

Fog / visibility forecast and verification at IGI Airport, New Delhi during the winter seasons of 2020-21 & 2021-22

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Abstract: The reduction in visibility due to fog leads to cancellation of flights, delays and diversions at Indira Gandhi International (IGI) Airport, New Delhi during the winter season. Accurate prediction of fog/ visibility is required within sufficient lead time to make the flight operations safer, economical and more convenient. This study attempts to improve the fog/visibility forecast at IGI airport for the months of December and January during the winter seasons of 2020-21 and 2021-22. Various meteorological parameters required to predict the fog/visibility are obtained from India Meteorological Department- Global Forecasting System (IMD-GFS) forecasted meteorological information which are valid for the next 24 and 48-hours. Forecast verification was performed using Meteorological reports (METAR) and synoptic observations. The results for 2020-21 fog/visibility forecast for 24-hours are promising with a Percentage of Detection (POD) of 0.92, Critical Success Index (CSI) as 0.68, and False Alarm Ratio (FAR) as 0.28. Moreover, the 2021-22 results for 24-hours fog /visibility forecast are also observed to be promising with a POD of 0.73, CSI of 0.54 and FAR at 0.32. This method gives fairly accurate predictions in point locations and can also be used for a larger spatial area. However, the 48-hours forecast performance needs further improvement. The method also predicted the wind speed and relative humidity which were found to be in agreement with the observed data to a great extent. In the upcoming years, the fog/visibility forecast method will be more robust with better prediction accuracy of meteorological parameters from model outputs and observations.

Keywords: Fog, Visibility, Forecast, IMD GFS, IGI Airport

1. Introduction

Indo-Gangetic Plains (IGP) experiences widespread fog episodes and associated low visibility conditions in every winter season (November- February) which acts as a major hazard to surface, marine and aviation transportation activities. Gultepe et al. 2007 have reported that the total economic loss which affects aviation, marine, and surface transport is comparable to those of tornadoes. The accidents during the winter months have been increased significantly in recent years (Singh et al., 2004). Moreover, Singh et al. (2012) reported that the number of accidents in the month of January is very high due to foggy weather and associated low visibility conditions.

Flight cancellations and diversions are more frequent at the IGI airport during the winter season which can cause huge economic losses to the aviation industry (Kulkarni et al., 2019). For an improved understanding of fog physics, variability of fog events, its duration and intensity need to be studied in detail which can further lead to better fog/visibility prediction for safer aviation, marine and surface transportation activities during the winter season.

In recent years, significant research contributions have been added in the field of fog detection, monitoring, nowcasting and forecasting over the IGP using various satellites, models and *in-situ* based observations (Bhushan et al., 2003; Mitra et al., 2008; Saraf et al., 2011; Singh et al., 2011; Chaurasia et al., 2011; Jenamani 2012; Srivastava et al., 2017; Dey 2018; Arun et al., 2018a; Arun et al., 2018b; Kutty et al., 2020; Arun et al., 2022).

Mohapatra et al., 1998 examined the performance of four different fog forecasting methods i.e., persistence, modified Taylor, synoptic, statistical and composite methods during the winter months of 1993-94 over the Bangalore airport. In addition, the detailed statistical analysis also showed that the composite method has better accuracy in fog forecasting over the study area. The spatial extent of fog over the IGP for the winter season 2002-03, 2003-04 and 2004-05 has been examined by Choudhury et al. (2007) in which fog prone areas are classified according to the intensity derived from fog maps. Moreover, an attempt has also been made for fog forecasting by using the available information on meteorological parameters such as temperature, humidity, wind speed etc. Syed et al. (2012) investigated the climatology, inter annual variability and trends in fog to understand the fog characteristics over the Indian sub-continent by using the observation data from 82 stations during the period from 1976-2010. The results of their study indicated that the trends in fog frequency are positive but not gradual. An attempt has been made by Bhowmik et al., 2004 in which an objective method consisting of statistical multiple discriminating analysis was implemented for the fog prediction over the Delhi region. In their analysis, synoptic observations and sounding have been used to find out the trend in fog occurrence over the Delhi region. Multi Rule based Diagnostic (MRD) approach using Weather and Research Forecast (WRF) model data has been used for the fog prediction over the Delhi region (Payra et al., 2014). In this approach, foggy and non-foggy days are distinguished in 94% of cases and the onset of fog is well captured within an accuracy of 30-90 minutes. The spatial visibility

forecast over the Kolkata airport has been performed by Dutta et al., 2015 by using an Artificial Neural Network (ANN). The study reported that visibility categorization is possible with the ANN in which the best visibility forecast has been observed in the range of 0-50 m where very dense fog conditions have been occurred. An analogue model has been introduced by Goswami et al., 2017 for the fog prediction over the IGP in which fog occurrence is represented in terms of visibility. The study investigated the performance of the model and found to have more success whenever the visibility is less than 500m and the duration of the fog event is more than 04 hours.

Further, Jayakumar et al. (2018) introduced a high resolution (~330m) unified model for the fog/visibility prediction over Delhi. Moreover, the study suggested that the visibility prediction by the model is highly sensitive to aerosols. The ability of various Numerical Weather Prediction (NWP) models such as the National Centre for Medium Range Weather Forecasting (NCMRWF) Unified model (NCUM) in visibility forecast over the IGP has been examined (Singh et al., 2018). In their study, Indian National Satellite (INSAT-3D) fog maps and visibility observations from METAR data have been used for verification purposes. The study indicated that the performance of NCUM is reasonably well in predicting the spatial extent of fog over the IGP with a lead time of one day. Further, Dey (2018) provided the theoretical explanation to the new Brightness Temperature Difference (BTD) threshold to improve the fog prediction over the IGP. Moreover, the study also discussed about the quantification of minimum droplet concentration for the identification of fog and also performed the sensitive study of critical droplet concentration on liquid water content. An Adaptive Neuro-Fuzzy Inference System (ANFIS) has been used for visibility prediction with a lead time of 12 hours over Delhi during the fog season (Goswami et al., 2020). The study reported that the forecast error of ANFIS is the least, i.e., 9.09%, as compared to other existing neural networks and forecast models and hence can be adopted as an alternate option for the fog/visibility forecast purposes. A high resolution (~330m) fog/visibility forecast model known as DM-CHEM and the aerosol scheme has been introduced by Jayakumar et al. (2021) which has been operational since 2020 and the performance of the model is reasonably well with the observed visibility.

The fog/visibility forecast over the IGP has been significantly improved with the introduction of the Winter Fog Experiment (WiFEx) campaign at the IGI airport since 2016 (Ghude et al., 2017). The main objectives of the project are to better understand the fog characteristics, fog microphysics, variability of fog events and associated thermodynamics to improve the fog prediction over the IGP. In addition, the sensitivity of the WRF model to simulate the life cycle of dense fog events has been investigated during the WiFEx campaign (Pithani et al., 2019). The study reported that the performance of quasi-normal scale elimination (QNSE) and MYNN 2.5 Planetary Boundary Layer (PBL) schemes in the simulation of fog life cycle is reasonably well as compared to the other schemes. Further, Pithani et al., 2020

investigated the performance of the Weather Research & Forecasting (WRF) model in 43 very dense fog events in real time forecasts at 2km horizontal grid spacing. The results indicated that the model has reasonably well predictive accuracy with a hit rate of 0.78 whereas the FAR (0.19) and missing rate (0.32) are low. Furthermore, Dhangar et al. (2021) extensively studied the physical and chemical structure of fog as well as the variability of fog events which can further be used to improve the fog prediction over the IGP. Moreover, to improve fog prediction and other surface meteorological parameters, the role of high resolution land data assimilation has been investigated (Parde et al., 2022). Later, the three dimensional structure of dense fog events has been studied with the help of the WRF model and other ground based observations during the WiFEx campaign (Yadav et al., 2022). The study indicated that the complexity and physical process during dense fog events are well captured by the WRF model.

