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The study of frost occurrence and risk analysis in Indo-Gangetic Plains of India during recent decades

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सार – तुषारापात, मौसम संबंधी एक महत्वपूर्ण चरम परिघटना है जिसका विशेष रूप से प्रभाव भारत के गांगेय मैदानी क्षेत्र के कृषि फसलों पर पड़ता है। तुषारापात की परिघटना के समय और इसकी आवृत्ति की जानकारी, तुषार के कारण होने वाले जोखिम और परिहार्य नुकसान को कम करने में मदद कर सकती है। इस अध्ययन ने तुषार सूचकांकों की घटना जैसे तुषार का आगमन, अवसान और तुषार मुक्त अवधि की जांच नवंबर से मार्च तक (151 दिन) भारत में गंगा के मैदानी इलाकों के छह राज्यों के नौ स्थानों पर 1980 से 2015 तक के दैनिक न्यूनतम तापमान का उपयोग करते हुए की गई है। इसमें कई जोखिम स्तर (90%, 70% और 50%) का उपयोग सभी तुषार सूचकांकों के लिए तुषारापात की घटना की संभावना को निर्धारित करने के लिए किया गया। गैर-पैरामीट्रिक मान-कैंडल परीक्षण का उपयोग करके तुषार सूचकांकों के रुझानों का विश्लेषण किया गया। प्राप्त हुए परिणाम दर्शाते हैं कि ज्यादातर तुषार की शुरुआत दिसंबर और जनवरी में दिखाई दी है, जबकि जनवरी से मार्च के दौरान तुषार के ठहराव में भिन्नता की शुरुआत और एक स्थान से दूसरे स्थान पर समाप्ति के साथ देखा गया। पिछले 36 वर्षों के दौरान तुषारापात अवधि का औसत मूल्य अमृतसर में 42 दिनों में और दिल्ली में 2 दिनों के लिए भिन्न होता है। तुषारापात के दिनों की संख्या ने नकारात्मक रुझान दिखाया जो तुषारापात की अवधि में कमी को दर्शाता है। तुषारापात की अवधि में कमी की दर स्थान के आधार पर प्रति दशक 0.5 दिन से 1.5 दिन तक हुई है। विभिन्न स्टेशनों पर इसकी शुरुआत, समाप्ति और तुषारापात मुक्त अवधि के लिए रुझान बदलते रहे हैं।

ABSTRACT. Frost, an important meteorological extreme event has discernible impacts on agricultural crops specifically in Indo-Gangetic plains. The information on time of occurrence of frost and its frequency can help in reducing the risks and avoidable losses due to frost. The study investigated the occurrence of frost indices *viz.*, onset, cessation and frost-free duration at nine locations in six States in Gangetic Plains of India during November to March (151 Days) using daily minimum temperature from 1980 to 2015. The multiple risk levels (90%, 70% and 50%) were used to determine the occurrence of frost probability for all frost indices. Trends in the frost indices were analyzed using the non- parametric Mann-Kendall test. The results showed the onset of frost mostly in December and January, whereas cessation of frost was observed during January to March with variations in date of onset and cessation from one location to another. The mean value of frost duration varied between 42 days at Amritsar to 2 days at Delhi during past 36 years. Number of frost days showed negative trends reflecting reduction in duration of frost. The rate of decrease in frost duration ranges from 0.5 day to 1.5 days per decade depending on the location. Trends for onset, cessation and frost-free duration were inconsistent at different stations.

Key words – Indo-Gangetic plains, Frost indices, Man-Kendall test, Climate change.

1. Introduction

Weather and climatic extremes have profound impacts on both human society and the natural environment. There is need to mitigate the effects of such events through use of value added climate and weather information and forecasts, early warning systems and appropriate methods of management of land and natural resources. Extreme events like droughts, cyclones, floods, forest and bush fires and frost pose a major challenge to Agricultural and socio-economic. Extreme temperature events can have serious impacts on our environment and society. Projections by both global and regional climate models, based on the different greenhouse gases emission scenarios, also indicated the considerable changes in surface air temperatures and temperature-related extremes, such as increase in the occurrence of hot days, changes in the length of heat waves and decrease in number of frost days in the future with diverse spatial and temporal variations (Altinsoy *et al.*, 2013; IPCC, 2013; Turp *et al*., 2015; Ozturk *et al*., 2015).

