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Characteristics of visibility for Chennai international airport

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सार–चेन्नई अंतर्राष्ट्रीय हवाई अड्डे पर दृश्यता (Visibility) में 2016 और 2024 के बीच भारी गिरावट देखी गई है, जिसका एक मजबूत नकारात्मक रुझान (R2 = 0.89) बढ़ते मौसम के व्यवधानों और बढ़ते शहरी प्रदूषण से जुड़ा हुआ है। दृश्यता (Visibility) में इस कमी के कारण उड़ानों में विलंब की घटनाएँ अधिक बार होने लगी हैं, विशेषकर प्रातःकालीन समय लगभग (06: 30 -07:30 भारतीय मानक समय (IST) के दौरान, जब METAR अभिलेखों में सामान्यतः दृश्यता का न्यूनतम मान दर्ज किया जाता है। मौसमी विश्लेषण नवंबर को सबसे खराब समग्र दृश्यता वाले महीने के रूप में उजागर करता है, जबकि सबसे गंभीर गिरावट अक्सर 1200 मीटर से नीचे और कभी-कभी 400 मीटर के नीचे दिसंबर से फरवरी के दौरान होती है। जनवरी में अत्यधिक कम दृश्यता की उच्चतम आवृत्ति दर्ज की जाती है, जिसमें 200 मीटर से नीचे की घटनाएं भी शामिल हैं। कोहरा आमतौर पर सुबह 03:30 IST के पास शुरू होता है और सुबह 07:00 IST के आसपास चरम पर होता है, जो सुबह के विमानन संचालन को सीधे प्रभावित करता है। औसतन, कोहरा जनवरी में 5.2 दिन, फरवरी में 4.8 दिन, दिसंबर में 3.9 दिन और मार्च में 3.1 दिन होता है, जिसमें अक्टूबर-नवंबर सालाना अन्य 3.2 दिन जोड़ते हैं। बैकवर्ड प्रक्षेपवक्र विश्लेषण (Backward trajectory analysis) बताता है कि एरोसोल परिवहन इन स्थितियों में योगदान देता है, जो स्थानीय प्रदूषण और क्षेत्रीय वायुमंडलीय प्रक्रियाओं दोनों की भूमिका को सुदृढ़ करता है। निष्कर्ष कम दृश्यता की बढ़ती चुनौतियों को कम करने के लिए सख्त वायु-गुणवत्ता उपायों, बेहतर हवाई अड्डे के बुनियादी ढांचे और अनुकूली परिचालन रणनीतियों की तत्काल आवश्यकता पर प्रकाश डालते हैं।

ABSTRACT. Visibility at Chennai International Airport has shown a marked decline between 2016 and 2024, with a strong negative trend ($R^2 = 0.89$) linked to increasing weather disturbances and rising urban pollution. This reduction in visibility has contributed to more frequent flight delays, particularly during early morning hours (around 06:30–07:00 IST), when the lowest values are typically recorded in METAR. Seasonal analysis highlights November as the month with the poorest overall visibility, while the most severe reductions often below 1200 m and sometimes under 400 m occur in December through February. January records the highest frequency of extremely low visibility, including occurrences below 200 m. Fog typically begins near 03:30 IST and peaks around 07:00 IST, directly affecting early morning aviation operations. On average, fog occurs 5.2 days in January, 4.8 days in February, 3.9 days in December, and 3.1 days in March, with October–November adding another 3.2 days annually. Backward trajectory analysis suggests aerosol transport contributes to these conditions, reinforcing the role of both local pollution and regional atmospheric processes. The findings highlight an urgent need for stricter air-quality measures, improved airport infrastructure, and adaptive operational strategies to mitigate the growing challenges of low visibility.

Key words – Fog characteristics, Visibility, Trend, METAR, Chennai.

1. Introduction

Atmospheric visibility plays a crucial role in various sectors, including aviation, transportation, and public safety. Several weather events, including haze, mist, smoke, fog, thunderstorms, and rainfall significantly reduce visibility over Chennai during the months of October to February. These reductions in visibility are primarily driven by meteorological conditions, such as high humidity, temperature fluctuations, and stagnant air masses; which facilitate the accumulation of particulate matter and water droplets in the lower atmosphere (Singh *et al*., 2017). The cooling of air near the surface facilitates moisture condensation, leading to fog formation (Gultepe *et al*., 2007; Lakra *et al*., 2022). This phenomenon is particularly pronounced in the winter months of October through February, when nocturnal radiative cooling intensifies, thereby increasing the probability of fog occurrence (Tardif and Rasmussen, 2007). Moreover, elevated relative humidity, and weak surface winds contribute to the persistence of fog layers by minimizing d ispersion and sustaining moisture accumulation (Ding *et al*., 2014).

Additionally, anthropogenic activities, including vehicular emissions and biomass-burning, exacerbate haze and smoke, compounding the effects of natural weather phenomena (Jiang *et al*., 2023). The interaction between fog/haze/mist and air pollution further amplifies visibility deterioration, particularly in densely-populated regions with high emissions (Qianhui *et al*., 2016). Poor visibility days have slightly increased over Mumbai, Chennai, Visakhapatnam, and Bhubaneswar without statistical significance, while Bengaluru records a significant reduction in visibility (De *et al*., 2001). Seasonal declines in visibility create major challenges for aviation and air traffic operations, impacting flight safety and efficiency. They also disrupt transportation networks and pose risks to public health, highlighting the need for advanced monitoring systems and targeted mitigation strategies.

Understanding the characteristics and underlying mechanisms governing fog formation over Chennai is essential for effective mitigation and forecasting. Fog is a type of atmospheric phenomenon characterized by the suspension of water droplets or ice crystals, leading to reduced horizontal visibility to less than 1 km (Gultepe *et al*., 2007). The formation and dissipation of fog depend on several meteorological parameters, including temperature, humidity, wind, and aerosol concentration (Tardif and Rasmussen, 2007). Western disturbances significantly impact winter meteorology across South Asia (Dimri *et al*., 2015); although their direct effect on Chennai is less pronounced than in northern India. This can influence regional atmospheric circulation leading to enhanced moisture transport and cloud development. The planetary boundary layer further modulates heat and moisture exchanges between the surface and the atmosphere, playing a pivotal role in fog dynamics and therefore causes visibility reduction (Fernando and Weil, 2010; Yingchuan, 2021). A shallow and stable boundary layer inhibits vertical mixing, trapping moisture and pollutants near the surface and exacerbating visibility reduction (Zhanqing, 2017). Coastal cities like Chennai are particularly susceptible to radiation fog and advection fog due to their proximity to large water bodies, which influence local temperature and moisture dynamics. Several studies have examined fog formation over Indian cities, highlighting the role of urban heat islands, land-sea interactions, and pollution in modulating fog events (Jenamani, 2007; Suresh *et al*., 2007; Badarinath *et al*., 2009; Gautam *et al*., 2014; Sawaisarje *et al*., 2014; Hingmire *et al*., 2018). Chennai's unique geographical location, bordered by the Bay of Bengal, contributes to the development of fog through the advection of moist air mass from the sea. Additionally, temperature inversions, which trap moisture and pollutants near the surface, further amplify visibility reduction through significant air quality deterioration (Nejad *et al*., 2023). The interplay between natural and anthropogenic factors significantly influences the intensity and frequency of fog occurrences in urban environments. The increasing concentration of particulate matter due to vehicular emissions, industrial activities, and biomass burning have been linked to the enhancement of fog formation (Prasad *et al*., 2006; Rounaq *et al*., 2024). Aerosols serve as cloud condensation nuclei, promoting the persistence of fog by providing a surface for water vapor condensation. In Chennai, rapid urbanization and industrialization may contribute to localized variations in fog characteristics. Previous research on fog in India has primarily focused on northern regions, where winter fog is more frequent and severe (Bhowmik *et al*., 2004; Singh, 2011). However, there is limited literature addressing fog formation and visibility reduction in southern coastal cities like Chennai. Given the potential implications for transportation safety and urban planning, it is imperative to conduct comprehensive studies on the temporal variability of fog in Chennai. Present study aims to address the followings:

(*i*) Investigation of temporal characteristics of visibility for 2016 to 2024.

(*ii*) Finding out of the significant months for categorical visibility.

(*iii*) Fog intensity, duration and frequency analysis.

Study also analyzes the meteorological conditions associated with fog formation over Chennai, by identifying the key contributing factors and assessing its impact on visibility. By leveraging observational data, this study provides insights into the evolving nature of fog events and contributes to the development of improved forecasting techniques for the region.