Even though a large number of research activities are going on in the field of fog detection and prediction using satellite, model and in-situ based observations, it still needs improvement, especially in the field of accurate fog/visibility predictions during the winter seasons. In this article, the authors made an attempt to give fog/visibility predictions at the IGI airport with a lead time of 24-hours and 48-hours which is followed by a detailed forecast verification with the observed data.

2. Data Used

The study has been performed during the months of peak winter season i.e. December and January of year 2020-21 and 2021-22 over the IGI Airport. Half hourly METAR and 3 hourly synoptic observations available at <https://olbs.amssdelhi.gov.in> provided the current weather information. IMD-GFS model runs with a horizontal resolution of ~12 km and 64 hybrid sigma pressure levels. The four-dimensional (4D) ensemble variational data assimilation (DA) system (4DEnsVar) of NCMRWF is used to generate the initial conditions of IMD-GFS models. The 4DEnsVar data assimilation is capable of assimilating various conventional and polar/geostationary satellite observations including the radiance values. The analysis is performed four times a day, i.e. 0000,0600,1200 and 1800 UTC and 10 days forecast is generated in each run. The IMD-GFS based specific aviation products are available in airport wise also. This includes charts, wind and temperature charts, wind and temperature numerical values and meteograms. These products include all weather parameters required for fog/visibility purposes. From a forecaster's point of view, these IMD-GFS specific aviation products are very much useful for generating fog/visibility forecasts in a more accurate way. For forecasting purpose, IMD GFS forecasted meteorological parameters which have a validity period of 24-hours and 48-hours have been used (<https://internal.imd.gov.in> and <https://nwp.imd.gov.in>). Currently, IMD-GFS model outputs are not available in the open domain for research purposes.

3. Methodology

The prime goal of this study is to enhance the prediction of fog/visibility forecast over IGI Airport during the winter season of 2020-21 & 2021-22. On a daily basis, current weather information obtained from METAR and synoptic observations were studied diligently to understand the trend in the present weather. The other meteorological parameters which have a significant role in fog formation such as minimum air temperature, dew point depression, wind speed and direction, backing and veering of wind, relative humidity, surface temperature inversion, cloud cover and Western Disturbance (WD) or any other significant synoptic system surrounding Delhivalid for next 24-hours & 48-hours are collected from IMD GFS Model outputs. The values of above mentioned parameters favorable for fog formation are mentioned in Table 1. The output of 24 and 48-hours IMD GFS model are used to predict fog/visibility over the IGI airport.

Table 1. Favourable conditions of meteorological parameters for fog formation (Singh, 2011; Arun et al., 2022).

Weather parameter	Favorable conditions for fog formation
Minimum air temperature (°C)	< 8 °C
Dew point depression (°C)	< 3°C
Relative humidity (%)	>75%
Wind speed (Knots)	02 to 04 knots
Wind direction	Depends up on wind speed
Wind veering/backing	Backing
Surface temperature information (°C)	>2 °C
Cloud information	Clear sky
Location of WD/other synoptic system over and around Delhi	Approaching or passing over IGP

There are a total of 9 meteorological parameters which are mentioned in Table 1 where each of the parameters has an equal weightage of 11%. The total percentage after combining all the favorable parameters gives the 24-hours and 48-hours probability forecast of fog formation and the corresponding lowest visibility as shown in Table 2. If all the parameters are favorable, then it indicates a 99% chance of fog formation with the lowest visibility of 00 m. Similarly, if 8 out of 9 parameters are favorable, then it indicates 88% chance of fog formation with a lowest visibility of 200m and so on. The complete analysis has been performed in a similar manner.

Table 2. Classification of probability of fog formation and corresponding visibility

Probability of fog formation (%)	Visibility (m)
99	00
88	200
77	400
66	600
55	800
44	1000
33	>1000
22	>1000
11	>1000
00	>1000

4. Results and Discussion

The present study has been carried out during the December and January months of the winter seasons of 2020-21 & 2021-22. The probability of fog formation and the corresponding lowest visibility have been calculated on daily basis with a lead time of 24-hours and 48-hours. The tabular format of the fog/visibility forecast issued on 8th Jan 2022 is shown in Table 3. Firstly, METAR and synoptic observations provided the present weather conditions on 8th Jan 2022. Considering the present weather and using the 24-hours and 48-hours forecasted meteorological parameters information, the probability of fog formation and lowest visibility expected for the next 24 and 48-hours are forecasted. According to data mentioned in Table 3, five & eight out of nine weather parameters are favorable for fog formation for 9th & 10th Jan 2022 respectively. Since, an equal weightage of 11% has been given to each favorable parameter, the probability of fog formation is 55% for 9th Jan 2022 & 88% for 10th Jan 2022 respectively. According to Table no. 3, the lowest visibility is forecasted as 800 m & 200 m for 9th and 10th of January 2022 respectively. The fog/visibility forecast for the entire season has been carried out in a similar manner.

Fog is classified into various categories depending upon the visibility which is discussed as follows. When visibility is ≤ 50 m, it is a very dense fog event; a dense fog event implies that visibility is ranging from 51 m to 200m, further if visibility is observed between 201 m to 500m, it is identified as a moderate fog event; shallow fog occurs when visibility is in between 501m to 800m and mist occurs if visibility is greater than 800m. In addition, runways are classified into different categories (i.e. CAT I, CAT II, CAT IIIA, CAT IIIB and CAT IIIC) based on the Runway Visual Range (RVR). When the visibility reported is above 800 m, it is classified as CAT I category whereas CAT II is defined when the visibility is above 350 m. CAT IIIA and CAT IIIB have visibility range of 200 m and 50-200 m respectively, whereas CAT IIIC have no visibility range. Currently, IGI airport is equipped with CAT IIIB facility on all the runways.

Table 3. General format of fog/visibility forecast issued at IGI Airport on 08.01.2022

Weather parameter at surface	08/01/22 00UTC		09/01/22 00 UTC		10/01/22 00 UTC	
Minimum air temperature (°C)	15.8	U	13	U	09	U
Dry bulb temperature (°C)	15	-	-		-	
Dew point temperature (°C)	15	-	-		-	
Dew point depression (°C)	00	F	00	F	00	F
Relative humidity (%)	100	F	95	F	95	F
Wind speed (knots)	05	U	06	U	04	F
Wind direction	E	U	SE	U	NW	F
Wind veering/backing	B	F	B	F	B	F
Surface temperature inversion (°C)	02	U	06	F	08	F
Cloud conditions	Cloudy Sky	U	Cloudy sky	U	Clear sky	F
Location of Western disturbance/any other synoptic system over and around Delhi	68°E 28°N	F	72°E 28°N	F	76°E 28°N	F
Present fog conditions	TSRA	U	-	-	-	-
Visibility (m)	1500	U	-	-	-	-

The time series plots of 24-hours forecast visibility and 48-hours forecast visibility with the observed visibility for the years 2020-21 & 2021-22 are shown in Figure 1 (a-d). In addition, the corresponding predicted surface wind speed (knots) and relative humidity (%) along with the observed data are shown in Figure 2 (a-d) and Figure 3 (a-d) respectively. The performance between observed and forecasted visibility, wind speed, relative humidity etc. are in agreement. For example, 24-hours forecast for 31.12.2020 and 01.01.2021 predicted a very dense fog event with the lowest visibility of 50 m. The predicted wind speed was also favorable for 31.12.2020 and 01.01.2021 being 04 and 02 knots respectively. The wind speed observed was 02 knots on both days which favored the fog formation. Similarly, the relative humidity was predicted to be 90% and 95% for 31.12.2020 and 01.01.2021 respectively. The relative humidity observed was also favorable at 94% for both days. Hence these events were correctly predicted and the observed lowest visibility was 50m only on both days.