The recent Assessment Report (AR5) of Working Group I of the Intergovernmental Panel on Climate Change concluded that globally averaged surface (combined land and ocean) temperatures increased by 0.85 °C (range 0.65 to 1.06 °C) over the period 1880-2012. The rate of warming over the period 1951-2012 was observed about 0.72 °C (range 0.49 to 0.89 °C) (IPCC, 2013). The IPCC Special Report on Global Warming (IPCC SR1.5) portrayed that the average global temperature increased to the tune of 0.87 °C (2006-2015), 0.93 ± 0.07 °C (2009-2018) and 1.04 ± 0.09 °C (2014-2018) above a pre-industrial baseline. IPCC reports have also predicted a rise in temperatures by 3 to 4 degree centigrade by the end of 21st Century in India. The average maximum and minimum temperatures have clearly deciphered increasing trend of the order of 0.6 °C, 1.02 °C and 0.20 °C during past 118 years (IMD, 2019). Most data sets also indicated that the observed surface warming associated with relatively larger increase in daily minimum night-time air temperatures (Tmin) than daily maximum day time air temperatures (Tmax) over the past 50 yr (Hansen *et al*., 2012; IPCC, 2013). Among other effects, the increase in minimum temperature since the 1950s might have been associated with a shift in the frequency distribution of Tmin-related extremes, such as a number of frost and frost-free days, last spring and first fall freeze dates and growing season length. Temperature variability has been identified as a major determining factor for crop production (Challinor *et al*., 2005). A single frost event during reproductive growth can have a moderate to severe impact on crop yields (Shroyer *et al*., 1995). The first and the last frost events usually caused damages to plants (Rosenberg *et al*., 1983; Geiger *et al*., 1995). The occurrence of the first fall frost at the beginning of the freezing period damages crops that are still in the field. Direct losses resulting from irregular frost damage of heading wheat and barley have been reported in Australia (Frederiks *et al*., 2011, 2012). WMO (1963, 1997) and Vestal (1971) have also reported damage to seedlings and young plants by the last spring frost occurring at the end of the freezing period. Frost has caused maximum damage to potato, tomato and peas in the range of 15 to 30 per cent in Punjab. It has caused a loss of 17,000 metric tonne of tomato crop which was sown on about 8300 hectares in Ludhiana, Kapurthala districts in 2008 (https://www.hindustantimes.com/chandigarh/frost-damages-crops-in-punjab).

In view of above, the present study has been undertaken to quantify the frequency of frost occurrence, beginning and end of frost season and frost risk assessment at multiple risk levels (90%, 70% and 50% probabilities) over Gangetic plains of India. Assessment of long-term trends of duration, onset and cessation of frost have also been attempted. Expected simulated dates for the onset of frost and cessation of frost can help farmers in preventing or reducing the damage to agricultural produce by taking suitable measures. The knowledge of the frost-free period can be used for the length of time available for crop production. The study could be very useful in planning sowing windows of vegetables, flowers and other frost sensitive crops to avoid the coincidence of the susceptible stages of the crops. Also, the findings could be utilized in breeding suitable varieties and for crop insurance purposes and taking remedial measures for high-value crops.

2. Data and methodology

2.1. *Climate database*

The daily minimum temperature data during winter season (November to March) for nine (9) stations in six (6) frost affected States in Gangetic Plains of India for the period 1980-2015 obtained from India Meteorological Department have been used in the analysis of frost risk assessment. Details of nine stations (Amritsar, Ghazipur, Delhi, Jaipur, Patiala, Karnal, Hisar, Shahjahapur and Patna) scattered in different parts of the study of six states (Punjab, Haryana, Rajasthan, Delhi, Uttar Pradesh and Bihar) are depicted in Fig. 1.