2. Data and methodology

2.1. *Study area*

The study region, Chennai International Airport, is located within the Chennai Metropolitan Area (CMA) in Tamil Nadu, India. Chennai, a coastal city along the Coromandel Coast of the Bay of Bengal, lies between latitudes 12.85°N-13.3°N and longitudes 79.9°E-80.37°E. The city’s highest elevation reaches 60 meters, while the average elevation is approximately 6.7 meters. The terrain features scattered ridges that slope eastward toward the Bay of Bengal. Chennai experiences a tropical wet and dry climate, characterized by hot and humid conditions throughout most of the year. The post-monsoon season accounts for the majority of the city's annual rainfall of 59.8%, which declined to 54.7% between 2006 and 2014 (Ramachandran and Anushiya, 2015). The city typically gets its highest temperatures in June and peak rainfall in November. The Chennai International Airport is situated at Meenambakkam, about 14 km inland from the coast. Fog is a relatively rare phenomenon at the Meenambakkam Airport in Chennai. According to IMD (1999), fog occurs for about 1.5 days each in January & February, dropping to around half a day in December. It appears only occasionally, for 0.1 to 0.3 days, during March and from September to November, totaling roughly 4.3 foggy days in a year. In addition to its climatic characteristics, Chennai is a major industrial and economic hub. As a significant port city, it supports extensive trade and shipping activities. Its economy is driven by diverse sectors, including the automobile industry, chemical and petrochemical production, software services, healthcare, and manufacturing. These activities collectively contribute to substantial emissions and varied forms of pollution across the region, which degrades the visibility.

2.2. *Datasets*

The datasets are briefly described in this section.

2.2.1. *Meteorological data*

Meteorological aerodrome report (METAR) is the international standardized format as per International Civil Aviation Organization (ICAO) for reporting current weather conditions at an airport. It is an essential tool used in aviation to communicate concise and compatible information about the weather to pilots, air traffic controllers, and other aviation professionals. METAR reports provide real-time information about current weather conditions at specific locations and valuable for studying short-term weather phenomena, such as thunderstorms, precipitation patterns, and wind shifts (Oo *et al*., 2023; Piticar *et al*., 2024). METAR station in Chennai is located at Chennai International Airport and observations are usually recorded every 30-min interval at a height of 12 m above Average Mean Sea-Level (AMSL). It contains present weather conditions, such as wind speed (knot), wind direction (degree), visibility (m), runway visual range (RVR, m), cloud types, height of cloud base, temperature (°C), and dew-point (°C). In the present study, we utilized the Chennai METAR data from January 2016 to December 2024. The study also used relative humidity and daily gridded rainfall (Pai *et al*., 2014) datasets from the India Meteorological Department.

2.2.2. *HYSPLIT air mass trajectory*

The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model, developed by the Air Resources Laboratory of NOAA, is utilized in this study to trace the source regions and transport pathways of aerosols. This model combines elements of Lagrangian and Eulerian frameworks, as comprehensively described by Stein *et al*. (2015).

2.2.3. *Soil moisture data*

The study extracted Level-4, 3-hourly high-resolution (9-km) surface soil moisture from the Soil Moisture Active Passive (SMAP) satellite for the ONDJFM period from 2016 to 2024. This extraction was done using the JavaScript programming in Google Earth Engine (GEE) within the area bounded by the CMA polygon. While the extraction focused on surface soil moisture (0-5 cm), SMAP also provides soil moisture data for the root zone (0-100 cm).

2.2.4. *Vegetation cover data*

The study also extracted high-resolution (250-m) vegetation cover, normalized difference vegetation index (NDVI), data from the Moderate resolution Imaging Spectro-radiometer (MODIS) (Terra, MOD13Q1 and Aqua, MYD13Q1). This extraction was also done using the JavaScript programming in GEE for the area bounded by the CMA, for the same period as mentioned above.

2.3. *Methodology*

Data used in this study are extracted from all India daily METARs from 2016 to 2024. SPECI and incorrect METARs are filtered out through data cleaning process. Daily METARs are converted into monthly METARs file for the ease of our analysis. Visibility corresponds to each month are extracted and mean visibility are estimated over different temporal time steps (diurnal, daily, monthly, and annual). The study incorporates different statistical measures to scrutinize the visibility. In this study, five-day backward trajectories of air masses were computed at 24-hour intervals, with arrival altitudes set at 500 m, 1000 m, and 1500 m, using 0.25° meteorological data from the Global Forecast System (GFS). The chosen trajectory duration of five days allows for the assessment of the impact of prevailing weather patterns on aerosol transport. By mapping the backward trajectories, HYSPLIT effectively reveals the routes taken by air masses. This enables the identification of dominant aerosol transport pathways and potential pollution source regions affecting visibility at the Chennai airport. The investigation also uses descriptive statistics, which are widely used in various fields of study to measure and summarize different aspects of data. Present study uses mean, median, minimum, maximum, 25th and 75th percentiles and inter-quartile range (IQR) statistics of the visibility dataset. The slope, intercept, and significance are computed using the linear regression (Wilks, 2007). Additionally, we use the Pearson’s correlation (r). Correlation coefficient arrived by this method shows the degree of linear association

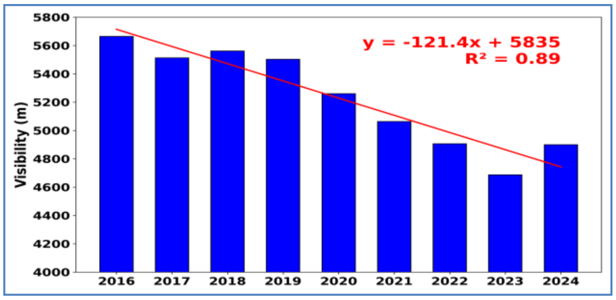


Fig. 1. Shows annual mean visibility for the period 2016-2024 for the Chennai International Airport. Red line represents the trend of visibility

TABLE 1

Fog intensity based on visibility criteria set by IMD 1982 and Laskar 2013

Visibility Range	Fog category
Visibility <1000 and >= 500 m	Light
Visibility < 500 and >= 200 m	Moderate
Visibility <200 and >= 50 m	Thick
Visibility < 50 m	Very Thick

between the two datasets; without consideration of any errors (Banerjee *et al*., 2021). Characteristic visibility frequencies are extracted for the visibility less than 5000 m, 4000 m, 3000 m, 2000 m, 1600 m, 1500 m, 1200 m, 1000 m, 800 m, 600 m, 400 m, and 200 m to investigates trends during 2016-2024. This analysis aims to identify the significant month responsible for each category. Visibility trends are estimated and level of significance of the correlation is assessed with probability value of ≤ 0.05 at 5% significance level. The study further investigates frequency, intensity, and duration of the fog events during the months October-March (ONDJFM), based on visibility criteria adopted by IMD, 1982 and Laskar, 2013, as highlighted in Table 1. To examine the environmental conditions associated with these fog events, zonal statistics algorithm is applied to extract the area-average rainfall, soil moisture, and NDVI data for the CMA.

3. Results and discussions

3.1. *Annual trend*

The mean annual visibility at Chennai International Airport shows a decreasing trend from 2016 to 2024, with r-square value of 0.89 (Fig. 1). This could be due to the increases in number of thunderstorms, drizzle, rainfall, mist, and foggy days along with increase in urban air pollution (Suresh *et al*., 2007; Sangeetha *et al*., 2020) over the area. As a result, the impact on flight operations has become more pronounced, leading to an increase in delays in recent years. These adverse weather conditions and environmental changes have posed significant challenges to aviation efficiency, affecting both departures and arrivals. Chennai, being a major aviation hub in south India, is experiencing operational disruptions, particularly during the monsoon and winter months, when adverse weather conditions as mentioned above are more prevalent. These challenges highlight the need for improved forecasting and mitigation strategies to ensure smoother air traffic management in the region.

3.2. *Diurnal variation*

The diurnal characteristics of the visibility at the Chennai international airport (Fig. 2) describes that at around morning 06:30 IST to 07:00 IST (01:00 UTC to 01:30 UTC) it experiences lowest visibility. As the day progresses, the mean diurnal visibility gradually increases and reaches its peak at around 14:00 IST (08:30 UTC). This diurnal characteristic varies significantly from one season to another. During MAM (Fig. S1b) and ON (Fig. S1d), visibility shows large variations during the period of lowest visibility, *i.e*., around 01:30 UTC, while for DJF (Fig. S1a) and JJAS (Fig. S1c), this variation is relatively lower. This could be due to the presence of characteristic aerosol particles loading in the vertical air column, which significantly vary from one season to another. These particles may come from either remote locations or regional sources, driven by wind (speed, direction) and maritime trade. Rise in sea-surface temperature could further amplify this effect during the MAM, when dust particles are coming from the Thar desert through long-range transport process (Fig.S2b). Their concentration may vary from one month to another during MAM and their interaction with light absorption changes significantly, as a result, large variation is observed. A similar pattern is observed in ON (Fig. S2d), when air masses arriving from the northeast carry pollution (biomass burning and industrial emissions) drifts over the Lower Gangetic Plains. This region itself acts as an elevated pollution clouds (Jain *et al*., 2024).

