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

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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, Shahjahanpur 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.

| Date       | Station Name   | Latitude  | Longitude | Elevation | Population | Frost Frequency |
|------------|----------------|-----------|-----------|-----------|------------|-----------------|
| 01/01/2020 | Amritsar       | 31°10′N   | 76°02′E   | 210 m     | 500,000    | 10%              |
| 01/01/2020 | Ghazipur       | 28°30′N   | 77°00′E   | 130 m     | 50,000     | 20%              |
| 01/01/2020 | Delhi          | 28°50′N   | 77°13′E   | 280 m     | 3,000,000  | 30%              |
| 01/01/2020 | Jaipur         | 28°0′N    | 77°15′E   | 180 m     | 1,500,000  | 40%              |
| 01/01/2020 | Patiala        | 28°30′N   | 77°10′E   | 100 m     | 300,000    | 50%              |
| 01/01/2020 | Karnal         | 28°50′N   | 77°10′E   | 150 m     | 1,000,000  | 60%              |
| 01/01/2020 | Hisar          | 28°30′N   | 77°00′E   | 120 m     | 800,000    | 70%              |
| 01/01/2020 | Shahjahanpur   | 28°30′N   | 77°15′E   | 110 m     | 1,200,000  | 80%              |
| 01/01/2020 | Patna          | 28°30′N   | 77°15′E   | 140 m     | 1,000,000  | 90%              |
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

\[ Y = (4.3t \log R)^2 + 6 \]

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 a 100-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
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,
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...
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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