Very dense fog with the lowest visibility of 50m was predicted in 24-hours forecast for 13.01.2022. The observed lowest visibility on 13.01.2022 was also

observed to be 50m which is in accordance with the predicted visibility. The parameters like Western Disturbance, relative humidity, wind category, and surface temperature inversion were predicted to be 78°E, 95%, backing wind & 6°C respectively. The observed meteorological parameters such as WD at 83°E, relative humidity of 100%, backing wind, and surface temperature inversion of 6°C were in agreement with the predicted data and also contributed in the formation of very dense fog. Moderate fog was predicted for 07.01.2022 in 24-hours forecast with the lowest visibility of 400 m. The predicted parameters like relative humidity (95%), WD (74 °E), inversion temperature (6°C), and minimum air temperature (12 °C) were in agreement with the observed values of relative humidity (98%), WD(67 °E), inversion temperature (6°C), minimum air temperature (13.2°C) which led to the formation of moderate fog with visibility of 500m. The 24-hours forecast for 14.12.2021 predicted shallow fog with the lowest visibility of 600m. Few predicted parameters such as clear sky, inversion temperature of 8°C, backing wind, relative humidity(95%) etc. were favorable for fog formation.

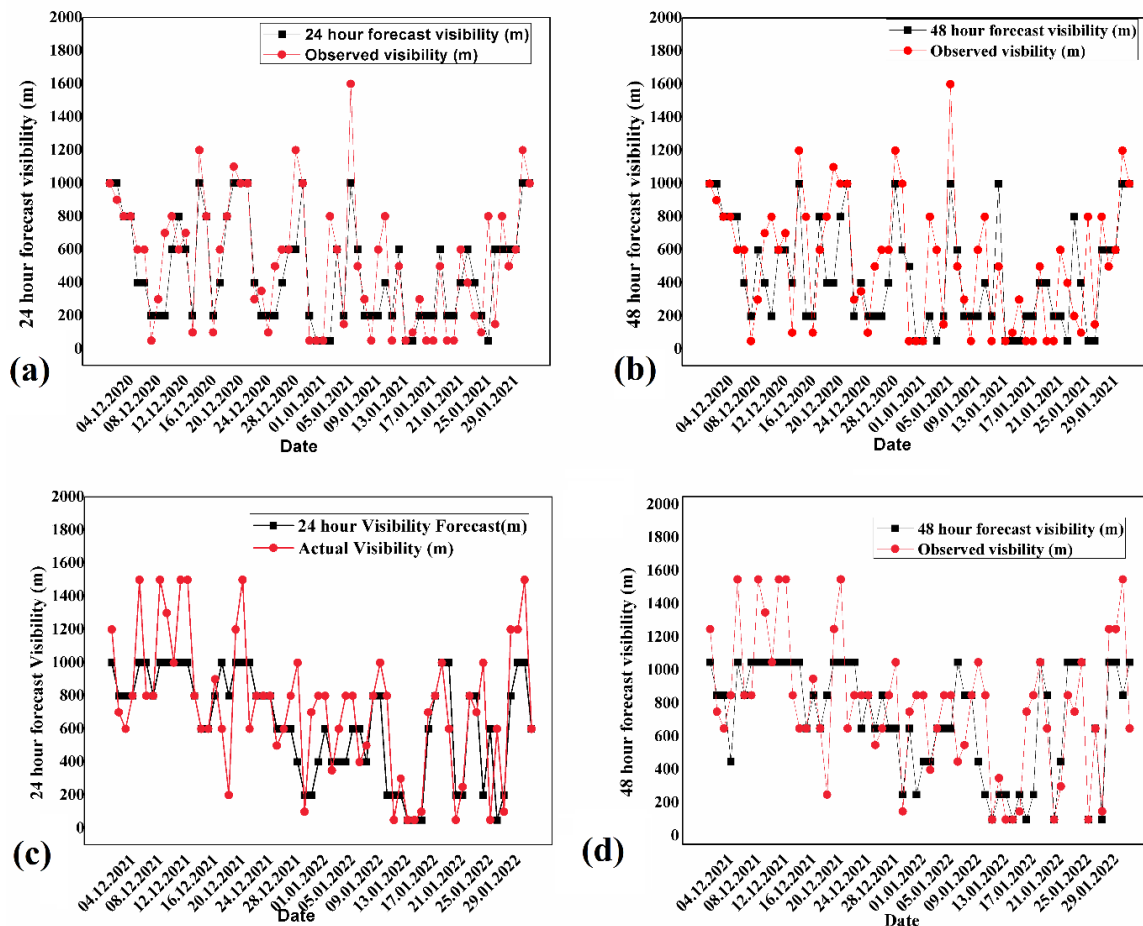


Figure 1 (a-d). Time series plots of forecast visibility and observed visibility. (a) 24- hours forecast, 2020-21, (b) 48- hours forecast, 2020-21, (c) 24- hours forecast, 2021-22 and (d) 48-hours forecast, 2021-22.

Later, observed meteorological conditions like clear sky, inversion temperature of 8°C, backing wind, relative humidity (98%) were also in favourable positions. Moreover, other parameters that were predicted to be unfavorable like wind speed (0 Knots), and minimum air temperature (9 °C) were also observed to be in unfavorable state only with reported wind speed of 0 knots & minimum air temperature of 10.5 °C. All of the above factors led to the formation of shallow fog with the lowest visibility of 600 m as predicted. Similarly, the 24-hours forecast for 15.12.2021 predicted the parameters as WD (70 °E), clear sky, inversion temperature (8°C), backing wind, relative humidity (95%), wind speed (0 knots), minimum air temperature (9 °C). Moreover, these parameters were in accordance with the observed values of WD (67°E), clear sky, inversion temperature (6°C), backing wind, relative humidity (91%), wind speed (0 knots), minimum air temperature (11.2 °C). Hence the observed visibility of 600m was in agreement with the predicted lowest visibility of 600m. The fog predicted for 17.01.2022 in 24-hours forecast was shallow fog with the lowest visibility as 800 m. The predicted parameters like relative humidity (90%), WD(90°E), inversion temperature (2°C), minimum air temperature (8°C), backing wind etc. were in agreement with the observed values of relative humidity (92%), WD (90 °E), inversion temperature (2 °C), min air temperature (7.8°C), backing wind, clear sky etc. which led to the formation of shallow fog with visibility of 800m as predicted.

