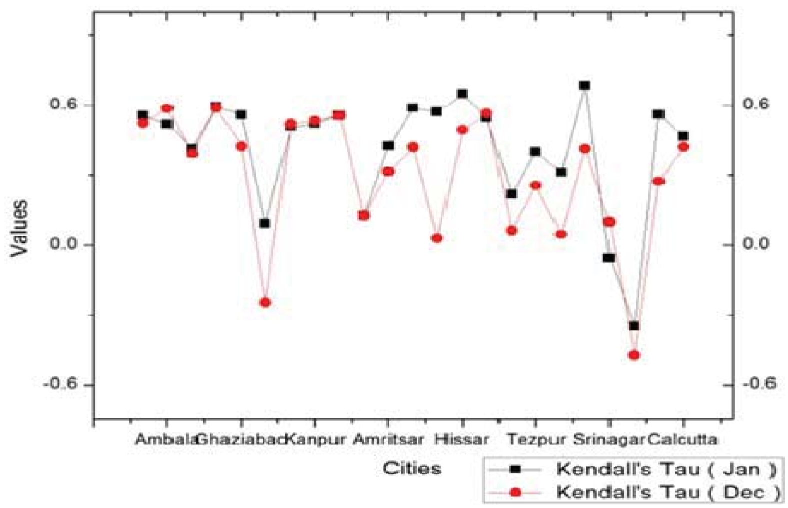


Fig. 8 Kendall Tau's correlation

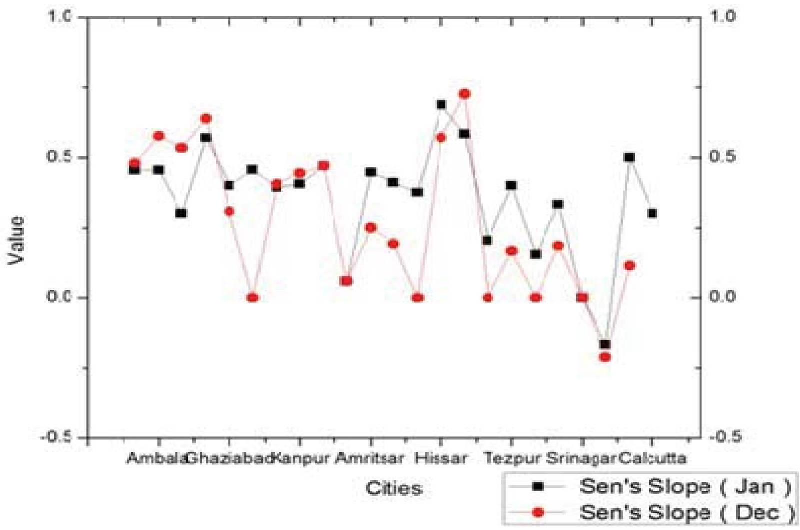


Fig. 9 Theil and Sen's Slope

TABLE III
TAU'S CORRELATION AND SEN'S SLOPE MAGNITUDE

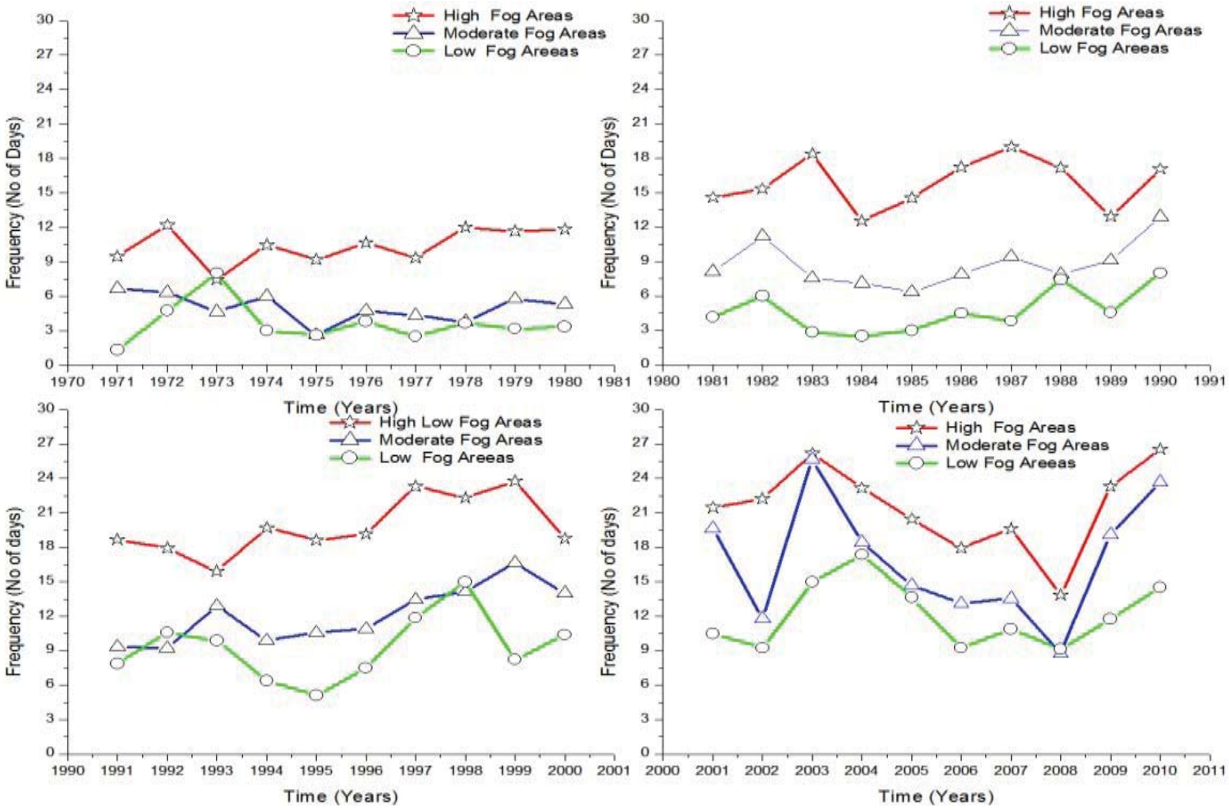
	Tau's(Jan)	Sen's slope(Dec)	Tau's(Jan)	Sen's slope(Dec)
Jalandhar	0.56	0.46	0.52	0.48
Ambala	0.52	0.46	0.59	0.58
Bhatinda	0.41	0.30	0.53	0.42
Ludhiana	0.59	0.57	0.59	0.64
Ghaziabad	0.56	0.40	-0.25	0.31
Saharanpur	-0.09	0.00	0.52	0.00
Bareilly	0.51	0.39	0.53	0.41
Kanpur	0.52	0.41	0.57	0.44
Allahabad	0.57	0.47	0.13	0.47
Jorhat	0.13	0.06	0.32	0.06

A. Decade Wise Time Series and Trend Analysis

To have a better appreciation on various characteristics of fog and to know precisely the most significant period of change, forty-year data were divided into four decades (1971-1980, 1981-1990, 1991-2000, 2001-2010). Figs. 10 (a) and (b) illustrate decade wise monthly mean frequency of fog for the peak winter months of January and December, respectively. It has been observed that the mean frequency of fog has increased continuously in each decade from 1971-1980 to 2000-2010. Percentage increase in frequency for all the three categories of fog prone zone during the month of January and December is illustrated in Figs. 11 (a), (b), and Table II. Over the high fog prone zone, the average fog frequency has been enhanced by approximately by 99 percentages during the month of December and January over IGP in last four decades. Over the high fog prone zone, during December, the maximum increase of the order of approximately 42 percentages was observed during 1990-2000. The increase of the order of 40% and 54% was seen for the moderate and low fog prone zone, respectively. However, during the month of January, the increase of the order of 44% and 74% was observed for high and moderate fog prone zone respectively during 1998-1990, whereas increase of 97% was seen over low fog prone zone during 1990-2000.