2.2. *Modelling dates of first and last frost occurrence and the frost-free period*

The minimum temperature data were arranged according to winter season from November to March of the following year. The first day of frost (onset of frost) and the last day of frost (cessation of frost) were determined at each of the stations and for each year. Frost generally occurs when the ground temperature falls to near zero degrees Celsius. This requires observations on grass minimum temperature which is generally not available at many places. Studies indicated that when the grass minimum temperature reached zero degrees Celsius corresponding to the minimum temperature in the screen is 4.1 °Celsius (Sentelhas *et al.*, 1994). Therefore, a day having a minimum temperature of 4 degree Celsius or less has been categorized as a frost day. The frost dates were converted to number days to facilitate statistical computations. The frost period was calculated for frost occurrences as the number of days between last and first frost. It is the index which marks the length of the growing period for most crops in the high frost vulnerable regions.

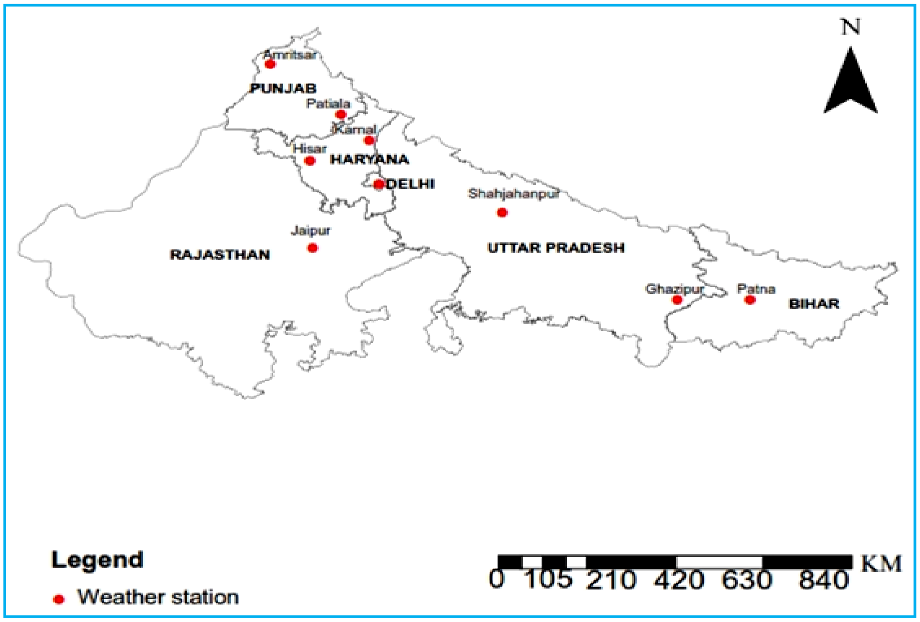


Fig. 1. Location of meteorological stations in the Gangetic Plains of India

2.3. *Control tests of data*

A minimum number of years of record is necessary to adequately estimate data characteristics and enough years to meaningful analysis is more complex and has been studied by several researchers. Porth *et al.* (2001) developed a technique to determine adequate sample size using a non-parametric technique that applies sub-sampling and return interval. However, the minimum daily temperature is a less temporally dynamic variable (Hunter and Meentemeyer, 2005). Rahimi *et al.* (2007) reported that 34 years of data is enough to have a good estimation of the frost risk. However, a simple test (Mackus's method) is conducted here to investigate data adequacy. Following Mackus's method, the minimum number of years, required Y, is determined as

$$Y = (4.3t \text{ Log} R)^2 + 6$$

where, t is the student's t-test value at the desired confidence level (here 90%) and (Y-6) degrees of freedom and R is the ratio of the Y value based on a100-year return interval to the Y value based on a 2-year return interval. Y is estimated using a trial and error procedure until an agreement between Y and t is fulfilled (Alizadeh, 1995). The length of the available data ranges between 35 to 36 years that is enough for a meaningful risk assessment.