3.3. *Monthly characteristics*

The monthly visibility statistics depicts that the study area experienced lowest visibility in November (Fig. 3). The mean visibility in November is observed to be around 3750 m. The highest mean visibility is observed to be 6100 m in April. The mean lowest visibilities for the months are highlighted in Table 2, which shows the mean lowest visibility in January (270 m). The monthly visibility trends are estimated from the nine years (2016-2024) daily mean visibility (Fig. 4). Significant ($p<0.05$) increasing trends are observed for the months of January, February, March, May, and December whereas, decreasing trends are obtained for the months of April, June, July, August, September, October, and November. These variations can be attributed to a combination of

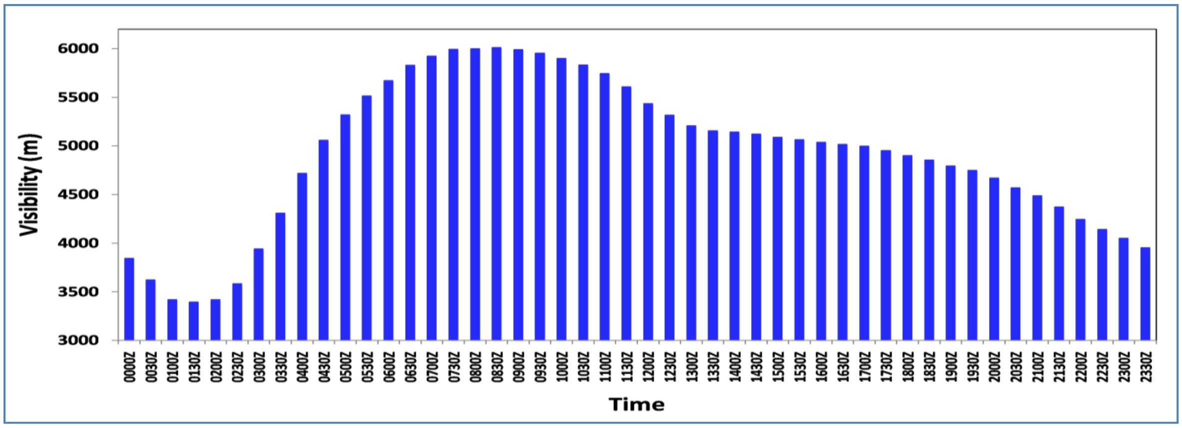


Fig. 2. Diurnal variation of visibility at the Chennai international airport based on half-hourly METAR observations.

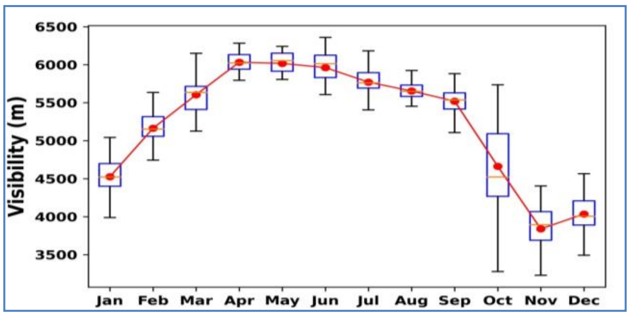


Fig. 3. Box-plot depicts monthly statistics of visibility. Red dots indicates mean where orange line denotes median

TABLE 2

Depicts mean lowest monthly visibility for the Chennai Airport during 2016-2024.

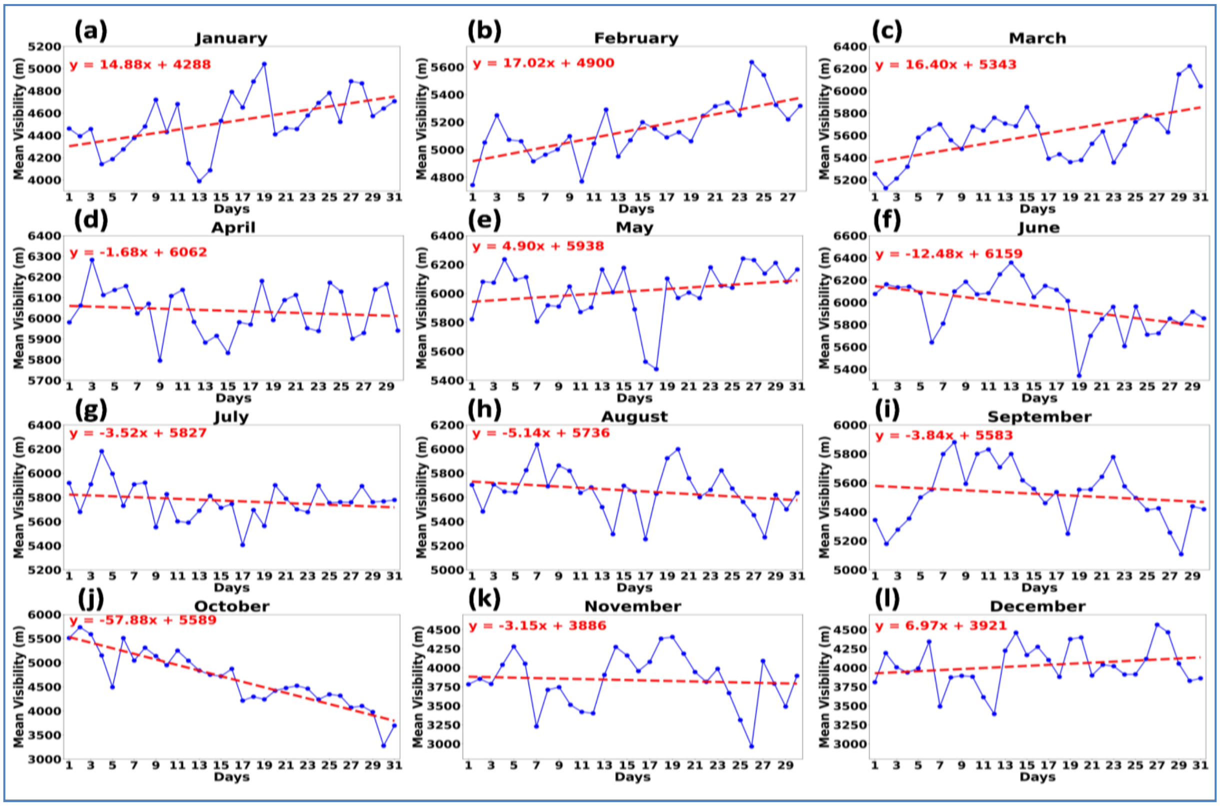
Months	Visibility (m)
January	270
February	730
March	1000
April	2250
May	2075
June	1275
July	1275
August	1067
September	1061
October	990
November	766
December	470

meteorological and pollution-related factors influencing Chennai's climate. The observed increasing visibility trends in DJF, March, and May (except April) suggest that while pollution sources exist, meteorological conditions (*e.g.*, insolation, sea-breeze, and temperature inversion) in these months favor dispersion rather than accumulation of pollutants. Conversely, the decreasing trends observed for June to November aligns with the onset and progression of the monsoon seasons (southwest monsoon (June–September) and northeast monsoon (October–November)). Stronger winds, increased humidity, and frequent rainfall events during these months help in dispersing pollutants and improving air quality. However, localized emissions and urban air pollution sources may still contribute to episodic pollution events, particularly in periods of weak rainfall or stagnant atmospheric conditions. April, being a transitional month between summer and pre-monsoon period, often experiences dry and stagnant conditions with less convective activity compared to May. The combination of high temperature, less amount of rainfall and localized emissions may lead to a buildup of pollutants, resulting in reduced visibility.

