Fog characteristics study over the IGI Airport, New Delhi during the winter seasons 2010-2022

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Abstract: Indira Gandhi International (IGI) Airport, New Delhi is one of the busiest Airports in the world which is being affected by severe fog in every winter season which results significant disruption to the aviation activities. In this view, a fog characteristics study has been performed during the winter seasons from 2010 to 2022 using the available Meteorological Aerodrome Report (METAR) data at IGI Airport. To better understand the trend in fog characteristics, a detailed analysis on monthly fog frequency, inter winter season comparison, fog duration and inter annual variability based on both fog days and duration have also been carried out. An increasing trend in fog frequency and duration for all categories of fog has been observed from November to January followed by a decrease in February. However, the fog frequency and duration of moderate, dense and very dense fog have been observed to be higher in February in comparison to November. Further, an increasing trend in fog frequency during 2010-17 season followed by a significant reduction during 2017-22 has also been identified. Moreover, the trend of shallow and moderate fog duration remains similar during the entire period of study whereas the dense and very dense fog have shown the similar characteristics during 2010-22 except in 2014-15 and 2015-16 seasons. Finally, all these better understanding of the fog characteristics can lead to substantial improvements on various fog now-casting/forecasting activities.

Keywords: Fog, IGI Airport, METAR, Winter, Aviation

1. Introduction

IGI Airport, New Delhi serves as the major domestic and international aviation hub of India and considered to be the busiest Airport in India in terms of both passengers traffic and number of flights. IGI Airport experiences severe visibility disruptions in every winter season which leads to flight delay, cancellation and diversion which causes huge economic loss to the aviation industry (Kulkarni et al., 2019). In order to reduce the impact of fog in aviation, a better understanding of the fog characteristics over the IGI Airport in the past years need to be analysed. Further, this knowledge can improve the accuracy of nowcasting/forecasting activities at IGI Airport which can lead to safer aviation activities in the winter seasons.

In recent years, many research contributions have been added in the field of fog characteristics, detection and forecasting over various Airports over India (Mohapatra et al., 1998; Bhowmik et al., 2004; Mishra et al., 2004; Suresh et al., 2007; Ram et al., 2008; Jenamani 2012; Laskar et al., 2013; Dutta et al., 2015; Kutty et al., 2019; Safai et al., 2019; Dhangar et al., 2021; Ahmed et al., 2021; Dhangar et al; 2022; Arun et al., 2022; Yadav et.al., 2022; Ghude et al., 2023). The performance of four different fog forecasting methods i.e., persistence, modified Taylor, synoptic, statistical and composite method during the winter months of 1993-94 over the Bangalore Airport has been examined (Mohapatra et al., 1998). Further, the study also observed that the composite method has better accuracy in fog forecasting out of all these methods. The fog frequency over the Chennai Airport has been examined using the current weather observation data during the period from 1981 to 2002 (Suresh et al., 2007). Moreover, the study reported that the annual fog frequency is ~21.5 days and maximum fog frequency observed in the month of January followed by February and March. In addition, most of the fog occurrences were noticed during 0000 to 0200 UTC with an average duration of 60 to 120 minutes. Further, a fog characteristics study has been performed over the Guwahati Airport during the winter seasons from 1994 to 2004 (Ram et al., 2008). A detailed analysis such as frequency of occurrence, time of onset, duration and dispersal time and intensity of fog have been carried out. In addition, the study reported that the 1200 UTC current weather observations and monitoring of dew point depression along with the surface wind speed were an effective tool in nowcasting of fog over the Guwahati Airport. An attempt has also been made to study the intensity based fog climatology over the IGI Airport using the 25 years (1981-2005) current weather observation data (Jenamani 2012). In this study, an alarming rise in dense and very dense fog frequency has been reported in both December and January. Similarly, a fog characteristics study has been performed over the Patna Airport during the period from 2000 to 2010 (Laskar et al., 2013). A significant increase in fog frequency has been reported in all four winter months during the period of study. The maximum fog frequency was observed in the month of December followed by January with an average duration of ~05 hours. Further, most of the fog occurrences were reported during 0000 to 0200 UTC followed by a dissipation during 0200 to 0500 UTC. A study on the now cast on spatial variability of fog using Artificial Neural Network (ANN) over the Kolkata Airport has been presented by Dutta et al., 2015. The study reveals that the

ANN method performance was satisfactory and the best results were observed in very dense fog event cases.
Moreover, Kutty et al., 2019 examined the categorization of fog frequency and other meteorological parameters over the Bengaluru Airport. In their study, maximum fog frequency was reported in the month of December followed by January. In addition, a significant positive correlation of 0.72 between fog frequency and north east monsoon has also been identified. Safai et al., 2019 investigated the relation between frequency and intensity of fog with the variations in aerosol optical properties and black carbon mass concentration. The study has been carried out during the winter season of 2015-2016 at IGI Airport and significant correlation between absorption and scattering coefficients with cloud condensation nuclei was noticed. Ahmed et al., 2021 investigated the catastrophic fog episodes over north India which attributed the tropical cyclone activity over the Arabian sea and Bay of Bengal. The study has been carried out during the winter seasons of 1998-99, 2013-14 and 2016-17 at IGI Airport. In addition, the result indicated that the persistence, intensity and areal extension of fog at IGI Airport were significantly contributed by the active tropical cyclones. Further, micrometeorological and structural evolution of dense fog events at the IGI Airport were analysed in detail during the WIFEX experiments (Dhangar et al., 2021). An attempt has been made in fog nowcasting at IGI Airport using decision tree method based on real time observational data (Dhangar et al., 2022). Further, detailed forecast verification has been performed with the observational visibility data leads to a success rate of 66%. A 24-hours and 48-hours fog/visibility forecast with a value addition method have been implemented at IGI Airport since 2020-21 winter season (Arun et al., 2022). Moreover, a detailed forecast verification has been carried out with visibility data which indicated to promising results with a hit rate of 0.92.