2.4. *Estimating suitable distribution for the data*

Minitab software (statistical software to use data analyses) was used to determine the appropriate probability distribution for onset, cessation and frost-free duration at each station. All the data for different frost variable were tested for Normal, Lognormal, Gamma, Exponential, Weibull, Logistic and Log-logistic distributions at 95% confidence level. The best distribution was selected based on the highest significant (>0.05) values. The onset of frost, cessation of frost and frost-free period were determined for different probability levels based on the selected distribution to assess frost occurrence.

2.5. *Trends in frost indices*

Non-parametric Mann-Kendall test was carried out at 95% confidence levels to determine the trends in the onset of frost, cessation of frost and duration of frost. In this test, If p-value is less than alpha = 0.05, one can reject the null hypothesis and data was considered statistically significant. If p-value is greater than alpha = 0.05, one cannot reject the null hypothesis and it was not statistically significant. Sen's slope estimation was employed for detection and estimation of trend in the time series data.

3. Results and discussion

3.1. *Quantification of frost occurrence*

Mean, median, standard deviation, latest occurrence, earliest occurrence and the range between them for the last frost and the first frost for all variables during 1980-2015 are presented in Table 1. The results indicated that the

TABLE 1

Quantification of first frost, last frost and frost-free duration during November-March (1981-2015)