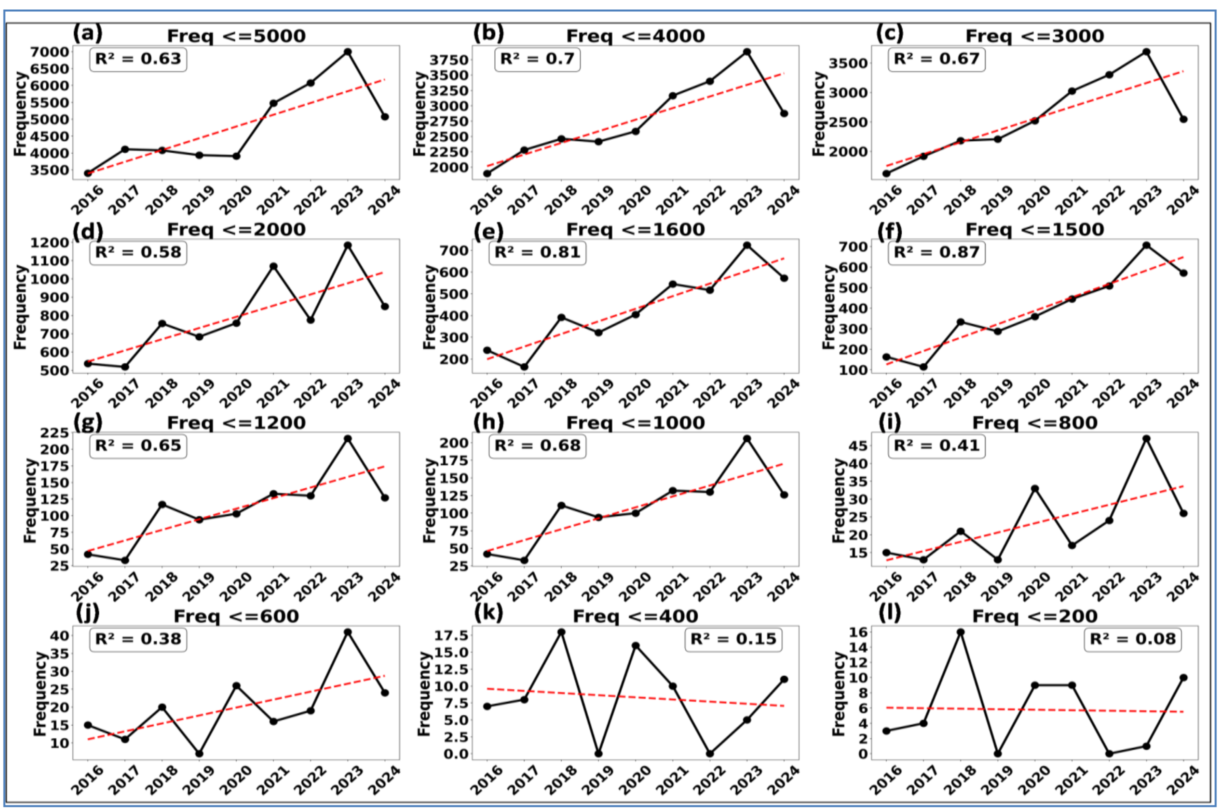
3.4. *Frequency and significant months with visibility*

The frequency of visibility between 5000 m and 600 m shows an increasing trend, (Fig. 5a-j) whereas the frequency of visibility less than 400 m shows a declining trend (Fig. 5k-l). This suggests a rise in moderate visibility reduction events, likely due to urban pollution, haze, and mist. However, the declining trend in occurrences of visibility below 400 m indicates fewer extreme low-visibility events. This reduction may be attributed to improved air quality management, changes in weather patterns or a decrease in intense fog occurrences over the period of 2016-2024.

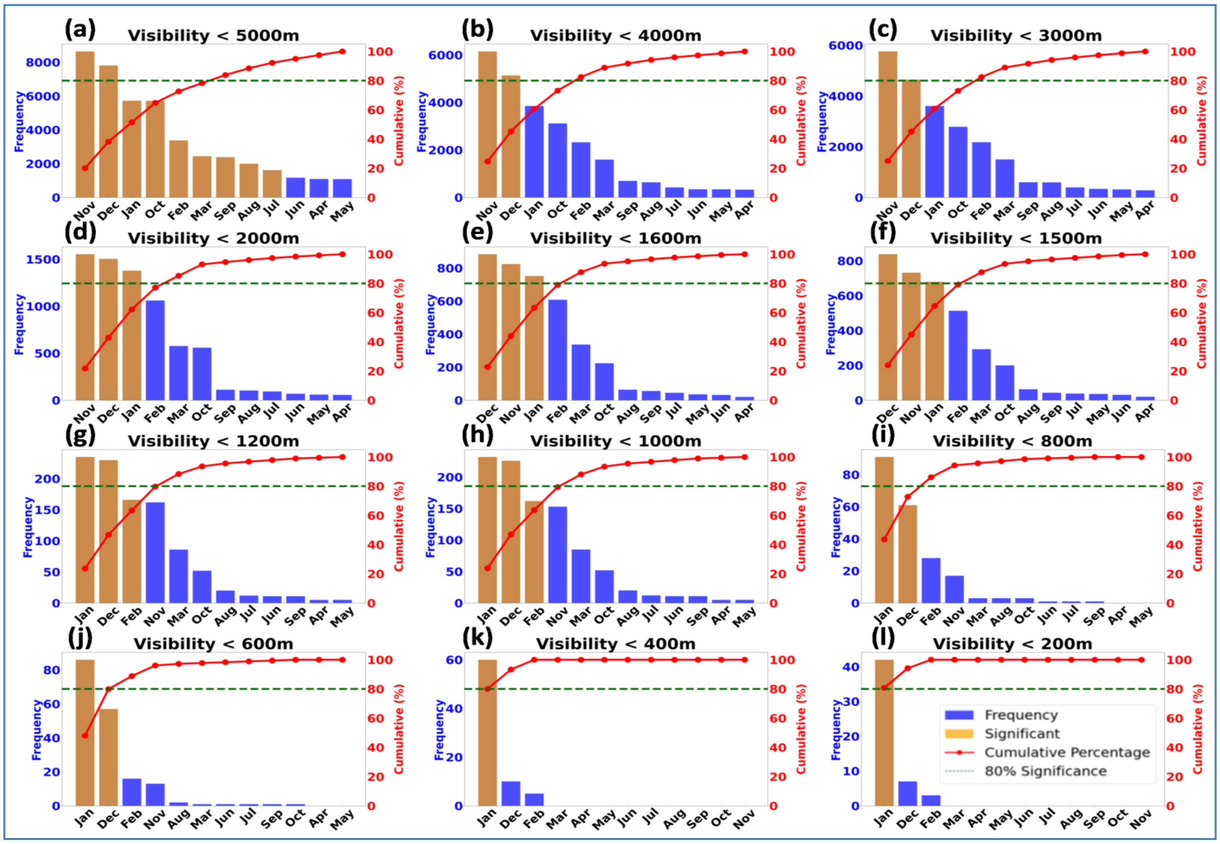
The study further identifies the specific months that significantly contribute to the distinct visibility characteristics. Fig. 6(a-l) depicts the significant months responsible for the visibility category less than 5000 m, 4000 m, 3000 m, 2000 m, 1600 m, 1500 m, 1200 m, 1000 m, 800 m, 600 m, 400 m, and 200 m based on pareto chart analysis, respectively. Visibility category of less than 5000 m (Fig. 6a) is observed significant for all the months except April-June. Whereas, visibility categories of less than 4000 m (Fig. 6b), and 3000 m (Fig. 6c) are found to



Figs. 4(a-l). represents monthly variation of visibility based on daily mean visibility from 2016-2024. Red line is the trend



Figs. 5(a-l). shows annual trend of different categorical visibility from 2016-2024



Figs. 6(a-l). highlights significant months with different categorical visibility. Significant months are represented by yellow bar. Red line demarked for cumulative percentage. Green line denotes the 80% significance cut-off

TABLE 3

Frequency of characteristic visibility over the Chennai airport during 2016-2024

Months	1500 < V <1200	1200 < V <1000	1000 < V <800	800< V <600	600 < V <400	400 < V <200	200 < V <100	100 < V <50	V<50
Jan	445	3	141	5	26	18	9	8	25
Feb	347	4	134	12	11	2	2	1	0
Mar	207	1	82	2	1	0	0	0	0
Apr	15	0	5	0	0	0	0	0	0
May	31	0	5	0	0	0	0	0	0
Jun	20	0	10	0	1	0	0	0	0
Jul	26	0	11	0	1	0	0	0	0
Aug	43	0	17	1	2	0	0	0	0
Sep	32	0	10	0	1	0	0	0	0
Oct	148	0	49	2	1	0	0	0	0
Nov	570	9	136	4	13	0	0	0	0
Dec	608	4	165	4	47	3	1	6	0

be significant for the months of November, and December. November, December, and January are the significant months for the visibility of less than 2000 m (Fig. 6d), and 1600 m (Fig. 6e). The visibility less than 1500 m has the operational significance, as during that time RVR need to be given in METARs for the flight operational safety measurements during the take-off and landing. December, November, and January are identified as significant months contributing to decreasing order of visibility below 1500 m (Fig. 6f). For visibility below

TABLE 4

Percentage duration of monthly characteristic visibility for the Chennai airport during 2016-2024

Months	V <1500	V <1200	V <1000	V <800	V <600	V <400	V <200
Jan	5.07	1.75	**1.73**	**0.68**	**0.64**	**0.45**	**0.31**
Feb	4.24	1.37	**1.34**	**0.23**	**0.13**	**0.041**	**0.02**
Mar	2.18	0.64	**0.63**	**0.02**	**0.007**	0	0
Apr	0.15	0.038	**0.04**	0	0	0	0
May	0.27	0.037	**0.04**	0	0	0	0
Jun	0.24	0.084	**0.08**	**0.007**	**0.007**	0	0
Jul	0.28	0.089	**0.09**	**0.007**	**0.007**	0	0
Aug	0.47	0.15	**0.15**	**0.02**	**0.015**	0	0
Sep	0.33	0.08	**0.08**	**0.007**	**0.007**	0	0
Oct	1.49	0.39	**0.39**	**0.02**	**0.007**	0	0
Nov	5.65	1.25	**1.18**	**0.13**	**0.10**	0	0
Dec	6.25	1.71	**1.69**	**0.45**	**0.42**	**0.07**	**0.05**