Even though, many studies have been carried out and in progress in the field of fog research, it still needs further improvement especially in the field of fog nowcasting/forecasting. In order to achieve this, a better understanding of the fog characteristics in the recent years to be analyzed in detail. In the present study, authors made an attempt to study the fog characteristics such as monthly fog frequency, fog duration, inter winter comparison and inter annual variability of fog at IGI Airport during the winter seasons from 2010 to 2022. The organization structure of the article is as follows. Data used in the present study is discussed in Section 2 and section 3 briefly discusses the methodology used. Further, results and discussion are discussed in section 4 followed by conclusion of the present study is discussed in section 5.

2. Data used and study area

Meteorological Aerodrome Report known as the METAR is generally issued by the Tower met officer in every half an hour which is disseminated to the air traffic controllers and pilots. These weather reports play a crucial role in flight take-off and landing decisions. In the present study, visibility and weather information in the winter months i.e. November to February from the METARS during the period from 2010-2022 have been used. The study region is shown in Figure 1.

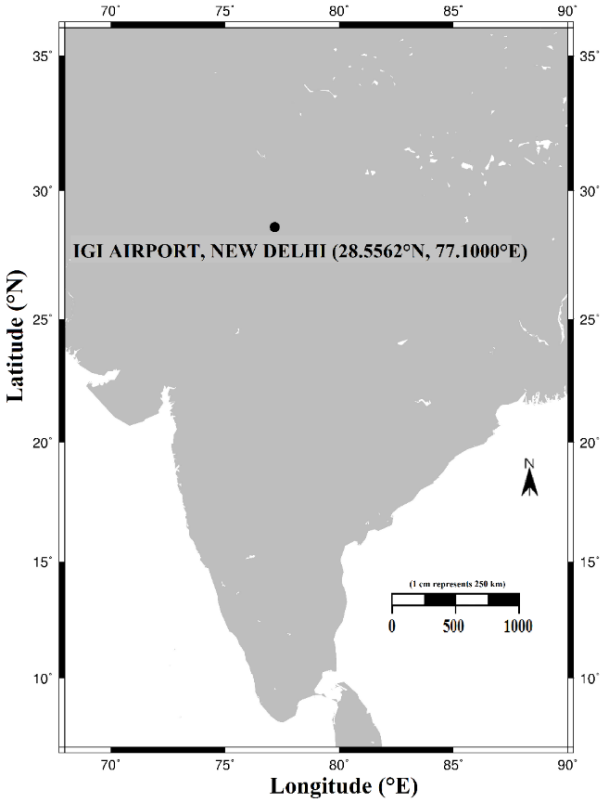

Figure 1. IGI Airport, New Delhi

3. Methodology

In order to have a better understanding of fog characteristics over the IGI Airport, the entire period of study has been classified into 12 winter periods i.e. 2010-11, 2011-12, 2012-13, 2013-14, 2014-15, 2015-16, 2016-17, 2017-18, 2018-19, 2019-20, 2020-21 and 2021-22 respectively. Further, the study has been divided into three major parts, i.e. monthly frequency, duration, followed by an inter winter comparison and inter annual variability of fog which are shown in Figure 2. Moreover, fog categorization based on the visibility condition is shown in Table 1.

Table 1. Fog categorization based on visibility (ICAO Annexure 3, SOP for aviation meteorology)

Fog category	Visibility (m)
Very dense	<50
Dense	51 to 200
Moderate	201 to 400
Shallow	401 to 800

In the first part, monthly fog frequency has been estimated for IGI Airport during the months of November, December, January and February based on the number of

fog days which is calculated as follows (Arun et al., 2021)

Mean fog frequency (%)= (Total number of fog days/Total number of days) X100 (1)

Followed by equation 1, the number of fog days for each month is calculated as follows

Monthly frequency of fog = (Mean Frequency of fog X Number of days in a month)/ 100) (2)

In the second part, inter winter comparison and inter annual variability of fog have been studied based on the fog frequency. In the final part, fog duration has been analysed followed by inter winter comparison and inter annual variability study based on the fog hours.

4. Results and discussion

The study has been carried out in the winter months i.e. November to February during the period from 2010-2022 over the IGI Airport, New Delhi. The detailed analysis such as monthly fog frequency, inter winter comparison and inter annual variability of fog and duration of fog are discussed as follows.

4.1 Monthly fog frequency

The monthly fog frequency over the IGI Airport during the period 2010-2022 is shown in Figure 3. Further, the fog types observed in each month were classified into shallow, moderate, dense and very dense fog. Maximum number of fog days which consist of all types of fog have been observed in the month of January (860 days) followed by December (691 days) whereas the number of fog days observed in the month of November and February were 405 and 476 days respectively. Out of the four fog category, shallow fog has been observed to be the most frequent type of the fog occurred over the IGI Airport (1189 days) followed by the moderate fog (656 days). The occurrence of other two types of fog which was classified as dense (382 days) and very dense fog (205 days) were less as compared to the shallow and moderate fog. The shallow fog frequency was maximum in the month of January and December (i.e. 334 and 323 days respectively) followed by November and February (i.e. 278 and 254 days respectively). However, the maximum moderate fog frequency was observed to be in the month of January (246 days) followed by December (209 days). In addition, the moderate fog frequency has been observed to be high in February (117 days) as compared to November (84 days). Further, the dense and very dense fog frequency were also observed to be maximum in the month of January (182 and 98 days respectively) followed by the month of December (Jenamani 2012) i.e. 102 and 57 days respectively. Moreover, the dense and very dense fog frequency have been observed to be higher in the month of February (i.e. 69 and 36 days) in comparison to November (i.e. 29 and 14 days). The overall study observed that there was an increase in trend of fog frequency for all types fog (i.e. shallow, moderate, dense and very dense fog) from November to January and a decrease thereafter. However, the moderate, dense and very dense fog frequency in the month of February were still higher than November whereas the shallow fog frequency observed to have a reverse characteristic (Arun et al., 2022).