The 48-hours visibility forecast were also predicted accurately in a substantial number of cases. For example, 48-hours forecasts for 04.01.2021 and 07.01.2021 predicted a dense fog event with the lowest visibility of 200m. Later on, the lowest visibility of 150m and 300m in dense fog conditions were reported on 04.01.2021 and 07.01.2021 respectively. The wind speed of 02 knots and 03 knots predicted for 04.01.2021 and 07.01.2021, respectively were highly in agreement with the observed wind speeds of 04 and 03 knots for the corresponding days. Similarly, the observed relative humidity of 98% on both days were close to the predicted value of 95% for both days. A very dense fog of 50 m was accurately predicted for 11.01.2022 in 48-hours forecast and the observed lowest visibility reported on 11.01.2022 was also 50 m. The predicted parameters like relative humidity (95%), wind speed 4 knots, WD (79°E), inversion temperature (6 °C), clear sky, backing wind etc. were in agreement with the observed values of relative humidity (100%), wind speed 3 knots, WD (75 °E), inversion temperature (6 °C), clear sky & backing wind etc.

Even though the predictions of fog/visibility are noticed to be in agreement with the observations in the majority of the events, there were some cases observed in which discrepancies were reported. Some examples are discussed as follows. The 24-hours forecast for 07.01.2021 predicted dense fog with the lowest visibility of 200 m as the wind

speed was predicted to be 6 knots which is in the unfavorable range. However, the actual wind speed observed on that day was 04 knots which is in the favourable range for fog formation which leads to the lowest visibility of 50 m in very dense fog conditions on 07.01.2021. The analysis revealed that the wrong prediction of wind speed led to an error in fog/visibility prediction. Similarly, the wrong prediction of wind speed of 06 knots for 08.01.2021 in 24-hours forecast is identified as the reason for the discrepancy as the observed wind speed was 02 knots. Thus, the very dense fog event (visibility 50 m) was observed on 08.01.2021 instead of the predicted visibility of 200 m in dense fog conditions. Furthermore, the 24-hours forecast predicted dense fog with the lowest visibility of 200m on both the days on 19.01.2021 and 20.01.2021. Later, very dense fog of lowest visibility of 50m was observed even though the WD was in the unfavorable range on both days. Dense fog with the lowest visibility of 200 m was predicted in the 24-hours forecast for 11.01.2022. Even though all parameters were predicted to be in the favourable range except the wind was predicted to be unfavorable being veering in nature. In actual observation, a very dense fog was observed at the IGI Airport with the lowest visibility of 50 m. This discrepancy may be due to the observed backing nature of wind which is favorable for fog formation, whereas it was predicted as veering in nature. Similarly, dense fog (visibility 200 m) was predicted in 48-hours forecast for 13.01.2022. All parameters were predicted to be in the favourable range except minimum air temperature (8°C) which was in the unfavorable range. Even though all other parameters were observed as predicted but discrepancies were observed in the value of minimum air temperature (6.6°C) which came under the favourable range. This led to the formation of very dense fog on 13.01.2022 instead of dense fog. Shallow fog with the lowest visibility of 800m was predicted in 24- hours forecast for 18.12. 2021. However, dense fog with the lowest visibility of 200 m was observed. This may be due to the prediction error in WD and minimum air temperature, i.e., no WD was predicted for 18.12. 2021, but a WD was observed at 74°E . In addition, the minimum air temperature was predicted in the unfavorable range being 9°C , but the observed value of minimum air temperature was 6.2°C . All of these favorable factors result in the formation of dense fog instead of shallow fog.

In some cases, an opposite scenario happened in which the predicted visibility was less, but the actual visibility was found to be sufficient for aviation requirements. For example, all meteorological parameters except cloud conditions were predicted to be favourable for 25.12.2020 which led to a prediction of a dense fog event with the lowest visibility of 200 m. But in actual observation, along with the cloud conditions, wind speed and wind direction were also observed to be in an unfavorable state causing shallow fog with the lowest visibility of 700 m which is not hazardous for aviation activities. Similarly, for 02.01.2021 and 25.01.2021, very dense fog with the lowest visibility of 50 m forecasts were issued. The predicted values of all meteorological parameters were in the favourable range for very dense fog formation. However, shallow fog with the lowest visibility of 800 m was

recorded on both days. Further analysis revealed that the minimum air temperature and wind speed on both days were unfavorable which led to the formation of shallow fog instead of very dense fog. Moderate fog with the lowest visibility of 400m was predicted in 24-hours forecast for 31.12.2021. However, the observed visibility was 800m in shallow fog. The reason for shallow fog instead of moderate fog may be due to the observed cloudy sky, WD (89°E) which has already been passed Delhi 3 days ago and due to which the impact of WD was low & relative humidity(88%) was also observed to be on the lower side. All of these conditions led to a low moisture supply which led to the formation of shallow fog only. 24-hours forecast of 30.12.2021 predicted dense fog with visibility of 200m. However, certain observed parameters like wind speed (0knots), wind direction and surface temperature inversion(2°C) were not found in the favourable range as predicted. These weather conditions contributed to the formation of shallow fog (visibility of 700m) instead of dense fog.

The 48-hour fog/visibility forecast is a more challenging task and more vulnerable to errors as compared to 24-hours forecast. The following section briefly discusses the discrepancies observed in those events where the predicted and observed visibility are not in agreement. Forecasts for 13.12.2020, 30.12.2020 and 19.01.2021 was of moderate fog with the lowest visibility of 400 m. The WD predicted was to be in the unfavourable range for 13.12.2020 & 19.01.2021, whereas the surface temperature inversion and wind speed predicted were in unfavourable range for fog formation on 30.12.2020. Still, in all the cases, a very dense fog of the lowest visibility of 50 m was observed. Very dense fog was predicted for 03.01.2021 and 25.01.2021 as all the parameters were predicted to be favourable for very dense fog formation. However, minimum air temperature & wind speed was observed to be unfavourable for both days. In addition, the WD and dew point depression were also observed as unfavourable for 25.01.2021 whereas for 03.01.2021, the unfavourable parameter was surface temperature inversion. All of the above parameters were related to the occurrence of shallow fog with the lowest visibility of 600 m on both 03.01.2021 and 25.01.2021 instead of very dense fog as predicted. Very dense fog (visibility of 50m) was predicted in 48-hours forecast for 16.01.2022 i.e. all the parameters were predicted to be favourable for fog formation. However, observed values of surface temperature inversion (2°C), minimum air temperature (8.1°C), wind speed (6knots) and wind direction were found to be unfavourable which leads to a shallow fog (700m) instead of very dense fog on 16.01.2022. Further, 48-hours forecast for 10.01.2022 predicted dense fog with a visibility of 200 m. However, the observed visibility was 800 m in shallow fog. This discrepancy may be due to the parameters like cloud conditions (clear sky), backing wind, surface temperature inversion (6°C) were predicted to be favourable for fog formation. However, cloudy sky, veering wind, surface temperature inversion (2°C) which were observed on 10.01.2022 were unfavourable for fog formation. This led to the formation of shallow fog instead of dense fog.