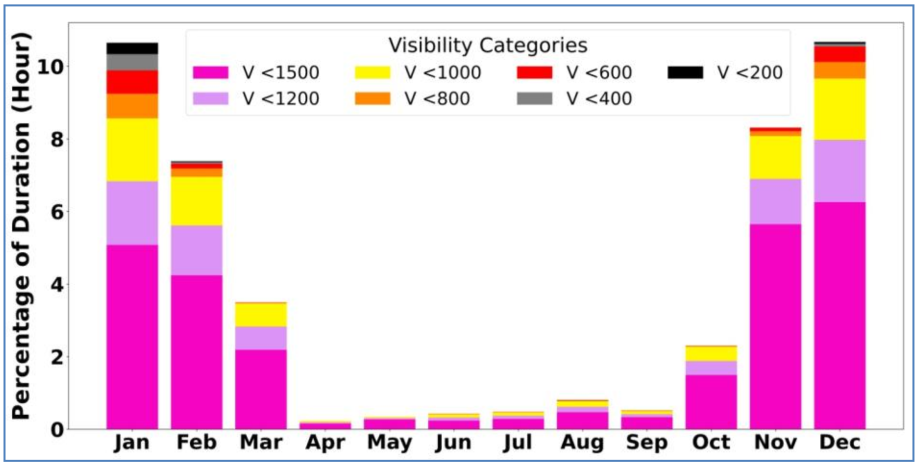


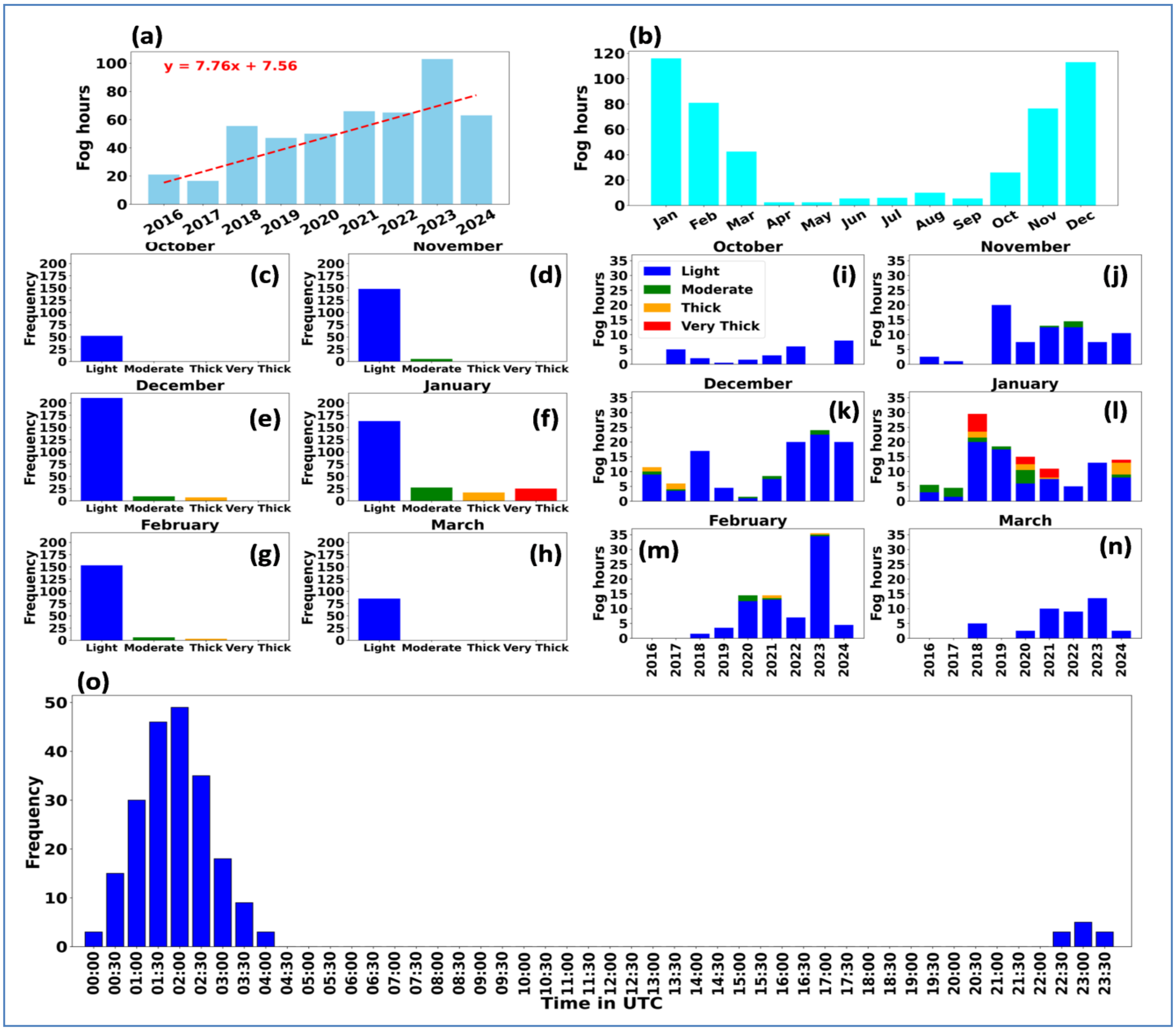
Fig. 7. Percentage duration of different categorical visibility

1200 m (Fig. 6g) and 1000 m (Fig. 6h), January, December, and February are marked as the most significant months. During January and December, frequency of visibility below 800 m, and 600 m are found significant. The frequency of visibility below 400 m and 200 m are significant only in January

3.5. *Duration*

Fig. 7 illustrates the monthly percentage distribution of different visibility categories over Chennai, highlighting seasonal variations influenced by atmospheric conditions. The percentage of hours with limited visibility (less than 1500 m) exhibits a pronounced seasonal cycle, reaching a minimum of 0.15% in April, and maximum at 6.25% in December. This pattern reflects the influence of summer and monsoon season minima, attributed to stronger winds and convective mixing. In contrast, post-monsoon and winter seasons exhibit maxima, likely due to enhanced moisture, temperature inversions, and aerosol accumulation in the air-column.

The frequency of low visibility events less than 1000 m follows a similar trend, with the lowest occurrence in April (0.04%). Meanwhile, January (1.73%) experiences the highest frequency, as winter conditions promote haze, mist, and fog due to nocturnal radiative cooling and moisture retention. Notably, visibility below 200 m is least frequent in February (0.02%), and most pronounced in January (0.31%). This pattern is likely driven by stable atmospheric conditions, increased condensation nuclei, and prolonged periods of calm winds, which is favorable for fog occurrence during winter due to nocturnal cooling and humidity buildup.



Figs. 8(a-o). Show based on METAR visibility, intensity, duration, and frequency analysis of the fog events 2016-2024. (a) represents fog hours from 2016 to 2024, red line indicates trend, (b) monthly fog hours, (c-h) highlights the frequency of main four types of fog categories during the ONDJFM, (i-j) is same as (c-h) but portray categorical fog hours during 2016-2024 and (o) represents the diurnal frequency of fog events during the period

