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Fog nowcasting over the IGI airport, New Delhi, India using decision tree

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सार – मॉडलिंग फ्रेमवर्क में, कोहरे के आगमन और इसके क्षीण होने के समय का तात्कालिक अनुमान देना चुनौतीपूर्ण कार्य है, आमतौर पर बहुत घने कोहरे (50m<Vis<0m) के मामलों में एक प्रभाव सीमा समस्या बन जाती है। इसके अलावा, खराब/कोहरे का गलत पूर्वानुमान एयरलाइन क्षेत्र के लिए खतरनाक स्थिति पैदा कर सकते हैं, जहां अल्प अवधि पूर्वानुमानों की सटीकता आवश्यक है। इस अध्ययन में, हमने इंदिरा गांधी अंतरराष्ट्रीय (आईजीआई) हवाई अड्डा, नई दिल्ली, भारत में घने कोहरे की परिघटनाओं को तात्कालिक पूर्वानुमान करने के लिए वास्तविक समय पर प्रेक्षित डेटा के आधार पर एक डिसीजन ट्री विकसित किया है। विंटर फॉग एक्सपेरिमेंट (वाइफेक्स) कैम्पेन के लिए तीन साल के लिए एक कालिक विभेदन प्रेक्षणीय डेटासेट उपलब्ध था। छह घने कोहरे की परिघटनाओं के लिए इस डिसीजन ट्री के प्रदर्शन को प्रेक्षित किए गए दृश्यता डेटा के साथ सत्यापित किया गया है। परिणामों से पता चलता है कि इस डिसीजन ट्री में लगभग 66% की सफलता दर के साथ बहुत घने कोहरे का पूर्वानुमान देने के लिए काफी कौशल है। तात्कालिक अनुमान के डिसीजन ट्री और दृश्यता के बीच यह संतोषजनक सहमति निर्णय ट्री के वर्तमान संस्करण में कुछ सूक्ष्म बदलाव के बाद भविष्य में अधिक घने / बहुत घने कोहरे की परिघटनाओं का पूर्वानुमान देने का विश्वास पैदा करता है।

ABSTRACT. In the modelling framework, nowcasting fog onset and its dissipation time is a challenging work, typically becoming a threshold problem in very dense fog (50m <Vis < 0m) events. In addition, poor/inaccurate fog forecasts may create hazardous/panic situations for the airline sector, where the accuracy of short-range forecasts is essential. In the current study, we have developed a decision tree based on real-time observational data to nowcast the dense fog events at Indira Gandhi International (IGI) Airport, New Delhi, India. For three years, a temporal resolution observational dataset was available for the Winter Fog Experiment (WiFEX) campaign. The performance of this decision tree for six dense fog events is verified with observed visibility data. The results reveal that this decision tree has considerable nowcasting skills for very dense fog prediction with a success rate of around 66%. This satisfactory agreement between the nowcasting decision tree and visibility builds the confidence to predict more dense/very dense fog events in the future after some fine-tuning in the present version of the decision tree.

Key words – Nowcasting, Horizontal visibility, Surface meteorology, Decision tree, WiFEX.

1. Introduction

Fog is a boundary layer weather phenomenon that negatively impacts atmospheric horizontal visibility (AHV) and poses a significant threat to transportation sectors globally (Bergot *et al.*, 2005; Brown & Roach, 1976; Croft P.J., 2003; Dupont *et al.*, 2018; Ghude *et al.*,

2017; Gulpepe *et al.*, 2006; Pruppacher & Klett, 1980; Sathiyamoorthy *et al.*, 2016; Singh & Kant, 2006; Wærsted *et al.*, 2017). The broad spatiotemporal variability of fog makes it more challenging to predict its formation, sustainment and dissipation. The widespread fog occurs most frequently over the Indo-Gangetic Plain (IGP) region from December to January. The dense fog

events deteriorate AHV below 200 m and could be sustained for several hours in the conducive metrological condition (Ghude *et al.*, 2017; Safai *et al.*, 2019). Maximum fog occurrence over northwest India is about 48 days (visibility < 1000 m) per year, and it occurs mainly during the December-January-February months. Providing accurate fog forecasts within a short time frame (nowcast; less than 24 hours) is crucial.