B. Diurnal Variability of Fog

To ascertain the most fog prone period in a day during peak winter months of January and December over IGP, fog diurnal variability analysis were carried out. The results are illustrated in Figs. 12 (a) and (b). It is observed that over the western and central parts of IGP, the fog occurrence duration in the month of January is maximum in the morning hours between 06:00 to 10:00 and minimum during the late afternoon hours till sunset generally between 14:00 and 18:00. Eastern parts of IGP which includes Northeast India, the fog occurrence duration in the month of January is maximum in the early morning hours between 06:00 and 08:00 and minimum during the noon till evening hours generally between 12:00 and 20:00. Diurnal fog duration is very less over the eastern IGP as compared to the central and western IGP. During the month of December over the western and central parts of IGP the fog occurrence duration is maximum in the morning hours between 06:00 and 10:00 and minimum during the late afternoon hours till sunset generally between 12:00 and 20:00. Eastern parts of IGP which includes Northeast India, the fog occurrence duration is maximum in the early morning hours between 06:00 and 08:00 and minimum during almost entire day between 10:00 and 02:00.



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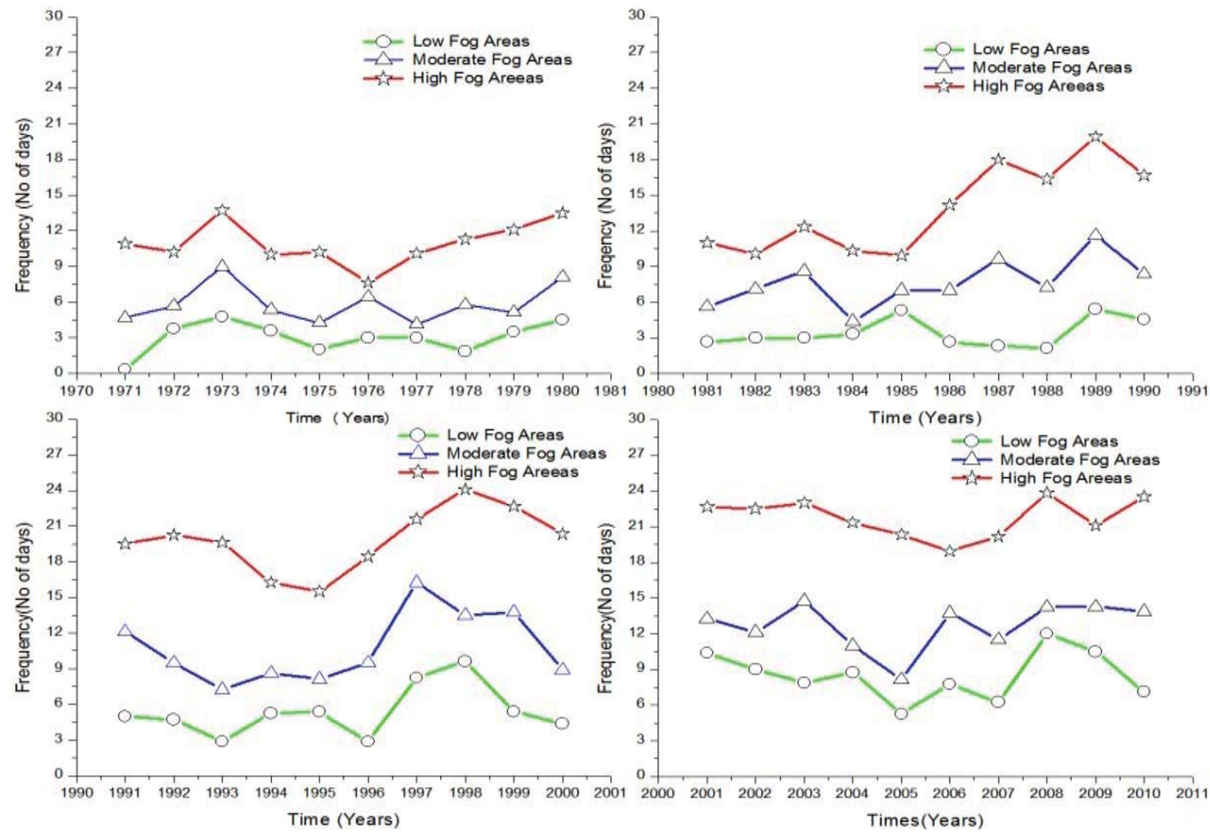