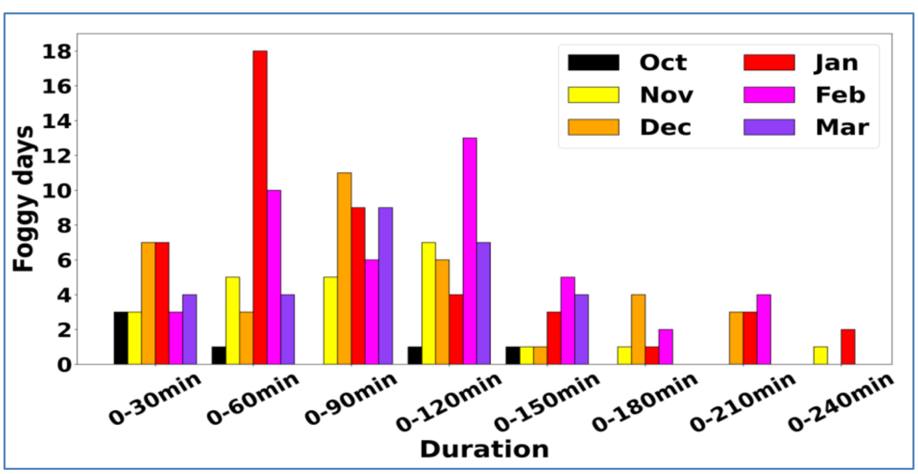


Fig. 9. Represent the duration of the foggy days

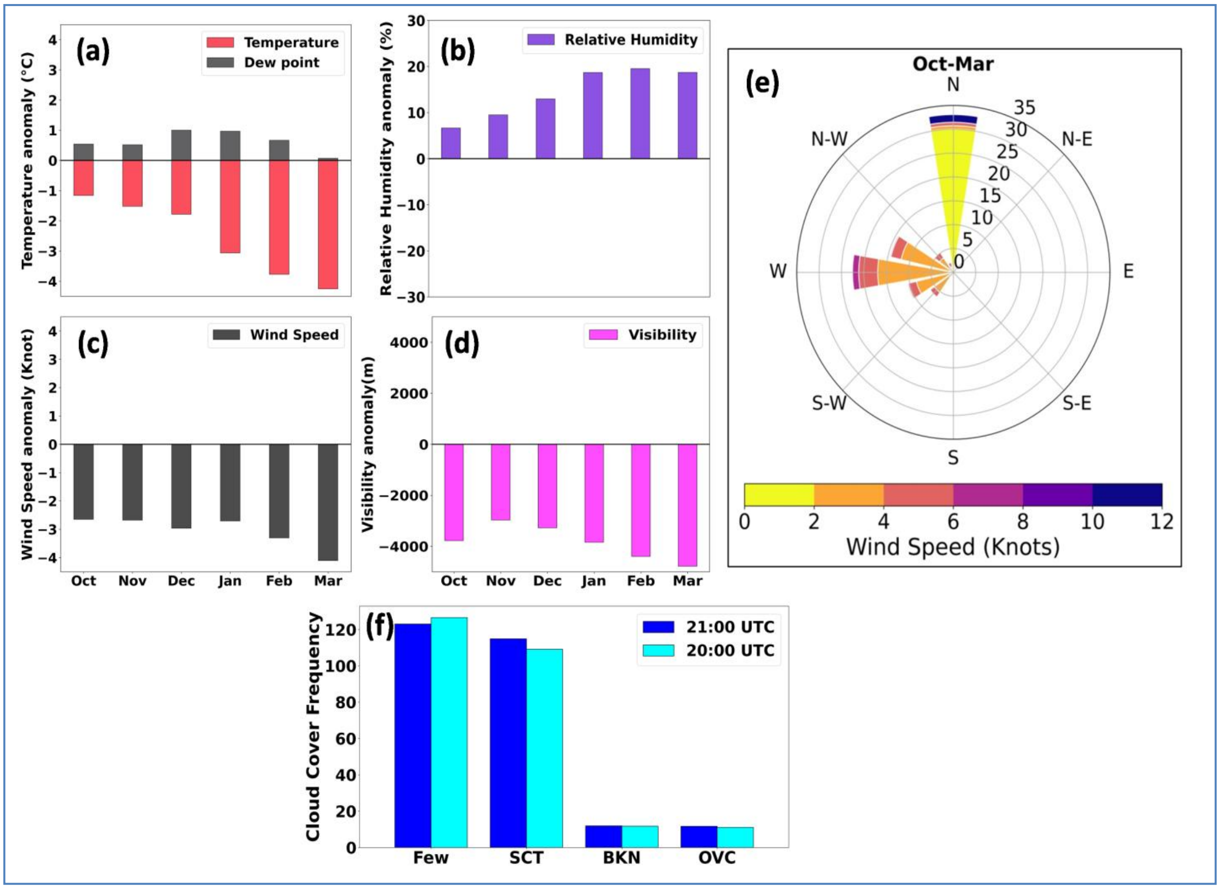
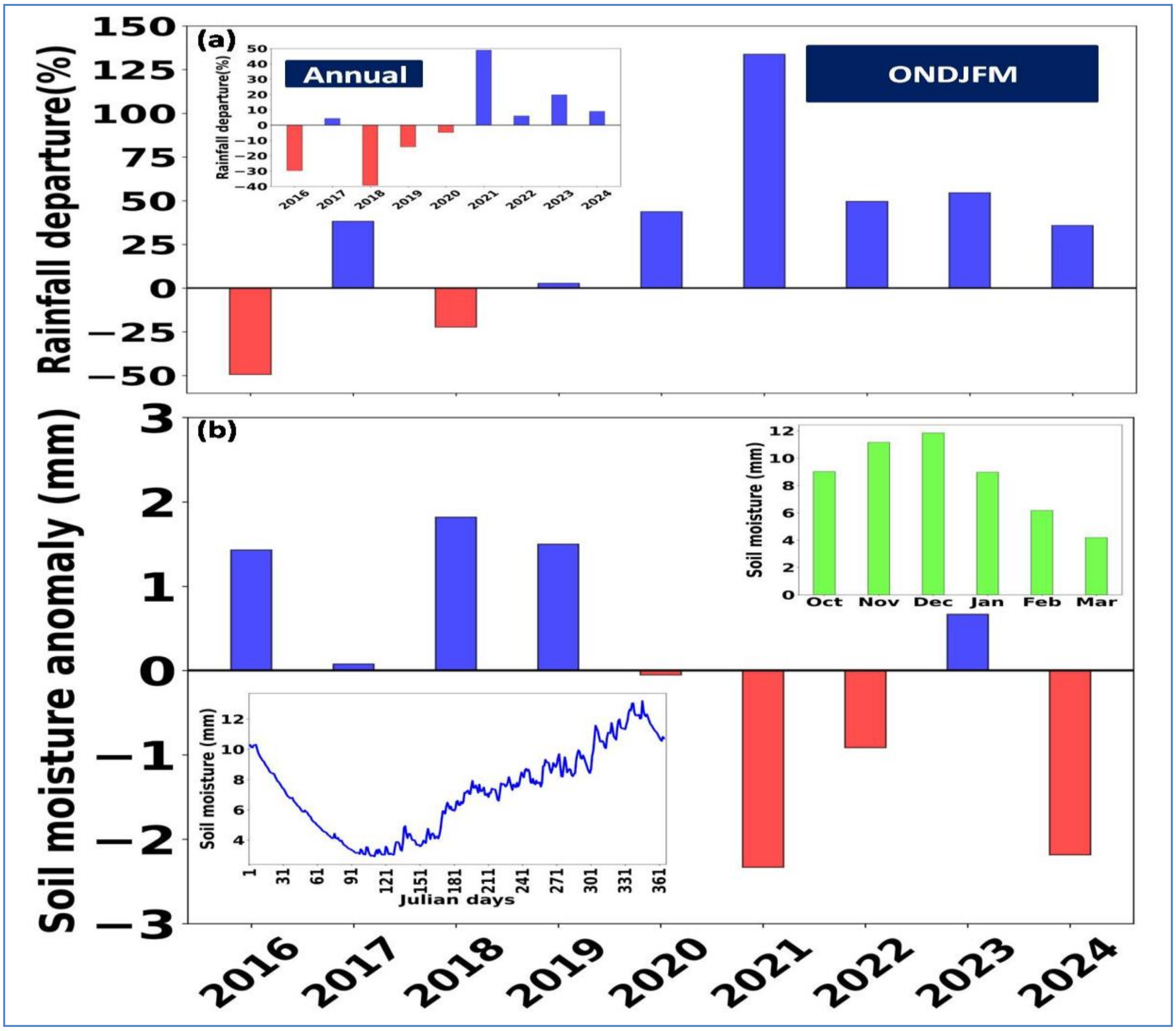


Fig. 10. Foggy days weather anomaly during ONDJFM. (a) represents temperature (red) and dew point (black) anomaly, (b) shows relative humidity anomaly (purple), (c) wind speed anomaly (black), (d) shows visibility anomaly (pink), (e) represents wind-rose diagram and (f) denotes frequency of different cloud cover types before 1-hr and 2-hr of fog onset

3.6. *Fog events characteristics*

Fig. 8 highlights the frequency, intensity, and duration of fog hours, as estimated based on observations from Chennai international airport. Based on visibility observations from 2016 to 2024, fog hours show an increasing trend (Fig. 8a). The maximum fog hours are observed in January (Fig. 8b). From the fog categorical analysis, it is unveiled that light category fog is prevalent in all the months of ONDJFM while maximum frequency of thick and very thick category fog are observed in January (Fig. 8c-h). The moderate category fog is observed in November-February with maximum frequency in January. While only thick category fog is found in December-February. The light category fog events are found increasing for all the months (ONDJFM) whereas, very thick category fog is seen with a declining trend in January (Fig. 8i-n). This study also investigates diurnal characteristics of fog events over Chennai airport, which is urgently required for the smooth operational services in the aviation sector. The diurnal characteristics show fog onset time and time at which its maximum frequency is observed (Fig.8o). Fog onset occurred at around 03:30 IST, based on METAR observations between 22:00 to 22:30 UTC and reported in 30 min after the observations. Over 80% of fog events occurred between 2200-0200 UTC and peaked at 0100-0129 UTC over Bengaluru (Shukla *et al.*, 2021). The maximum fog frequency over the Chennai International Airport is observed around 07:00 IST (01:30 UTC) and reported in METAR at 02:00 UTC.