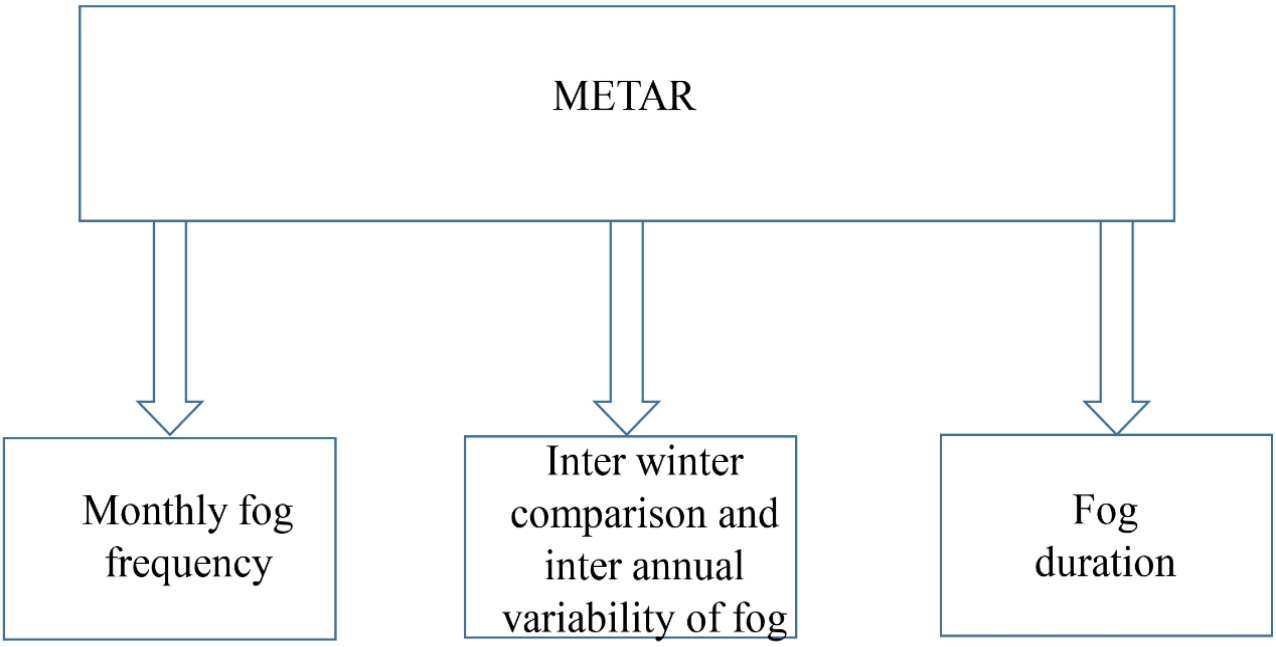

Figure 2. Flow chart of general methodology

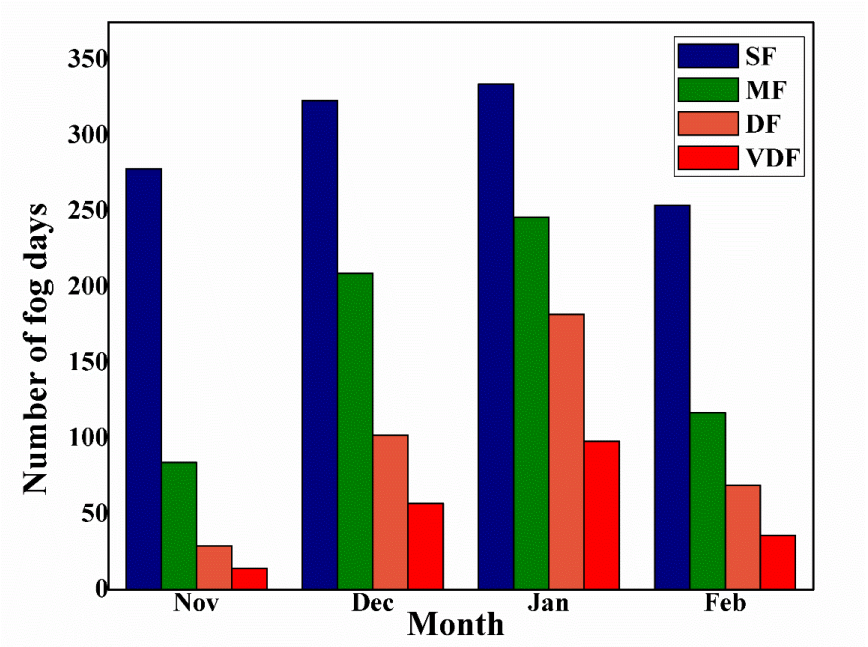

Figure 3. Fog frequency over November, December, January and February at IGI Airport, New Delhi during the winter period from 2010-22

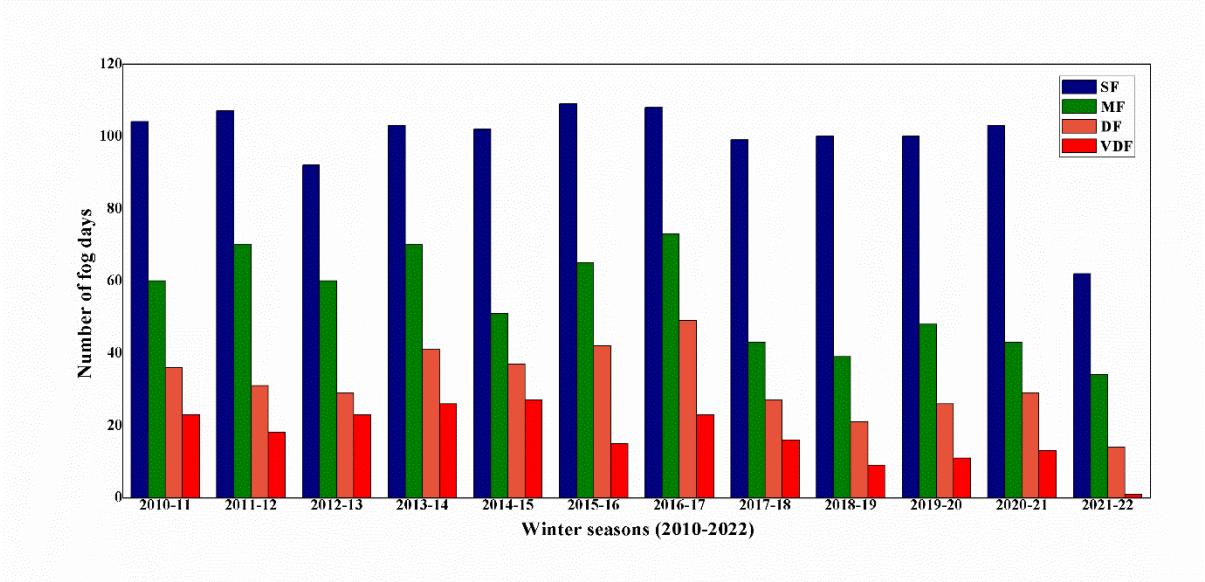

Figure 4. Fog frequency at IGI Airport, New Delhi during various winter seasons from 2010-22