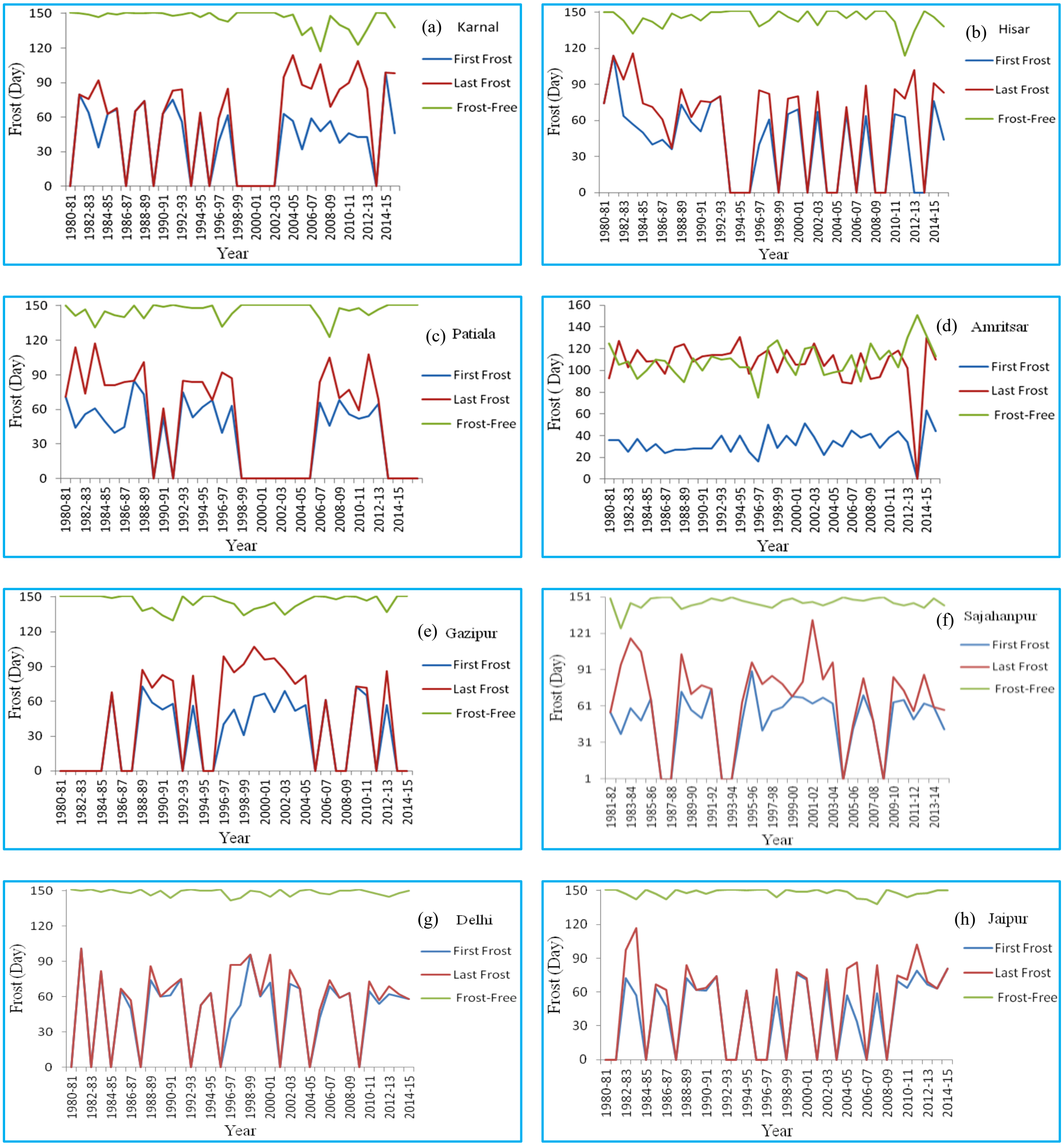
Station	No. of Years	Earliest	Latest	Range	Mean	Median	SD
First Frost							
Amritsar	36	16 Nov	2 Jan	47	4 Dec	3 Dec	11.03
Patiala	36	10 Dec	24 Jan	45	26 Dec	26 Dec	16.65
Karnal	36	2 Dec	7 Feb	67	25 Dec	28 Dec	18.96
Hisar	36	6 Dec	26 Feb	78	30 Dec	3 Jan	20.51
Ghazipur	35	1 Dec	12 Jan	42	23 Dec	28 Jan	16.60
Shahjahanpur	34	8 Dec	29 Jan	52	27 Dec	30 Dec	16.02
Delhi	35	11 Dec	9 Feb	60	1 Jan	1 Jan	18.32
Jaipur	35	4 Dec	20 Jan	47	1 Jan	3 Jan	17
Last Frost							
Amritsar	36	27 Jan	10 Mar	43	15 Feb	20 Jan	21.62
Patiala	36	29 Dec	25 Feb	58	20 Jan	23 Jan	23.18
Karnal	36	29 Dec	22 Feb	55	18 Jan	23 Jan	22.11
Hisar	36	7 Dec	24 Feb	79	17 Jan	19 Jan	22.40
Ghazipur	35	31 Dec	15 Feb	46	18 Jan	22 Jan	21.82
Shahjahanpur	34	28 Dec	12 Mar	74	16 Jan	18 Jan	24.85
Delhi	35	19 Dec	8 Feb	52	8 Jan	6 Jan	19.67
Jaipur	35	31 Dec	25 Feb	56	12 Jan	14 Jan	24.25

Frost Period (Day)

Station	No. of Years	Mean	Median	Standard Deviation	Max. No. of frost Days in a year
Amritsar	36	42	42	14.64	76
Patiala	36	5	3	6.78	28
Karnal	36	5	2	8.34	34
Hisar	36	6	5	7.69	37
Ghazipur	35	5	3	6.31	21
Shahjahanpur	34	5	4	4.85	26
Delhi	35	2	1	2.48	9
Jaipur	35	3	2	3.44	13

onset of frost was found mostly in the month of December and January where as cessation observed from December to March. The mean frost period varied from 42 days at Amritsar to 2 days at Delhi during study period, while maximum frost days in any single year were observed to be 76 at Amritsar. Frost free duration varied between 109 and 149 days at different locations. The occurrence of frost was found negligible at Patna, hence, not presented in tables and figures.