Fig. 9 portrays the duration of the foggy days during ONDJFM. The maximum foggy days are observed in January with duration of 1-hr. The second highest foggy days are observed during February with duration of 2-hr. The third highest frequency is found in December with duration of 1.5-hr. Most fog episodes over the Hyderabad International Airport persisted for nearly an hour (Chandu *et al.*, 2022). The longest duration of fog events over the Chennai International airport is observed in January and November with 4-hr durations.

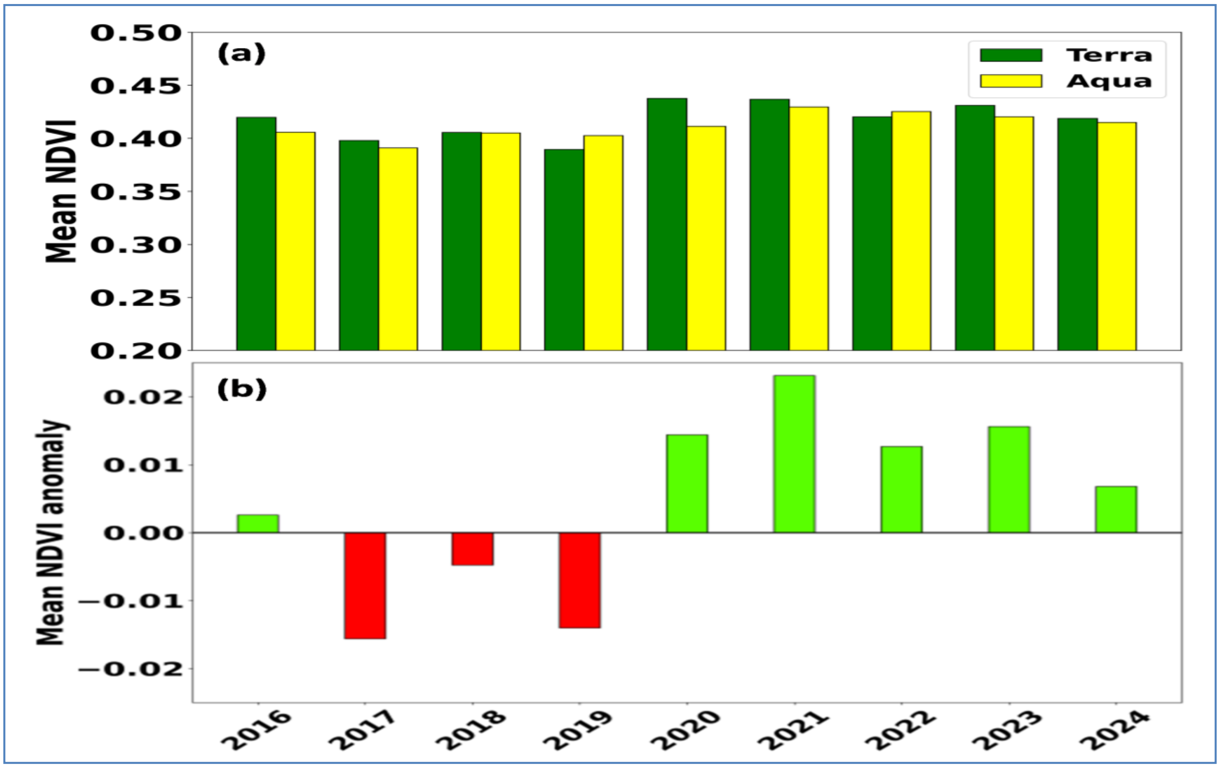


Figs. 11(a&b). (a) Rainfall and (b) soil moisture anomaly for 2016-2024 during ONDJFM. Blue line shows daily mean variation of soil moisture for the CMA where green bars represents mean soil moisture during the period for ONDJFM

3.7. *Influence of thermal, moisture, and land surface conditions on fog development*

The lowest mean temperature is observed during January, when dew point anomaly is about 1°C (Fig. 10a). Increased RH anomaly (Fig. 10b) along with lowest wind speed anomaly (Fig.10c) further facilitates the fog formations. Visibility anomaly is found lowest in November (Fig. 10d), when Chennai experiences maximum rainfall and thunderstorm activities. Winds during the fog months (ONDJFM) show a major contribution from northerly (33%) and westerly (22.5%) directions (Fig. 10e). The cloud-cover observations, 1 to 2 hours prior to fog onset, indicate that maximum contributions come from FEW (1-2 Octa) and SCT (3-4 Octa) cloud cover (Fig. 10f). When cloud cover is mostly BKN and/or OVC, significant reduction in visibility sometimes goes below 100 m, making the situation worse for the flight-operational service at Chennai airport. In addition to cloud-cover, surface soil moisture plays a crucial role in fog formation during the night-time in ONDJFM by enhancing radiative cooling, when temperature inversion occurs in the lower part of the boundary layer.

Despite the increase in rainfall amount in recent years (Fig. 11a), which contributes to sufficient surface soil moisture availability, higher temperatures may have intensified evapotranspiration from increased vegetation cover in recent years (Fig. 12). This could potentially



Figs. 12(a&b). (a) Mean vegetation cover variation by MODIS (Terra and Aqua) NDVI. (b) NDVI anomaly for the period 2016-2024

offset moisture gains and lead to a negative soil moisture anomaly (Fig. 11b). During the first quarter of ONDJFM (OND), fog frequency shows a significant ($p<0.05$) negative correlation with NDVI (-0.38) and a strong positive correlation with soil moisture (0.95) (Fig. S3). These relationships indicate that reduced vegetation cover and higher surface soil moisture favor fog formation through enhanced near-surface cooling. In contrast, last quarter (JFM) shows a different pattern. Fog frequency is significantly ($p<0.05$) positively correlated with both NDVI (0.46) and soil moisture (0.50). It suggests that increased vegetation greenness and sustained soil moisture contribute to stable and humid conditions, and promote fog persistence. Additionally, urbanization, deforestation, and shifts in land management practices may have further reduced the soil's capacity to retain moisture. However, even under declining soil moisture trends, the remaining moisture can still support fog formation and contributes to surface cooling through evaporative effects and nighttime radiative cooling.

4. Conclusions

The interplay of aerosol accumulation, synoptic-scale weather patterns, and seasonal soil moisture variations contributes significantly to visibility impairment, posing increasing challenges for aviation operations and urban transportation.

(*i*) The analysis reveals a consistent decline in visibility at Chennai International Airport from 2016 to 2024, with annual mean values exhibiting a statistically significant downward trend.

(*ii*) Daily mean visibility shows a marked decrease ($p < 0.05$) during April and from June to November, indicating increasing operational challenges in both the summer and post-monsoon months.

(*iii*) Diurnal characteristics indicate that the lowest visibility typically occurs around 06:30 IST, a critical time for flight departures and arrivals, while greater variability is observed during the pre-monsoon (MAM) and post-monsoon (ON) seasons.

(*iv*) On a monthly scale, November records the lowest mean visibility, underscoring its importance for flight scheduling and risk management.

(*v*) Frequency analysis shows that moderate to low-visibility events (5000–600 m) are becoming more frequent, whereas the most extreme category (≤400 m) exhibits a decreasing long-term tendency. However, January continues to show a significantly higher occurrence of extreme events, including those below 400 m and even 200 m.

(*vi*) The seasonal distribution of events below 1000 m reveals minima during the summer & monsoon months & maxima during the post-monsoon and winter seasons, with the lowest frequency in April (0.04%) & the highest in January (1.73%).

(*vii*) Fog occurrence follows a distinct seasonal cycle, typically forming around 03:30 IST and peaking near 07:00 IST coinciding with early-morning aviation operations. The maximum fog duration of up to four hours is most frequently observed in January and November.

(*viii*) Light-category fog events have increased during the October–March (ONDJFM) period, while very thick fog remains largely confined to January. On average, fog occurs 5.2 days in January, 4.8 days in February, 3.9 days in December, and 3.1 days in March, while transitional months (October–November) contribute an additional 3.2 foggy days annually.

These findings have important implications for aviation safety and forecasting systems. The rising frequency of fog necessitates strengthened Runway Visual Range (RVR) monitoring, enhanced instrument landing capabilities, and proactive crew preparedness to ensure passenger safety and minimize economic losses. Identification of fog onset and peak times provides a critical lead window for nowcasting, while trajectory-based aerosol transport analyses can further improve predictive skill. Integrating these climatological insights into operational planning, urban air-quality management, and aviation forecasting frameworks will be essential to mitigate risks, reduce delays, and enhance flight safety under worsening visibility conditions.