In the last three decades, the climatological based studies revealed that the increasing trend of fog and its intensity is problematic in the densely populated regions of IGP (Ghude *et al.*, 2017; Jenamani & Tyagi, 2011; Kutty *et al.*, 2020; Sanjay Kumar Srivastava *et al.*, 2016). It is estimated that IGI Airport, New Delhi, loses around 120 million per year due to flight cancellations, diversions, and delays caused by dense fog events (Kulkarni *et al.*, 2019). Therefore, nowcasting has become a priority in recent years, especially during the winter months in northern India. Several attempts at short-range fog forecast were made in numerical weather prediction (NWP) models. It was found that fog reproduces reasonably well in the concise range forecast of the model, but it cannot predict fog onset and dissipation time accurately (Mitra *et al.*, 2008; Goswami & Sarkar, 2017; Pithani *et al.*, 2019, 2020; Saraf *et al.*, 2011; Yadav *et al.*, 2022). Pithani *et al.* (2020) revealed that the surface temperature and relative humidity had 1°C and 5% differences near the surface, indicating a marginal fog prediction strategy with the NWP model. In addition, there were many possible reasons enlisted in earlier studies about fog forecast failure where they suggested the inaccurate representation of the physical and land-surface processes in the model, error in initial conditions, model resolution, etc. (Teixeira & Miranda, 2001; Gulpepe *et al.*, 2006; Payra & Mohan, 2014; C. Román-Cascón *et al.*, 2016; Pithani *et al.*, 2019, 2020; Carlos Román-Cascón *et al.*, 2019; Parde *et al.*, 2022b).

In recent years, Soft Computing has become known for its ability to resolve complex and non-linear problems in weather forecasting. The Fuzzy Inference System is an approach where its algorithm is valid for evaluating several meteorological issues, *viz.*, operational meteorology forecast, ocean, atmospheric dynamics and fog prediction, respectively (Bardossy *et al.*, 1995; Murtha & Edmonton, 1995; Hansen, 1997; Mitra *et al.*, 2008). However, limited studies were attempted with observation data to develop objective methods to predict the fog and nowcast the spatial visibility over the airport (Dutta & Chaudhuri, 2015; Roy Bhowmik *et al.*, 2004). In essence, to develop and improve the skills of such statistical tools, it is necessary to reach the depth of the relevant fog formation mechanisms through detailed investigations of

observations and derived meteorological variables. Formation, dissipation, and persistence of fog are affected by several meteorological variables, like cloud conditions, surface temperature and humidity, wind vector, aerosols, vegetation, topography, and tropical cyclone intensity, which vary under distinct circumstances (Pasricha *et al.*, 2003; Badarinath *et al.*, 2009; Syed *et al.*, 2012; Tiwari *et al.*, 2011; Sawaisarje *et al.*, 2014; Dimri *et al.*, 2015; Menut *et al.*, 2014; Dhangar *et al.*, 2021; Ahmed *et al.*, 2021; Parde *et al.*, 2020, 2022a, 2022b; Sengupta *et al.*, 2022; Nivdange *et al.*, 2022). Due to the sensitivity of fog to small changes in the micro-meteorological variables in the lowest layers of the atmospheric boundary layer, a high-quality measurement was essential. The present study aims to reveal the results of comprehensive research based on an indigenously developed statistical tool that successfully predicts dense fog events considering both the earlier research gap and the demand of the nowcasting process in various sectors. A temporal resolution micrometeorological (Temperature, Relative Humidity, Wind speed, Soil temperature, Soil Moisture) data from 3 years of the Winter Fog Experiment (WiFEX) campaign is utilized. In Section 2, synoptic features of New Delhi, observational site, data, methodology, and the flow-chart are presented. The results are elaborated in section 3. The succeeding conclusions section is given in the context of subsequent achievements and future works.