Annual onset, cessation and frost free duration during 1980-2015 at all the stations are depicted in Figs. 2(a-h). The variations in annual frost occurrence were observed at all the locations. The onset of frost was found in months of December and January at all the station except Amritsar showing during November to January. Cessation of frost was not uniform and observed during January to March at different stations. However, lesser variations were found over Amritsar. Annual variations in frost-free duration were found more at Amritsar,



Figs. 2(a-h). Time series of onset , cessation and frost free duration from 1981 to 2015 for (a) Karnal, (b) Hisar, (c) Patiala , (d) Amritsar, (e) Ghazipur, (f) Shahjahanpur, (g) Delhi and (h) Jaipur

Ghazipur, Delhi and Jaipur and less over Patiala, Karnal, Hisar and Shahjahapur.

3.2. *Trends in frost indices*

The onset of frost showed positive trends over the Gangetic plains of India which were significant at a 5% significance level (Table 2). The positive trend indicated late onset of frost. The onset of frost was observed late by an average of 1 to 3 days per decade at more number of stations. In contrast, Patiala, Karnal and Hisar showed negative trends which indicated early onset of frost. Cessation of frost showed a negative significant trend at higher number of stations. Negative trends implied that

TABLE 2

Trends in frost indices for Gangetic plains of India

Station	Onset of frost	Cessation of frost	Free - Frost duration
Amritsar	Positive & significant	Negative & nonsignificant	Positive & significant
Patiala	Negative& significant	Negative & significant	Positive & significant
Karnal	Negative & nonsignificant	Positive & significant	Negative & significant
Hisar	Negative & nonsignificant	Negative & significant	Positive & nonsignificant
Ghazipur	Positive & significant	Positive & nonsignificant	Positive & nonsignificant
Shahjahanpur	Positive & nonsignificant	Negative & nonsignificant	Positive & nonsignificant
Delhi	Positive & nonsignificant	Positive & nonsignificant	Negative & nonsignificant
Jaipur	Positive & nonsignificant	Positive & nonsignificant	Negative & nonsignificant

TABLE 3

Monthly frequency of frost occurrence

Station	November	December	January	February	March
Amritsar	1.80	17.20	19.10	8.60	0.25
Patiala	0.00	1.54	3.03	0.46	0.00
Karnal	0.00	1.69	3.08	0.64	0.00
Hisar	0.00	1.76	3.81	0.41	0.00
Ghazipur	0.00	0.79	4.03	0.23	0.00
Shahjahanpur	0.00	1.15	3.12	0.29	0.00
Delhi	0.00	0.63	1.60	0.75	0.00
Jaipur	0.00	0.53	1.58	0.33	0.00

cessation of frost advanced over time. Frost-free duration showed positive trends reflected in reduction in duration of frost. This is due to increase in minimum temperatures coinciding with global warming. Observations of late onset and early cessation of frost indicated reduction in frost duration. Frost occurrence showed decreasing trend during last 36 years (1980-2015) in Indo-Gangetic Plains (combining data of all stations) which might be attributed to global warming (Fig. 3). Junhu *et al.* (2013) have also reported decreasing trend in spring frost -1.52 and -2.22 days/decade in the Northeast China and North China respectively.

3.3. *Monthly variation of frost occurrence*

Maximum frost occurrence was observed in the month of January followed by December and February at all the stations. Amritsar observed highest number of days of frost occurrence (19.1 days) while lowest was observed at Jaipur (1.48. days) in the month of January. Frost occurrence in the month of November and March was observed only at Amritsar at few occasions (Table 3).

3.4. *Distribution fitting*

The probability distribution for frost occurrence was found best fit from Logistic distribution (significant at 95%) and the distribution results at different probability levels, *viz*., 90%, 70% and 50% are depicted as under:

3.4.1. *Probability distribution of onset of frost*

Chances of occurrence of the first frost at 90% and 70% probability were found in the month January and at 50% in December at all stations expect in Amritsar when it was in December at all these probability levels (Table 4).