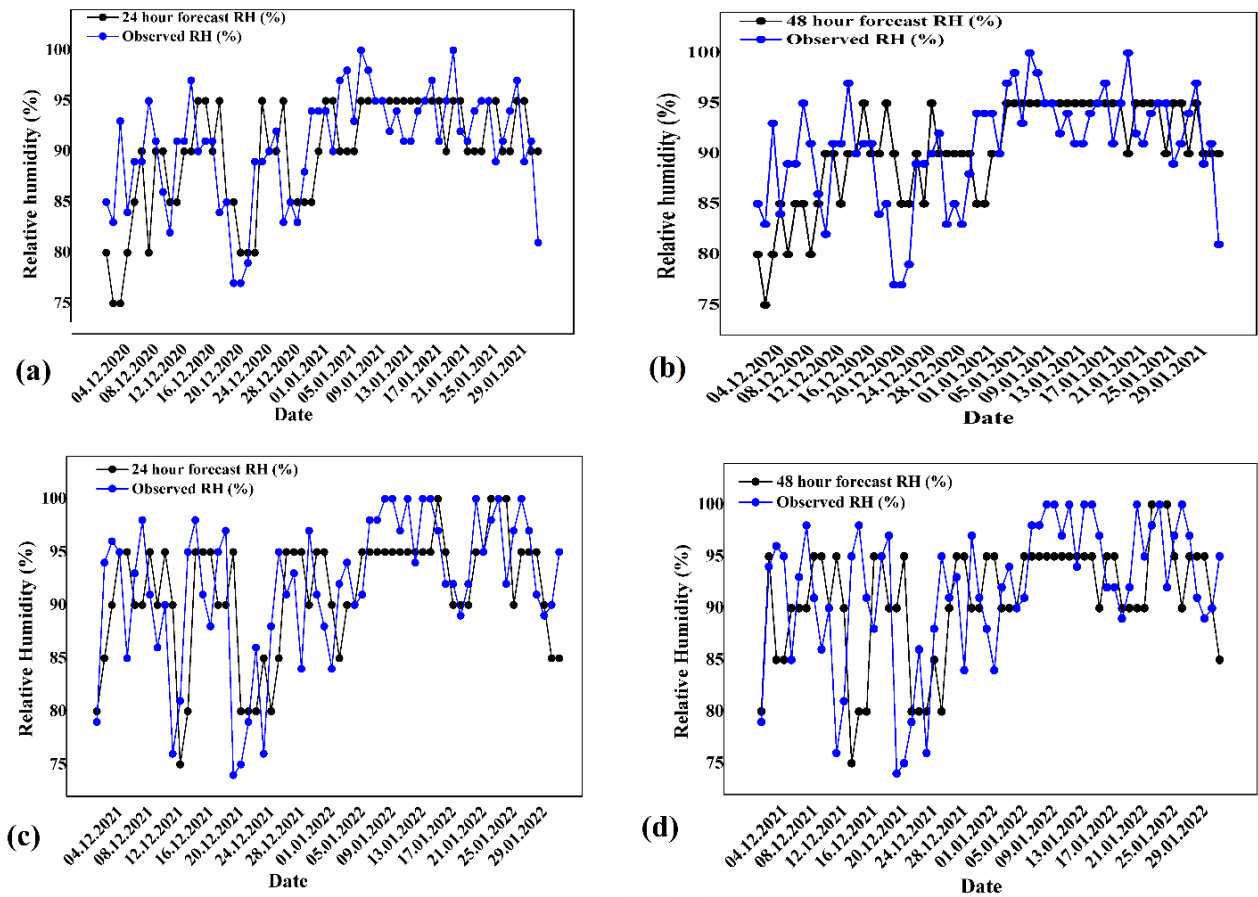


Figure 2 (a-d). Time series plots of forecast relative humidity and observed relative humidity. (a) 24-hour forecast, 2020-21, (b) 48-hour forecast, 2020-21, (c) 24-hour forecast, 2021-22 and (d) 48-hour forecast, 2021-22.

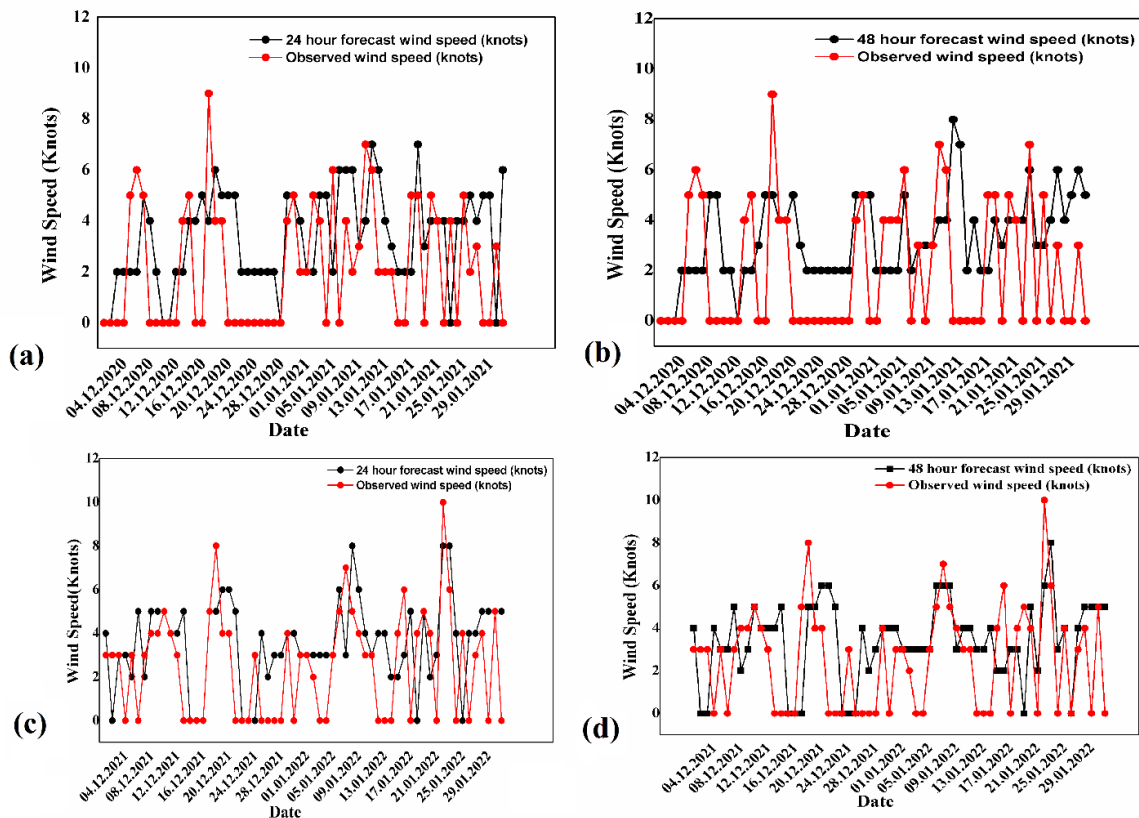


Figure 3 (a-d). Time series plots of forecast wind speed and observed wind speed. (a) 24-hour forecast, 2020-21, (b) 48-hour forecast, 2020-21, (c) 24-hour forecast, 2021-22 and (d) 48-hour forecast, 2021-22.

Furthermore, it has also been observed that in some events (13.01.2022 and 14.01.2022), very dense fog has been reported even though the observed wind speed was 0 knots which is considered to be unfavorable for fog formation in the present analysis. This may be due to the error in reporting the wind speed i.e., wind speed of 1-2 knots may sometimes be reported as calm (0 knots). Hence the range of wind speed favorable for fog formation may be changed in the future course from 2-4 knots to 0 - 4 knots. It has also been noticed in few cases like on 11.01.2022 that even though the temperature was reported to be slightly higher than 8 °C, still very dense fog was observed on that day. Air temperature is generally reported on the higher side for safety purposes in aviation meteorology. This is because engine efficiency is lower & lift is less with higher temperatures and thus reporting temperature on the higher side enables the adequate planning of fuel and load in the aircraft. Hence the range of minimum air temperature favorable for fog formation might be changed from less than 8 °C to less than 10°C. Overall analysis showed that the role of each meteorological parameter should be given different weightages instead of giving equal weightage to each of them.