4.2 Inter winter comparison and inter annual variability of fog

Inorder to study the uncertain pattern of fog, the entire period of study has beeen divided into 12 winter periods i.e. 2010-11, 2011-12, 2012-13, 2013-14, 2014-15, 2015-16, 2016-17, 2017-18, 2018-19, 2019-20, 2020-21 and 2021-22 respectively. A time series analysis has been performed using the METAR data which is shown in Figure 4.

The winter season 2016-17 has been observed to be the peak winter period among all seasons with a maximum number of fog days of 253 (sum of all types of fog) which is followed by the winter season 2013-14 with fog days of 240. Moreover, the winter seasons 2010-11, 2011-12, 2012-13, 2014-15 and 2015-16 were also observed to have significant number of fog days i.e. 223, 226, 204, 217, and 231 respectively. The winter season 2021-22 observed to have the least number of fog days i.e. 111. The study also observed that there was a noticeable change in the number of fog days since 2016-17. The winter season 2017-18 ends up with 185 fog days which indicated the reduction of 68 fog days as compared to the previous winter season. The winter seasons 2018-19, 2019-20, 2020-21were also observed to have fewer number of fog days as compared to 2016-17 season i.e. 169, 185 and 188 respectively. Further, the winter season 2021-22 witnessed the lowest number of fog days i.e. 111 among all winter seasons during the period from 2010-22. In general, the study identified an increase trend in number of fog days till 2016-17 season and a significant decrease thereafter (Arun et al., 2021).

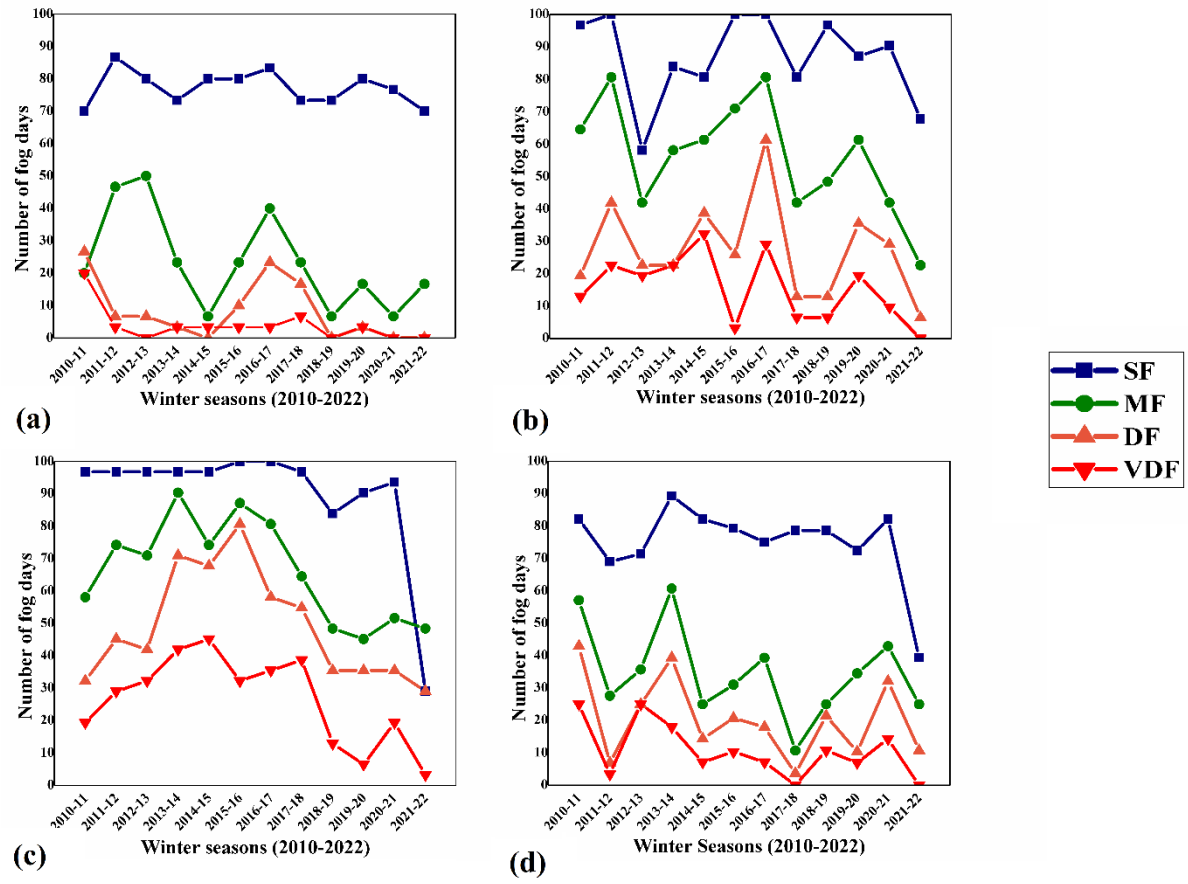

Figure 5. Inter annual variability of fog frequency in month wise during the winter seasons 2010-22, (a) November, (b) December, (c) January and (d) February