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Authors'contributions

Arkadeb Banerjee: Writing – original manuscript, conceptualization, methodology, data processing, computation in python, and formal analysis. (*email:arka354deb@gmail.com*).
V. R. Durai: conceptualization, overall supervision, and review. (*email:durai.imd@gmail.com*).

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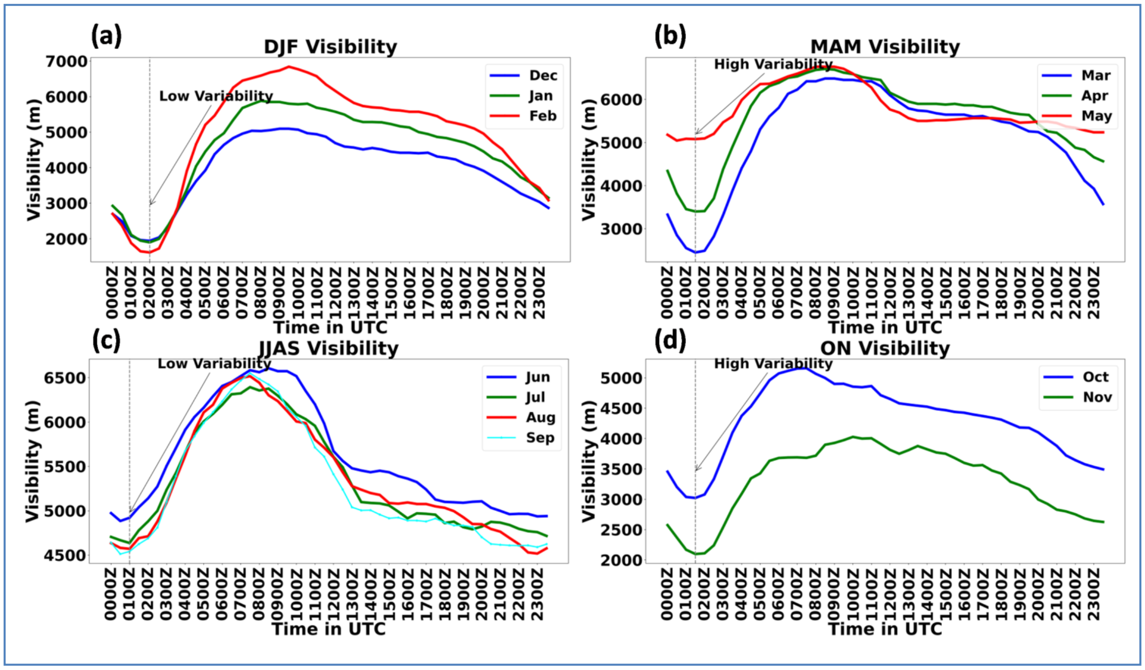
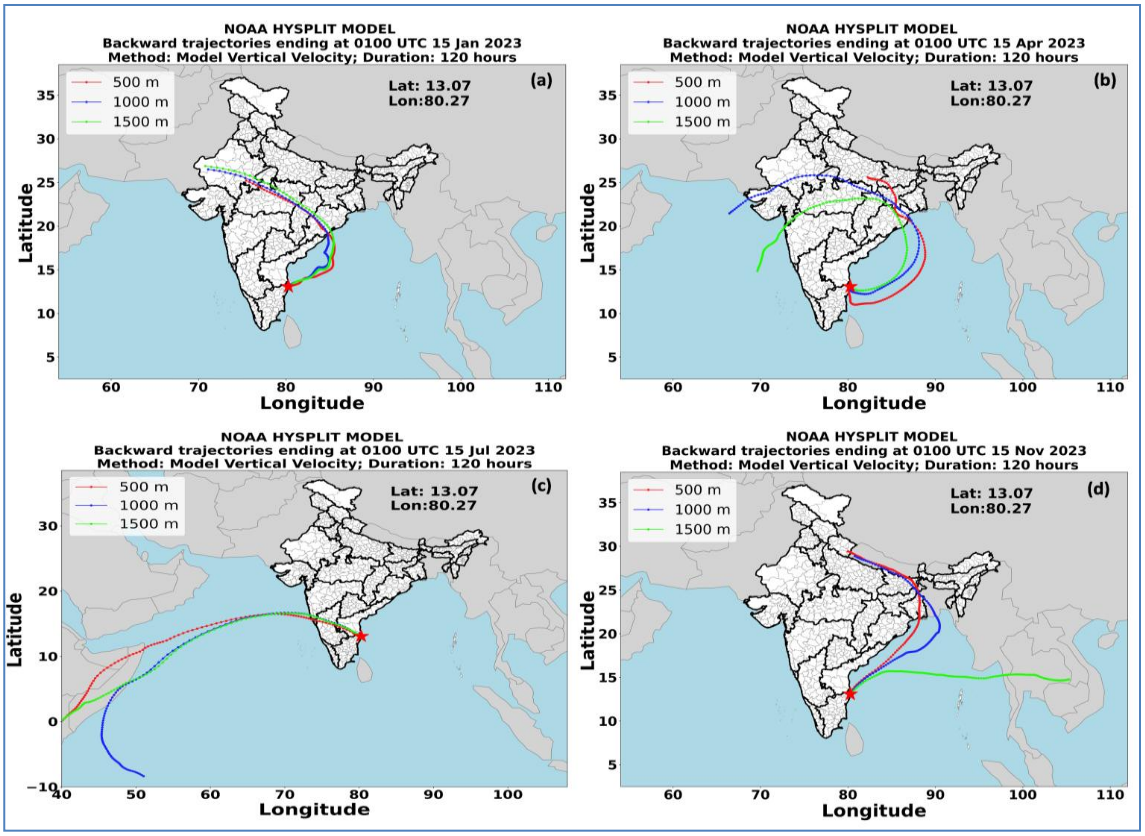
Suplementry Figs.



Figs. S1(a-d). Diurnal variation of visibility for the Chennai international Airport. (a) Dec-Feb, (b) Mar-May, (c) Jun-Sep and (d) Oct-Nov. Black line indicates the time of lowest visibility



Figs. S2(a-d). Hysplit model backward trajectory run for 120 hours for heights of 500 m, 1000 m, and 1500 m above ground level (AGL) for 15th day of January (a), April (b), July (c), and November (d), by taking seasonal central month of DJF, MAM, JJAS, and ON to investigate the parcel trajectory

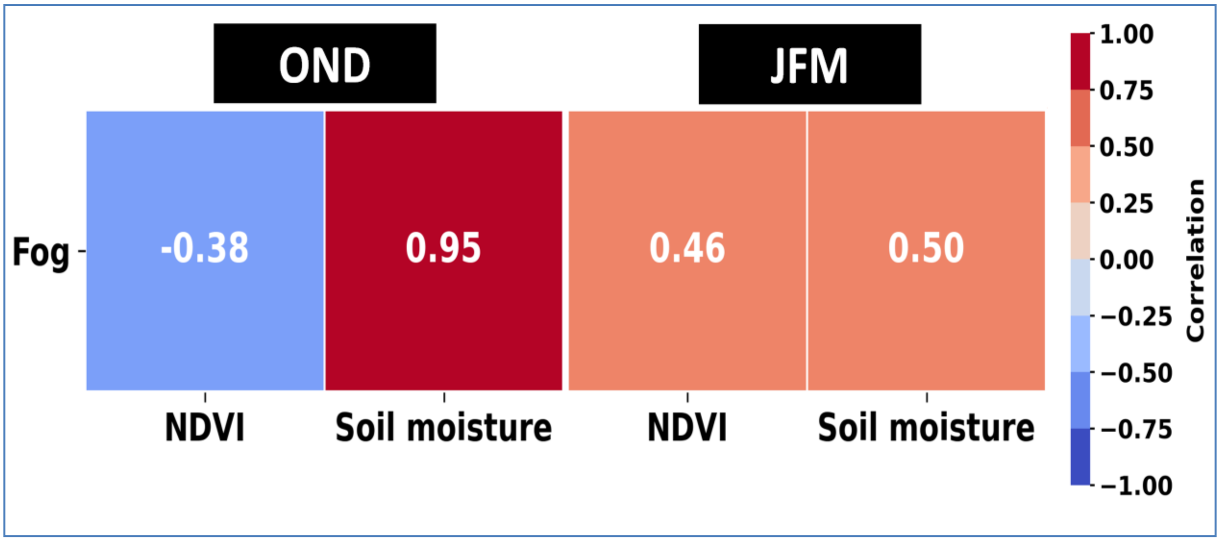


Fig. S3. Correlation of fog frequency with NDVI and soil moisture for Oct-Dec (OND) and January-March (JFM)