This is because throughout the winter season, the parameters like relative humidity, dew point depression, cloud conditions and backing of wind are mostly in favourable ranges for fog formation and hence do not impact the variations in fog intensity significantly. However, the remaining parameters like wind speed, WD, surface temperature inversion, minimum air temperature affect the genesis and dissipation of fog in a dominant way throughout the winter season. Hence depending upon the supremacy, the weightage must be changed accordingly. This factor will be taken into consideration in the upcoming fog/visibility forecast studies. Finally, the present study also revealed that the 24-hours forecast has better accuracy as compared to 48-hours forecast. Normally, 6-hours lead time forecast is sufficient for the proper management of aviation transportation activities at the IGI airport. However, considering the complete requirements of the aviation sector, 24-hours forecasts can also play a crucial role. Therefore, in future studies, 24-hours fog/visibility forecast which will be updated in every 06 hours will be implemented which can further increase the accuracy of the fog/visibility predictions at the IGI airport.

The bar diagrams in Figure 4 (a-d) represent the overall number of types and occurrence of various fog events

observed along with the 24-hours and 48-hours fog forecasts for 2020-21 and 2021-22 winter seasons. In 2020-21, 12 very dense fog events, 8 dense fog, 8 moderate fog, 23 shallow fog and 11 mist events were reported. In 2021-22, the number of observed events of very dense fog, dense fog and moderate fog were 5, 4 and 6 respectively which were less as compared to 2020-21 data. But the reported shallow fog and mist events in 2021-22 were 30 and 17 respectively which were higher than that in 2020-21 data.

The following section briefly discusses about the statistics between the predicted and observed fog events over the IGI airport. In 2020-21, 12 very dense fog events were occurred. The 24-hours and 48-hour forecasts of 2020-21 accurately predicted 8 out of them but missed out the remaining 4 events. However, in 2021-22, 24 and 48-hours forecasts predicted 4 & 6 very dense fog events respectively which were very close to the observed no of 5 very dense fog events. Further, in 2020-21, the number of dense fog events predicted were 17 and 19 respectively for 24 and 48-hours forecasts, but dense fog occurred only 8 times out of them which indicates the overestimated dense fog predictions in 2020-21. Similar scenario was observed in 2021-22 as well in which the predicted dense fog events for 24 and 48-hour forecasts were 9 and 7 respectively, but the actual occurrence of dense fog was observed only on 4 events out of them.

The prediction of moderate fog was quite near to the actual observations for both the years. The 24-hours and 48-hours forecast predicted 10 and 12 moderate fog events respectively for 2020-21 in which moderate fog was observed on 8 times out of them. Similarly, in 2021-22, the 24-hours and 48-hours forecasts predicted 6 & 5 moderate fog events respectively. in which moderate fog was observed on 6 times out of them. The shallow fog events were predicted to be 17 & 14 in 24-hours and 48-hours forecasts respectively for year 2020-21. However, shallow fog was observed in 23 events in 2020-21. Similarly, in 2021-22, the shallow fog was observed in 30 events, but it was predicted only for 27 & 23 events in 24-hours and 48-hours forecasts. Overall, underestimation in shallow fog prediction was observed in both the years 2020-21 and 2021-22. Finally, 11 mist events were observed in 2020-21. Moreover, 24-hours and 48-hours forecasts of 2020-21 were quite near to the actual number of events i.e., 10 and 9 mist events respectively. In 2021-22, 17 mist events were reported and 24-hours & 48-hours forecasts predicted 16 and 21 events respectively.

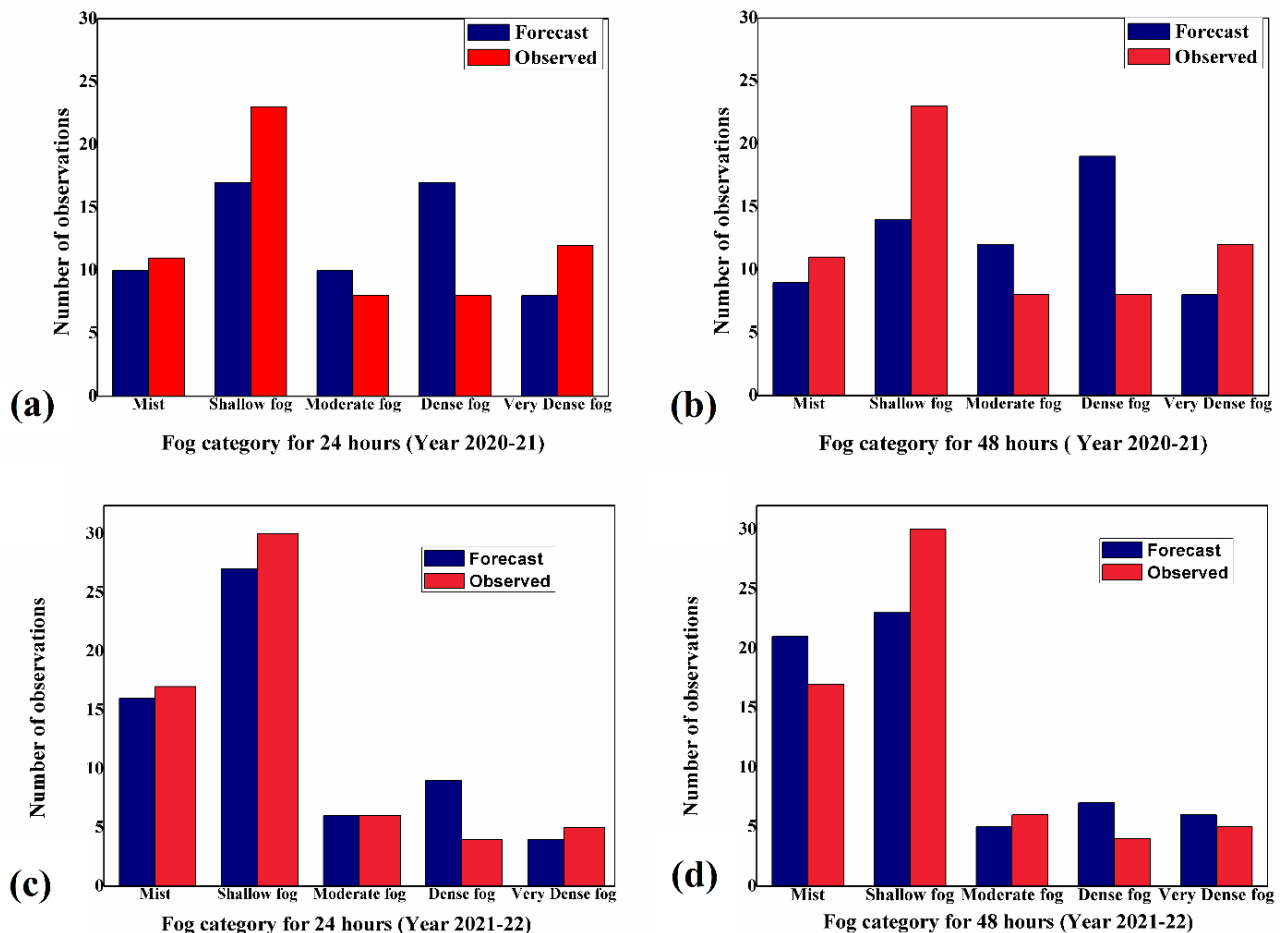


Figure 4 (a-d). Bar diagram plots between forecasted and observed fog events at IGI airport. (a) 24-hour forecast, 2020-21, (b) 48-hour forecast, 2020-21, (c) 24-hour forecast, 2021-22 and (d) 48-hour forecast, 2021-22.