It has been observed that the shallow fog events were ~100 days in all seasons till 2020-21 and there was no significant trend has been identified. The 2021-22 season witnessed only 62 shallow fog events which were 41 days less as compared to its previous season. The moderate fog events were ~ 60-70 days during the period from 2010-2017 except in 2013-14 which reported only 41 such events. A significant trend in decrease of moderate fog events have been observed from 2017-18 season onwards. The average moderate fog days reduced to ~ 42 days during the period from 2017-2022 seasons with the lowest reported on 2021-22 i.e. 34 days. Similarly, the dense fog events have also been analyzed and observed to have ~ 35-45 days during the period from 2010-17 except 2011-12 and 2012-13 which witnessed 31 and 29 dense fog days respectively. Similar to shallow and moderate fog events, a noticeable decrease in dense fog events have been observed from 2017-18 season. There was a reduction of 22 dense fog days have been identified in 2017-18 season as compared to its previous season i.e. 2016-17. The average number of dense fog events have also been reduced to ~ 23 days during the period from 2017-2022. The winter season 2021-22 reported the lowest number of dense fog events i.e. 14 days. Finally, the very dense fog events have also been analyzed in the similar manner. The very dense fog events of ~20-25 days have been reported during the period from 2010-17 except the season 2015-16 where 15 such events were occurred. Similar to all other fog categories, very dense fog events have also been identified with a decreasing trend since 2017-18 season. The average number of very dense fog events during 2017-22 season reduced to ~12 days which were almost half of the such events during 2010-17. Surprisingly, the winter season 2021-22 experienced only one very dense fog event which was much lower than all other seasons. The overall study suggested that the number of days of all types of fog have been significantly reduced after 2016-17 winter season.

The inter annual variability of fog in month wise has also been estimated during the time period from 2010-22 which is shown in Figure 5. The detailed analysis is as follows.

November: It has been observed that there was no significant change in fog frequency during shallow fog events. In most of the seasons, fog frequency varies between 70-80 % and there was no sudden increase/decrease in fog frequency has been identified. However, in moderate fog events, there was an alternate increase and decrease in fog frequency have been noticed. Moderate fog frequency increased to 50 % in 2012-13 which was almost double the fog frequency of 2010- 11 season. The fog frequency decreased to 23.3% in 2014-15 and 6.7% in 2015-16. However, the fog frequency increased to 40% in 2016-17 and thereafter the moderate fog occurrences reported were less than 20% only during 2017-22 season. The dense fog frequency reported on 2010-11 season was 26.7 % and thereafter the fog frequency decreased to less than 10% till 2015-16 season. Dense fog frequency of 23.3% and 16.7% were reported in 2016-17 and 2017-18 season and the fog frequency

reduced rapidly thereafter and even no dense fog events were reported in 2018-19, 2020-21 and 2021-22 seasons. A similar pattern was followed in very dense fog events also, i.e. the very dense fog frequency reported on 2010-11 was 20% and thereafter the fog frequency reduced to less than 10% in all the remaining seasons. In addition, no very dense fog events were reported in 2012-13, 2020-21 and 2021-22 seasons.

December: The shallow fog frequency of more than 80% was reported in most of the seasons except 2012-13 and 2021-22 seasons were the corresponding fog frequency was observed to be 58.1% and 67.7% respectively. In addition, there was a 100% occurrence of shallow fog events were reported in 2011-12, 2015-16 and 2016-17 seasons. In moderate fog events, there was an alternate increase and decrease in fog frequency have been noticed. Fog frequency increased to 80.6% in 2011-12 season as compared to its previous season i.e. 2010-11 where the fog frequency reported was 64.5%. Further, a gradual increase in fog frequency has been observed during the period from 2013-2017. Moderate fog frequency reduced to half of its value in 2017-18 i.e. 41.9% as compared to its previous season. Further, the lowest moderate fog frequency of 22.6% was reported on 2021-22 season. In dense fog events, there was an alternate increase and decrease in fog frequency have been identified in the entire period of study. Maximum dense fog frequency has been observed in 2016-17 season, i.e. 61.3% and the minimum was observed in 2021-22 season, i.e. 6.5%. A gradual increase in fog frequency has been observed in very dense fog events during the season from 2010-14 except the 2012-13 season. A rapid decrease in fog frequency has been observed in 2015-16 season i.e. 3.2% followed by an increase of 29% in 2016-17 season. The very dense fog frequency reduced to less than 10% during the 2017-22 seasons except in 2019-20 where the reported fog frequency was 19.4%. Furthermore, no very dense fog events were reported in 2021-22 season.

January: It has been observed that the shallow fog frequency was more than 85% during the seasons from 2010-21. In addition, a 100% fog frequency has been observed in 2015-16 and 2016-17 seasons whereas the least fog frequency was reported in 2021-22, i.e. 29% only. In moderate fog events, an alternate increase and decrease have been identified during 2010-15 and a gradual decrease was noticed thereafter till 2019-20. The maximum moderate fog frequency of 90.3% has been observed in 2013-14 season whereas the minimum reported was 45.2% on 2019-20 season. Moreover, there was an alternate increase and decrease have been noticed in dense fog events during 2010-16 out of which maximum fog frequency of 80.6% was reported in 2015-16 season. However, a gradual decrease has been observed during the period 2016-22 with lowest fog frequency of 29% in 2021-22. A gradual increase in fog frequency has been observed in very dense fog events during the period from 2010-15 followed by a gradual decrease during the period 2017-22. In addition, the maximum fog frequency of 45.2% was reported in 2014-15 season whereas the 2021-22 season witnessed the lowest fog frequency of 3.2%.

February: In most of the seasons, shallow fog frequency has been observed to be greater than 70% except in the 2021-22 season where the reported fog frequency was 39.3% only. A random increase and decrease in fog frequency have been observed in moderate fog events with maximum fog frequency of 60.7% was reported in 2013-14 season whereas the minimum of 10.7% reported in 2017-18 season. Similarly, a random increase/decrease have also been observed in dense fog events as well during 2010-15 season thereafter an alternate increase and decrease have been identified in the remaining seasons i.e. 2016-22. Maximum dense fog frequency of 42.9% has been observed in 2010-11 season whereas the minimum of 3.6% reported in 2017-18 season. In case of very dense fog events, an alternate increase and decrease have been noticed during 2010-14 and 2018-22 seasons with a maximum frequency of 25% in 2010-11 season. In addition, there is no very dense fog was reported in 2017-18 and 2021-22 seasons.