3.4.2. *Probability distribution of cessation of frost*

Chances of cessation at 90% probability were found in the month February and at 70% and 50% probability in the month January at all stations expect in case of Amritsar which were in the month of March and February, respectively (Table 5).

TABLE 4

Dates of the onset of frost at stations for various probabilities

Station	Probability (%)		
	90	70	50
Amritsar	16 - Dec	08 - Dec	03 - Dec
Patiala	16 - Jan	04 - Jan	26 - Dec
Karnal	17 - Jan	03 - Jan	26 - Dec
Hisar	22 - Jan	08 - Jan	31 - Dec
Ghazipur	16 - Jan	03 - Jan	23 - Dec
Shahjahanpur	15 - Jan	04 - Jan	27 - Jan
Delhi	21 - Jan	09 - Jan	02 - Jan
Jaipur	20 - Jan	09 - Jan	03 - Jan

TABLE 5

Dates of the last frost occurrence at stations for various probabilities

Station	Probability (%)		
	90	70	50
Amritsar	09 - Mar	25 - Feb	18 - Feb
Patiala	15 - Feb	31 - Jan	21 - Jan
Karnal	13 - Feb	30 - Jan	21 - Jan
Hisar	11 - Feb	28 - Jan	19 - Jan
Ghazipur	15 - Feb	30-Jan	18-Jan
Shahjahanpur	17 - Feb	29 - Jan	16 - Jan
Delhi	30 - Jan	17 - Jan	08 - Jan
Jaipur	04 - Feb	23 - Jan	14 - Jan

TABLE 6

Average frost-free periods for each selected station at various probability levels

Station	Probability (%)		
	90	70	50
Amritsar	128	117	110
Patiala	149	147	145
Karnal	150	145	138
Hisar	149	147	144
Ghazipur	150	148	146
Shahjahanpur	149	147	145
Delhi	149	148	146

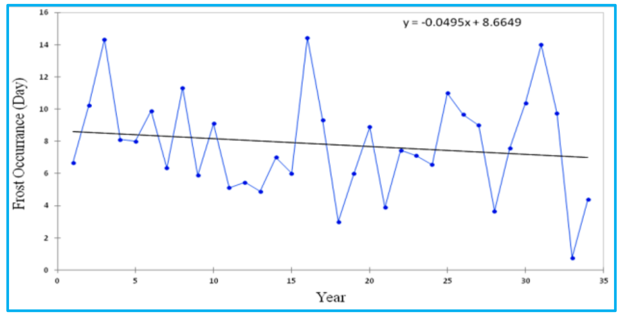


Fig. 3. Trend of frost occurrence in Indo-Gangetic plains of India

3.4.3. *Probability of frost-free duration*

Risk levels of frost-free duration at various probabilities *viz*., 90%, 70% and 50% are presented in Table 6. The frost free duration varied between 110 to 128 days at 90 to 50% probabilities level at Amritsar where as it was between 136 and 150 days at other stations at these probabilities.

4. Conclusions

(*i*) The onset of frost showed significant variation from one location to another owing to the variability of climate over the Gangetic Plains of India during 1980-2015.

(*ii*) Onset of frost was mainly observed in the month of December and January at most of the stations. Cessation of frost also showed a lot of variations from one station to another and was observed mainly in January and February. Annual frost-free duration showed more variation at Amritsar, Ghazipur, Delhiand Jaipur and less variation at Patiala, Karnal, Hisar and Shahjahanpur.

(*iii*) Amritsar is most vulnerable to frost and Delhi the least among all the stations under study.

(*iv*) Maximum frost occurrence observed in the monthly of January followed by December and February at all the locations

(*v*) Frost occurrence period decreased with late occurrence and early cessation amongst all stations under study reflecting impact of changed climatic conditions.

(*vi*) Number of frost days showed negative trends reflecting reduction in duration of frost during 1980-2015. The rate of decrease in frost duration ranges from 0.5 days to 1.5 days per decade depending on the location.

(*vii*) Trend analysis showed a tendency of mostly positive trend and non-significant inferring that duration of frost-free days is increasing.

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