In the present study, the 24-hours and 48-hours forecasts of visibility for 2020-21 and 2021-22 have been compared with the corresponding observed visibility from METAR and synoptic observations which are indicated as scatter plots shown in Figure 5(a-d). From Figure 5(a-d), the correlation between the forecasted and observed data sets were estimated. The correlation coefficient for 24-hours forecast is promising with values of 0.79 & 0.70 for 2020-21 & 2021-22 respectively. However, the correlation coefficient for 48-hours forecast is 0.65 & 0.66 for 2020-21 & 2021-22 respectively which is lower than 24-hours forecast. The most probable reason may be as the lead time of forecast increases, accuracy of various meteorological parameters from the model outputs which were used to predict the visibility may decrease. This implies that the 48-hours forecast is a challenging task as compared to 24-hours forecast.

To get more insights to the statistical analysis, the 24-hours and 48-hours visibility forecast were categorized further into two categories i.e. visibility with an error of $\pm 100\text{m}$ & $\pm 200\text{m}$ for the years 2020-21 (Table 4) & 2021-22 (Table 5). The Probability of Detection (POD) of 24-hours forecast is excellent with values of 0.92 & 0.98 for visibility error of $\pm 100\text{m}$ & $\pm 200\text{m}$ respectively for 2020-21. The POD for 48-hours forecast of 2020-21 is lower as compared to 24-hours forecast as it is 0.79 & 0.85 for visibility error of $\pm 100\text{m}$ & $\pm 200\text{m}$ respectively. Similarly, the POD of 24-hours forecast for 2021-22 also observed to be high i.e., 0.73 & 0.87 for visibility error of $\pm 100\text{m}$ & $\pm 200\text{m}$ respectively. However, the POD for 48-hours forecast of 2021-22 is comparatively lower than 24-hours forecast i.e., 0.61 & 0.81 for visibility error of $\pm 100\text{m}$ & $\pm 200\text{m}$ respectively.

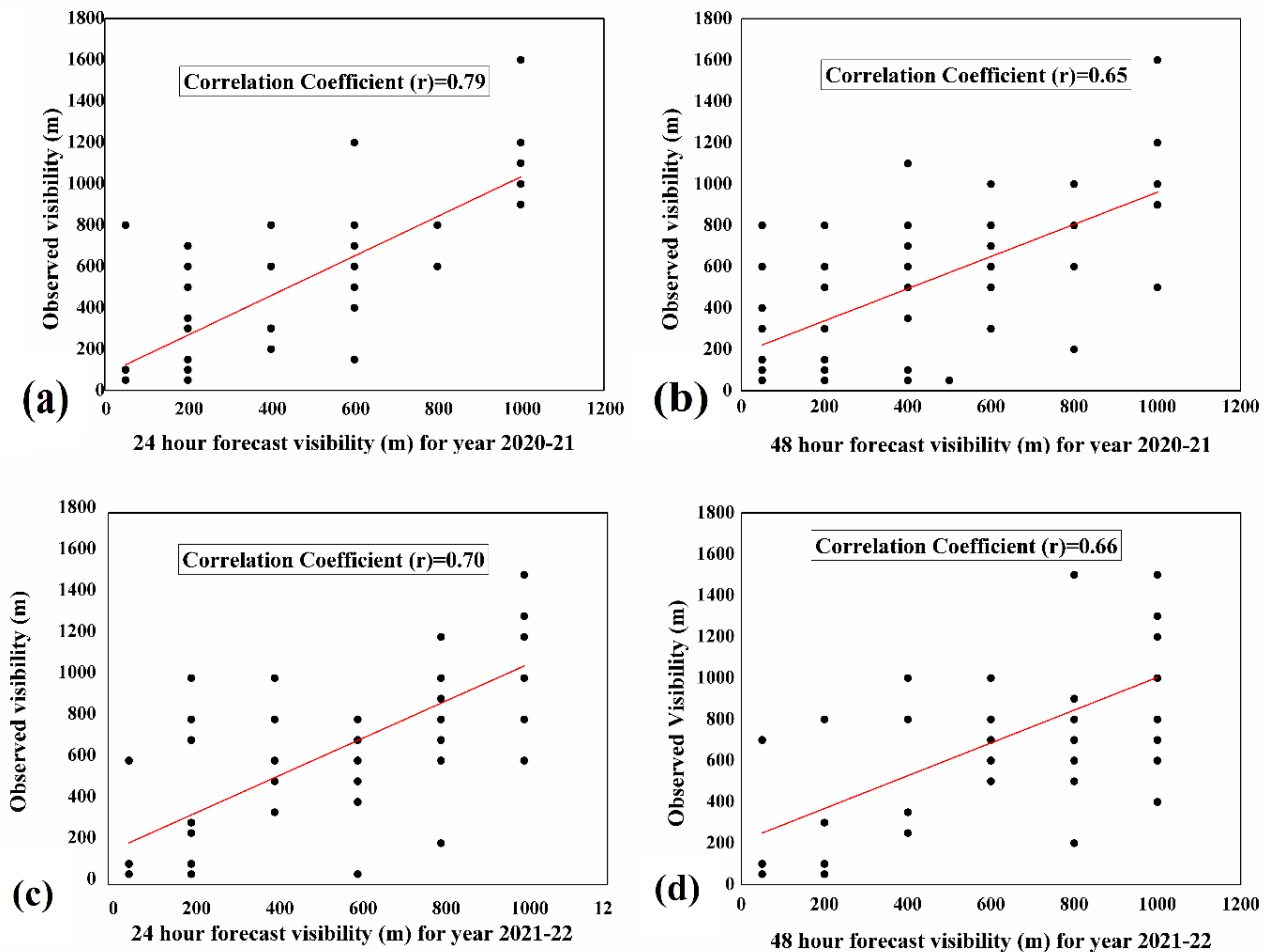


Figure 5(a-d). Scatter plots of forecast and observed visibility. (a) 24-hours forecast, 2020-21 (b) 48-hours forecast, 2020-21, (c) 24-hours forecast, 2021-22 and (d) 48-hours forecast, 2021-22.