Overall study suggested that there was no significant trend in shallow fog frequency in all the four months. However, an alternate increase and decrease in fog frequency have been observed in moderate fog events in November, December and January whereas the random variation were noticed in February in most of the seasons. In dense fog events, an alternate increase/decrease in fog frequency have been noticed in December and January whereas the random variations were observed in November and February. A gradual decrease in very dense fog frequency has been observed in November. However, an increase of very dense fog frequency has been observed in both December and January during the 2010-17 season followed by a decrease in 2017-22 season. In February, an alternate increase and decrease of fog frequency have been identified.

4.3 Fog duration

In order to understand the persistence of various types of fog over the IGI Airport, a fog duration study has also been performed during the period 2010-22 which is shown in Figure 6. It has been observed that the maximum duration of all types of fog occurred in the month of January (3669.5 hours) followed by December (3191 hours). Moreover, February experienced to have least fog duration i.e. 1396 hours whereas November observed to have a 2165.5 hours of fog during the period of study. From the analysis, it has been noticed that the duration of shallow fog i.e. 6702.5 hours was the highest among the four fog categories followed by moderate fog (2174.5 hours). The remaining two fog types, i.e. dense and very dense fog observed to have a duration of 994.5 and 550.5 hours respectively. Overall study analyzed that the duration of all types of fog has been increased from November to January and thereafter a decrease was observed in February. However, the duration of moderate, dense and very dense fog in February were still higher than that of November whereas the shallow fog duration remains higher in November as compared to February.

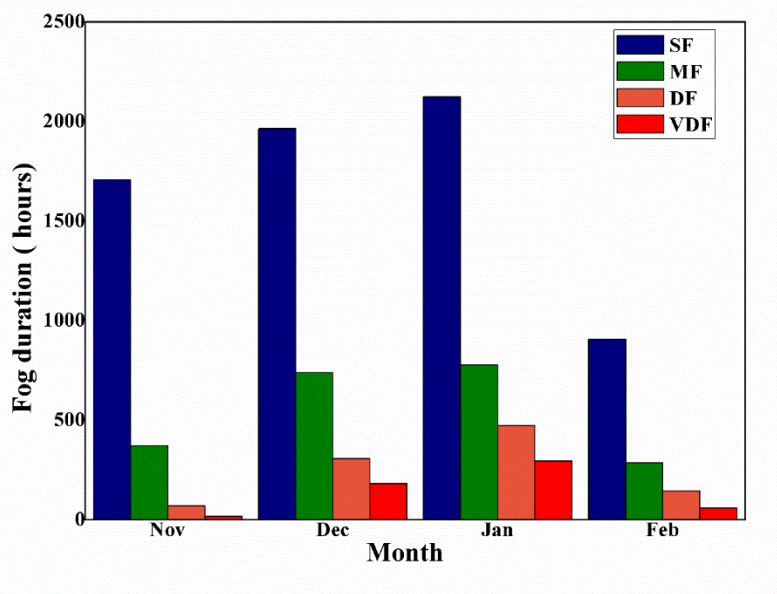

Figure 6. Fog duration over November, December, January and February at IGI Airport, New Delhi during the winter period from 2010-22

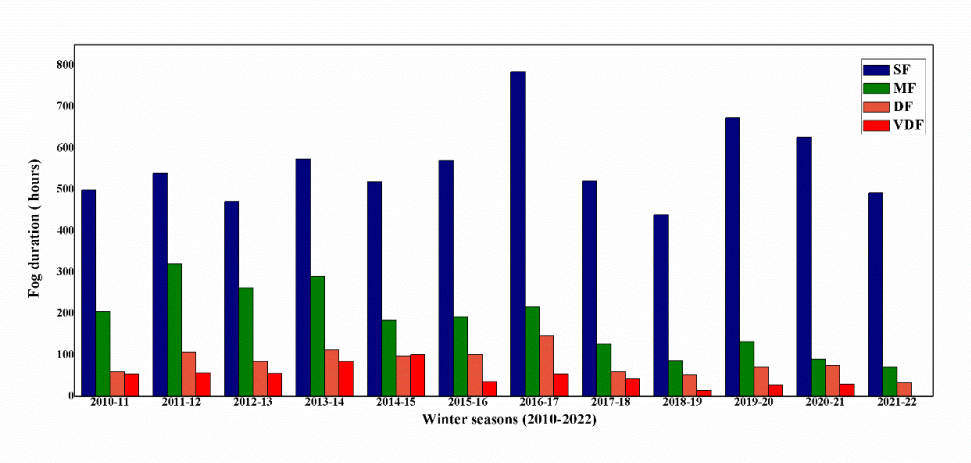

Figure 7. Fog duration at IGI Airport, New Delhi during various winter seasons from 2010-22