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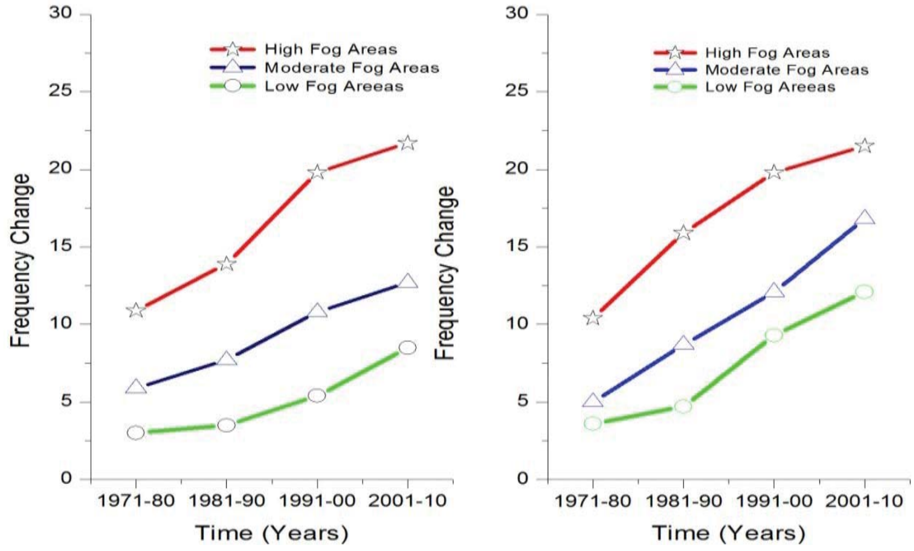
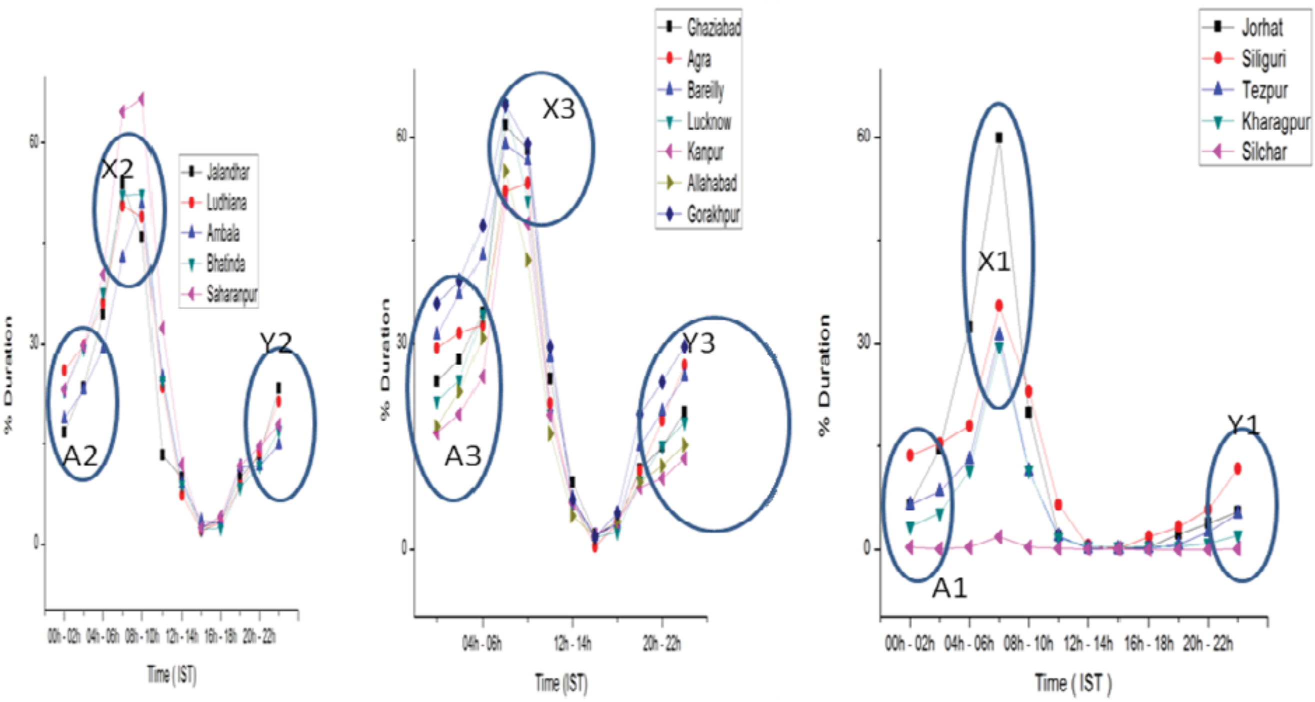
Fig. 10 (a) Decade wise Trend Analysis (January), (b) Decade wise Trend Analysis (December)