Overall analysis indicated that the accuracy is highest in 24-hours forecast (visibility ± 200 m), i.e., 0.89 & 0.79 in 2020-21 & 2021-22 respectively. The lowest accuracy is observed in 48-hours forecast (visibility ± 100 m), i.e., 0.54 & 0.56 in 2020-21 & 2021-22 respectively. Accuracy of 24-hours forecast (visibility ± 100 m) & 48-hours forecast (visibility ± 200 m) are observed to be in moderate range i.e., 0.73 & 0.68 respectively for the year 2020-21. Similarly, for 2021-22, the accuracy of 24-hours forecast (visibility ± 100 m) & 48-hours forecast (visibility ± 200 m) are noticed to be in the moderate range i.e., 0.63 & 0.74 respectively. It has also been observed that the accuracy of 24-hours forecast for both visibility errors of ± 100 m & ± 200 m for year 2020-21 is greater than that of 2021-22. However, opposite trend is observed for 48-hours forecast accuracy as it is found to be greater in 2021-22 than that in

2020-21 for both visibility errors of ± 100 m & ± 200 m. The general trend observed in accuracy analysis is followed in success ratio analysis as well. Out of all the four cases, the success ratio is highest in 24-hours forecast (visibility ± 200 m) i.e., 0.88 & 0.82 in 2020-21 & 2021-22 respectively. The lowest success ratio is observed in 48-hours forecast (visibility ± 100 m) i.e., 0.56 & 0.63 in 2020-21 & 2021-22 respectively. Success ratio of 24-hours forecast (visibility ± 100 m) & 48-hours forecast (visibility ± 200 m) are observed to be in moderate range i.e., 0.72 & 0.71 respectively for the year 2020-21. Similarly, for 2021-22, success ratio of 24 -hoursforecast (visibility ± 100 m) & 48-hours forecast (visibility ± 200 m) are also observed to be in moderate range i.e., 0.68 & 0.76 respectively.

Table 4. Statistical report of 24-hours and 48-hours visibility forecast for the years 2020-21

Statistical Term	24-hour forecast		48-hour forecast	
	Visibility ± 100 m	Visibility ± 200m	Visibility ± 100m	Visibility ± 200m
Probability of Detection (POD)	0.92	0.98	0.79	0.85
Accuracy	0.73	0.89	0.54	0.68
Success ratio	0.72	0.88	0.56	0.71
Critical Success Index (CSI)	0.68	0.87	0.49	0.63
False Alarm Ratio (FAR)	0.28	0.12	0.44	0.29
Bias score	1.28	1.10	1.41	1.20
Heidke skill score	0.35	0.65	0.05	0.23

Table 5. Statistical report of 24-hours and 48-hours visibility forecast for the years 2021-22

Statistical Term	24-hour forecast		48-hour forecast	
	Visibility±100m	Visibility±200m	Visibility±100m	Visibility±200m
Probability of Detection (POD)	0.73	0.87	0.61	0.81
Accuracy	0.63	0.79	0.56	0.74
Success ratio	0.68	0.82	0.63	0.76
Critical Success Index (CSI)	0.54	0.73	0.45	0.64
False Alarm Ratio (FAR)	0.32	0.18	0.37	0.24
Bias score	1.08	1.07	1.18	1.05
Heidke skill score	0.22	0.55	0.11	0.20

The Critical Success Index (CSI) is also calculated and found to be highest in 24-hours forecast (visibility±200 m) i.e., 0.87 & 0.73 for 2020-21 & 2021-22 respectively. The lowest CSI is observed in 48-hours forecast (visibility ±100 m) i.e., 0.49 & 0.45 in 2020-21 & 2021-22 respectively. However, the performance of CSI has been observed to be in the moderate range for 24-hours forecast (visibility±100 m) & 48-hour forecast (visibility±200 m), i.e., 0.68 & 0.63 respectively for 2020-21 and 0.54 & 0.64 respectively for 2021-22. Furthermore, the False Alarm Ratio (FAR) over all the seasons were investigated and it is observed to be lowest in 24-hours forecast (visibility±200 m), i.e., 0.12 & 0.18 for years 2020-21 & 2021-22 respectively. However, the highest FAR are observed in 48-hours forecast (visibility±100 m), i.e., 0.44 & 0.37 for the year 2020-21 & 2021-22 respectively. However, 24-hour forecast (visibility±100 m) & 48-hours forecast (visibility±200 m) cases have moderate FAR, i.e., 0.28 & 0.29 respectively for 2020-21 and 0.32 & 0.24 respectively for 2021-22. In addition, the bias score of all forecasts is calculated and found to be above one for all the

cases in 2020-21 & 2021-22 which implies an over forecast scenario. The best bias score is observed in 24-hours forecast (visibility±200 m), i.e., 1.10 & 1.07 for the year 2020-21 & 2021-22 respectively. Finally, the Heidke Skill score is also estimated and give reasonably good values, i.e., 0.65 & 0.55 for 24-hours forecast (visibility±200 m) for the year 2020-21 & 2021 -22 respectively.

The overall statistical analysis shows that 24-hours forecast (visibility ±200 m) gives the best statistical results having the highest POD, accuracy, SR, CSI & Heidke skill score and lowest FAR, bias score in both the years of 2020-21 & 2021-22. However, an opposite scenario was observed in 48-hours forecast (visibility±100 m), i.e., the statistical results like the lowest POD, accuracy, SR, CSI, Heidke skill score and highest FAR and bias score in both the years of 2020-21 & 2021-22. Moreover, the 48-hours forecast (visibility±100 m) performance needs to be improved. The study also indicated that the improvement in accuracy of visibility to an error of ±100 m over a long

period of 48 hours is a challenging task, whereas the shorter period (24 hours) with a greater range in visibility ($\pm 200\text{m}$) gives promising results. As the lead time required to make a decision for aviation purposes is approximately 06 to 08 hours, then 24-hour fog/visibility forecasts can fulfil aviation requirements in any aspect. Further, fog is also categorized based on the visibility range as well. Combining all the factors, a 24-hours (visibility $\pm 100\text{ m}$) fog/visibility forecast which will be updated in every 06 hours, can fulfil the aviation requirements during the winter seasons at IGI airport. In the upcoming years, as the accuracy of the model output improves, correspondingly, the fog/visibility forecast will also be more accurate.

5. Conclusion

The primary objective of the present study is to improve the accuracy of fog/visibility forecast over the IGI Airport during the winter seasons of 2020-21 and 2021-22. Various meteorological parameters collected from IMD GFS model outputs have been used to innovatively predict the 24-hours and 48-hours fog/visibility over the IGI Airport. Daily forecasts are issued which are valid for the next 24 hour and 48 hours consist of information on fog, visibility, wind speed and relative humidity etc. The verification of these forecasts is carried out using the METAR and synoptic observations prepared at IGI Airport by the Meteorological Watch Office. Results have show that the 24-hours forecast has the highest hit rate of 0.92, accuracy (0.73), success ratio (0.72), CSI (0.68) and fairly low FAR (0.28) & bias score (1.10) for the 2020-21 winter season. Similarly, the results of 24-hours forecast of 2021-22 also encouraged a hit rate of 0.73, accuracy (0.63), success ratio (0.68), CSI (0.54) and low FAR (0.32) & bias score (1.08). However, the 48-hours forecast of all seasons has lesser accuracy than 24-hours forecast. The 48-hours forecast scheme needs further improvement for better results. In future, the revised weightage criteria for each parameter instead of equal weightage can also have a scope to improve the fog/visibility forecast. The study has also suggested various findings that can be implemented in the future course to improve the fog/visibility forecast over the IGI airport during the upcoming winter seasons.

Author Statement

AC: Conceptualization, formal analysis, investigation, methodology, validation, visualization and writing original draft
 ASH: Conceptualization, formal analysis, investigation, methodology, validation, visualization, writing-review and editing and supervision.
 CS: Conceptualization, formal analysis, supervision and writing-review and editing and supervision.
 SJ: Visualization and writing-review and editing.

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