An inter annual variations in duration of fog have also been studied in detail which is shown in Figure 7. It has been observed that the 2016-17 season experienced the maximum fog duration of 1200 hours followed by 2013-14 and 2011-12 with a fog duarion of 1060.5 and 1022 hours respectievely. Morover, significant fog duration of ~700 to 900 hours has also been observed in 2010-11, 2012-13, 2014-15, 2015-16, 2017-18, 2019-20 and 2020-21 seasons whereas the least fog duration observed in 2018-19 season(589.5 hours) followed by 2021-22 season (594.5 hours). An alternate increase and decrease in fog duration have been noticed during 2010-17 and thereafter a significant decrease during 2017-22 season except in 2019-20 and 2020-21 seasons. In addition, there was a significant decline of 452 hours of fog has been identified in 2017-18 season in comparison to 2016-17 season. In case of shallow fog, the maximum duration has been noticed in 2016-17 season with 784 hours whereas the least observed in 2018-19 season i.e. 438.5 hours. Further, an alternate increase and decrease in fog hours have been identified during 2010-16 season followed by a decrease during 2016-19 season. Furthermore, an increase in shallow fog hours has been observed during 2019-20 season followed by a decrease in 2020-22 season. In case of moderate fog, the maximum duration of 320.5 hours has been observed in 2012-13 season whereas the minimum reported in 2021-22 season (70 hours). Moreover, the trend in moderate fog hours has also been observed to be similar to shallow fog hours. Similiarly, the dense and very dense fog hours analysis have been carried out. In case of dense and very dense fog, maximum fog hours have been observed in 2016-17 (146 hours) and 2014-15 (100.5 hours) season respectievely. In addition, minimum dense and very dense fog hours observed in 2021-22 season with fog hours of 32.5 and 0.5 respectievely. An alternate increase and decrease in dense fog hours have been observed during 2010-16 season followed by a decrease in 2017-19 season. Further, dense fog hours shown an increasing trend in 2019-21 season and decreased to the minimum in 2021-22 season. However, very dense fog shown an alterntae increase and decrease in fog hours during 2010-18 season except in 2014-15 season. In addition, very dense fog hours further reduced to 13.5 hours in 2018-19 season. Furthermore, very dense fog

hours increased in 2019-21 followed by a decrease in 2021-22 season. Overall study suggested that the trend in shallow and moderate fog hours during 2010-22 season was similar whereas the trend in dense and very dense fog hours is also similar during 2010-22 except in 2014-16 seasons. The inter annual variability of fog duration in month wise was also estimated during the time period from 2010-22 which is shown in Figure 8. The detailed analysis is as follows.

November: It has been observed that the maximum shallow fog duration observed in 2016-17 (32.4%) whereas the minimum reported in 2018-19 season i.e. 9.4%. Moreover, a random increase and decrease in shallow fog duration have been observed during 2010-2016 season and gradual decrease thereafter in the 2017-22 season except in 2019-20. However, there was no significant variation has been noticed in the duration of moderate fog. Moreover, in all seasons, the moderate fog duration reported to be less than 10% except in 2012-13 season (14.8%). Further, there was no substantial change in fog duration has also been observed in both dense and very dense events. In both cases, the reported fog duration is less than 5% and even no such events were reported during 2018-22 season.

December: An alternate increase and decrease in shallow fog duration have been observed during 2010-21 seasons except in 2015-16 and 2019-20. Maximum shallow fog duration of 36.1% has been reported in 2019-20 season whereas the minimum observed was in 2012-13, i.e. 13.5%. In case of moderate fog duration, an alternate increase and decrease have been noticed during 2010-14 seasons whereas a gradual decrease was identified during 2015-22 seasons except in 2019-20. Moreover, the maximum dense fog duration has been reported in 2016-17 (7.1%) and the minimum observed in 2021-22, i.e. 0.5%. In addition, an alternate increase and decrease in dense fog duration have been noticed during 2010-18 seasons except in 2013-14. Further, a decrease in dense fog duration also reported during 2018-22 seasons except in 2019-20. An alternate increase and decrease in very dense fog duration have been noticed during 2010-17 seasons except in 2014-15 and thereafter a significant decrease was reported during 2017-22 except in 2019-20.