(a) (b)

Fig. 11 (a) Decadal change in fog frequency (January), (b) Decadal change in fog frequency(December)



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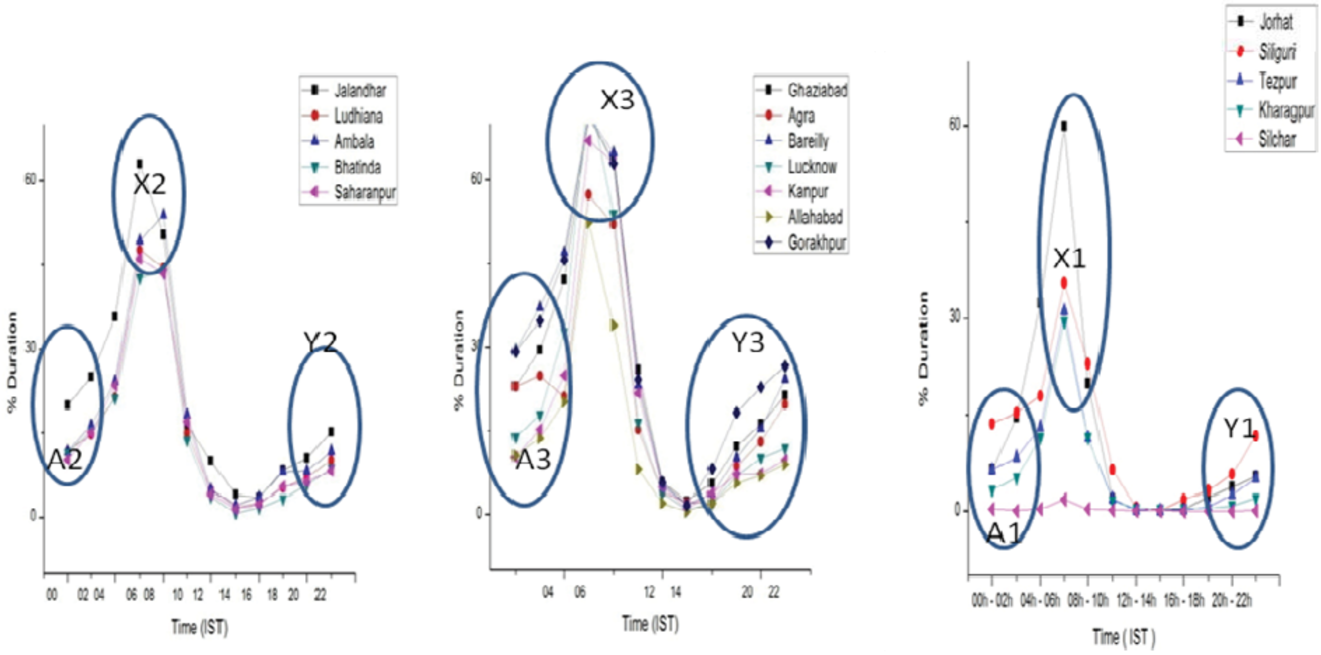