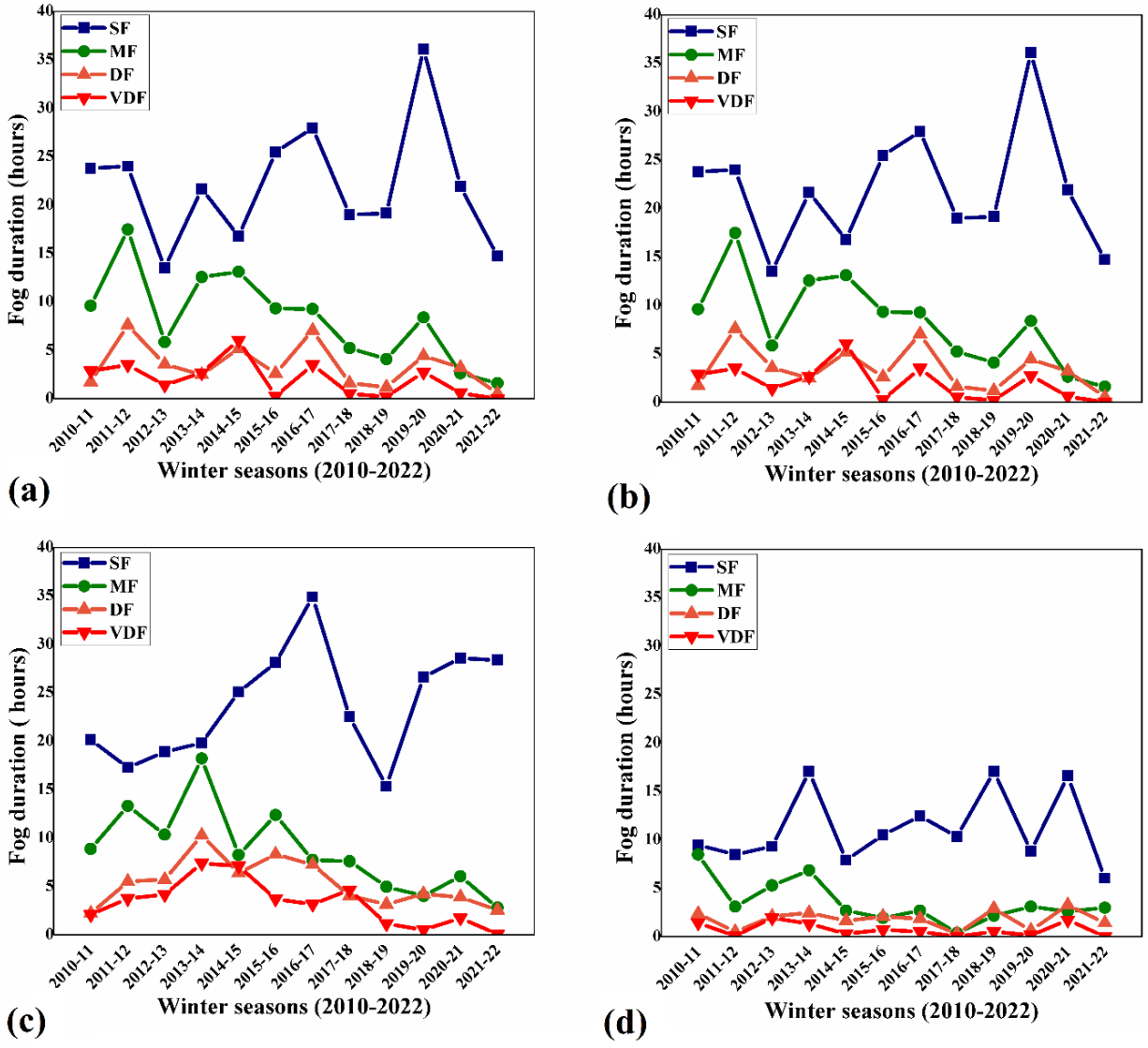

Figure 8. Inter annual variability of fog duration in month wise during the winter seasons 2010-22, (a) November, (b) December, (c) January and (d) February

January: In all seasons, the shallow fog duration has been observed to be higher than 15% and the maximum was reported in 2016-17, i.e. 34.9%. In addition, an increase in shallow fog duration has been observed during 2011-17 and 2019-22 seasons. In case of moderate fog duration, an alternate increase and decrease in fog duration have been noticed during 2010-17 followed by a gradual decrease during 2017-22 except in 2020-21. Further, an increase in dense fog duration has been observed during 2010-14 with a maximum of 10.3% in 2013-14 followed by a substantial decrease during 2016-22 seasons except in 2019-20. Similarly, an increase in very dense fog duration has been observed during 2010-14 followed by a significant decrease in 2015-22 except in 2017-18 and 2020-21 seasons.

February: An alternate increase and decrease in shallow fog duration have been noticed during 2010-22 seasons except in 2013-14 and 2016-17. In addition, the maximum shallow fog duration of 17% has been observed in 2013-17 whereas the minimum reported in 2021-22 season, i.e. 6%. Moreover, random increase and decrease in moderate fog duration have been identified during the entire period of study. An alternate increase and decrease in dense fog duration have been observed during 2016-22 seasons whereas the variations were random during 2010-2016 seasons. Furthermore, there was no significant change in very dense fog duration has been observed during the period from 2010-22 and even no very dense fog duration has been reported in 2017-18 and 2021-22 seasons. In all seasons, the very dense fog duration reported was less than 2% only.

Overall study suggested that the variations in shallow fog duration was random during the period from 2010-16 followed by a decrease during 2017-22 in the month of November. However, an alternate increase and decrease in shallow fog duration have been reported in December and February during 2010-22. In addition, an increasing trend in shallow fog duration has been reported in January during 2010-17 followed by a random variation during 2017-22. The variations in moderate fog duration were observed to be insignificant in November whereas random variations were observed in February. An alternate increase and decrease in moderate fog duration during 2010-14 followed by a gradual decrease during 2017-22 have been noticed in December and January. Further, no substantial changes in dense fog duration were observed in November whereas random variations were reported in February. An alternate increase and decrease during 2010-14 followed by gradual decrease was reported in December. However, the variations were alternative during 2010-18 in January followed by a gradual decrease in 2018-22. Further, there was no significant change in very dense fog duration were reported in November and February. However, the reduction in very dense fog duration has been reported in both December and January during the period 2017-22.

5. Conclusion

The present study analysed the fog characteristics over the IGI Airport, New Delhi during the winter seasons from 2010 to 2022. A detailed analysis on monthly fog frequency, inter winter season comparison and inter annual variability of fog have been presented. An increase in trend of fog frequency has been observed for all types fog from November to January and a decrease thereafter. However, the moderate, dense and very dense fog frequency in the month of February were still higher than November whereas the shallow fog frequency observed to have a reverse characteristic. The winter season 2016-17 observed to have maximum number of fog days whereas the minimum reported in 2021-22 season. Moreover, an increasing trend in fog frequency has been observed during the period 2010-17 followed by a significant decrease in 2017-22 season.

The study indicated that the shallow fog frequency is greater than 75% in all the four months and no significant trend has been identified in the entire period of study. However, an alternate increase and decrease have been observed in moderate and dense fog frequency in December and January. In addition, moderate fog frequency shown random variation in February whereas dense fog frequency shown similar characteristics in both November and February. Further, an increase trend in frequency of very dense fog has been reported during 2010-17 seasons followed by a substantial decrease in 2017-22 seasons.

The fog duration analysis indicated that January (3669.5 hours) experienced maximum fog hours followed by December (3191 hours). Moreover, the shallow fog duration (6702.5 hours) has been observed to be more frequent among all types of fog followed by moderate fog (2174.5 hours). In addition, dense and very dense fog duration have been observed to be less than 1000 hours only i.e. 994.5 and 550.5 respectively. Similar to fog frequency, fog duration has also shown an increasing trend from November to January followed by a decrease in February. Moreover, the trend in shallow and moderate fog hours during 2010-22 seasons were similar whereas the trend in dense and very dense fog hours was also similar during 2010-22 except in 2014-15 and 2015-16 seasons. Further, no significant changes in duration of dense fog has been observed in November whereas the variations were random in February. Moreover, the very dense fog duration change has been observed to be insignificant in Novemebr and February whereas gradual decrease was noticed in December and January during 2017-22. The overall study suggested that the fog frequency and fog duration have been significantly reduced over the IGI Airport since 2017-18 season onwards. Further, the understanding of all these fog charaectristics discussed in the present study can be used to improve the fog forecasting at the IGI Airport which will benefit the aviation sector in both saftey and economical manner.

Author statement

SK: Conceptualization, formal analysis, investigation, methodology, validation, visualization ASH: Conceptualization, formal analysis, investigation, methodology, validation, visualization, writing original draft review, editing and supervision. CS: Conceptualization, formal analysis, supervision and

writing-review and editing and supervision. SJ: Visualization and writing-review and editing. RK: writing-review and editing.

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