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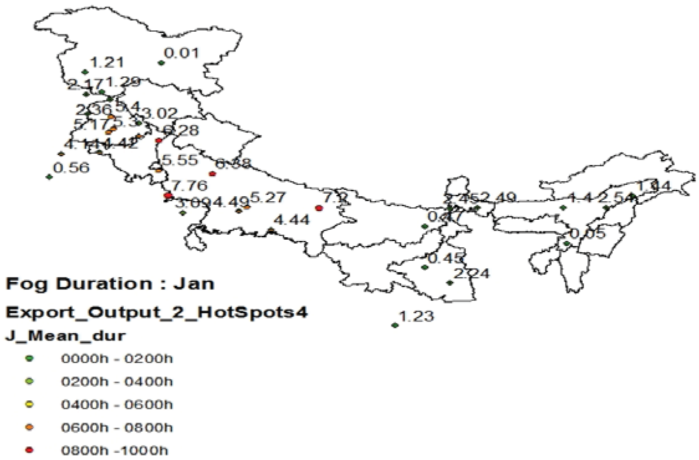
Fig. 12 (a) Diurnal Variability(Jan), (b) Diurnal Variability (Dec)



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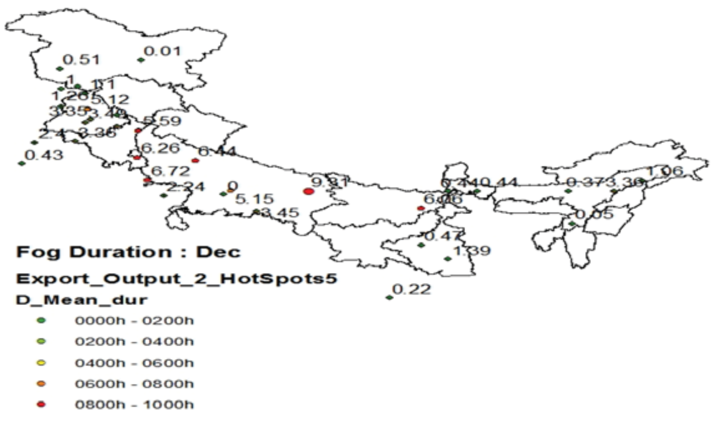

(b)

Fig. 13 (a) Average Daily Persistence (January), (b) Average Daily Persistence (December)

C. Average Daily Persistence

The knowledge on the average daily persistence of fog over different location of IGP is important to reduce the negative impact of fog on day to day activities of the habitants of one of the most densely populated region of the world. Figs. 13 (a) and (b) show the average persistence of fog in a day during January and December, respectively, over various locations of IGP. During the month of December, average fog persists for 5 to 7 hours in a day over the central IGP with the maximum average duration reaches up to 9 hours in a day over Gorakhpur. Further, over the western IGP, the average fog in a day persists for 3-4 hours which is less than the average duration as compared to the central IGP. The average fog duration further reduces to just less than I hours in a day over Northeast India except over Jorhat where the average duration is 3-4 hours. As the winter season progresses, during the month of January, the average fog persistence duration in a day over the western IGP increases to 4-5 hours, whereas the average fog persistence duration remains 5-7 hours over the central IGP. In addition, over Northeast India, also the average fog persistence duration increases to 1-2 hours except over Jorhat where it reduces from 3-4 hours in December to 2-3 hours in January.

IV. Conclusion

The present work analyzed the fog characteristics over the IGP of India, covering the period 1971-2010. The frequency of occurrence of fog over the entire IGP has increased significantly in the peak winter months of December and January during the last four decades. In addition, time series analysis carried out to ascertain the trend based on data of the last forty years by using Mann-Kendall test, confirmed with 95% confidence level showing that there exists a positive (increasing) trend during the peak winter months almost over the entire IGP. The results of this study would offer remarkable insight and 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 could be caused due to changing trend of fog over the entire IGP in the years to come.

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