2. Synoptic features of New Delhi during the winter season

New Delhi (28.61°N, 77.23°E) is India's capital, located in the IGP region. The extreme weather conditions were noticed over New Delhi, scorching summer (March, April, May, and June) and cold winter seasons (November, December, January, and mid-February). During summer, the average temperature in New Delhi varies between 32-45°C, where its peak is generally noticed in the May-June months. North-westerly winds typically from western deserts make the air dry and hot over the region. The occurrence of heatwaves, dust storms, thunderstorms, lightning, low humidity, and high-temperature activity is frequently noticed during the summer period. In contrast, the winter season begins in November-December and becomes severe in January, during the period fog, haze and mist form over the entire New Delhi region. In addition, extratropical systems like Western disturbance (WD) during the winter season bring moisture and even light rain over the area. During the northeast monsoon, the incursion of moisture over the region by the prevailing boundary layer easterlies from the Bay of Bengal manifests in cold weather over the area (Roy Bhowmik *et al.*, 2004). Overall, the dominating synoptic features over New Delhi exhibit consistent high pressure in the upper atmosphere

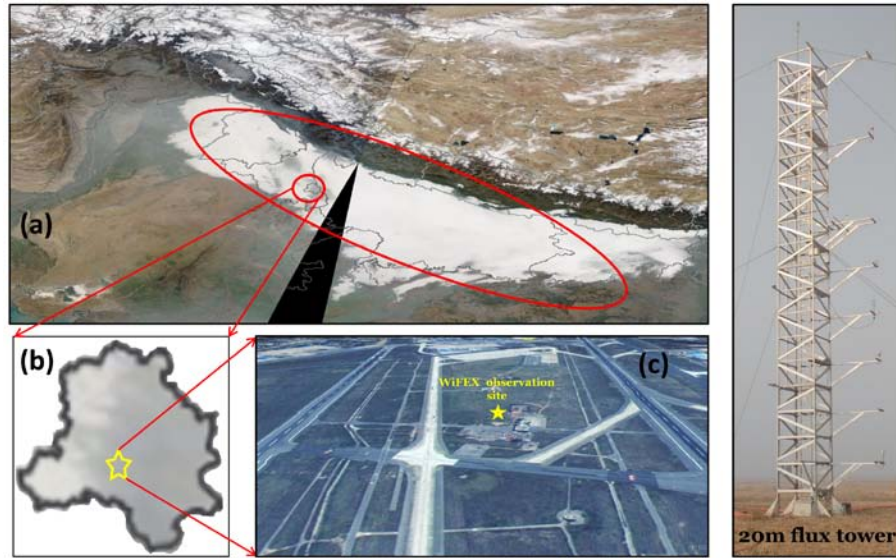


Fig. 1. A blanket of fog over the Indo-Gangetic Plains seen from MODIS Terra images (middle column at 1030 IST (0500 UTC) on 04 Jan 2018), (b) Geographical map of New Delhi with the location of IGI airport, (c) the location of WiFEX site inside the airport

TABLE 1

The following is a tabulation of the average number of fog hours and fog days for the period of 1991–2020 (30 years) at IGI Airport, Delhi, in December and January months

Month	Fog episode intensity							
	Fog Hours				Fog Days			
	Vis < 1000 m	Vis < 500 m	Vis < 200 m	Vis < 50 m	Vis < 1000	Vis < 500	Vis < 200	Vis < 50
Dec	278	102	41	25	26	15	7	5
Jan	290	127	66	38	26	18	11	8
Total	568	229	107	63	52	33	18	13

and calm weather conditions on the ground during the winter season (Dhangar *et al.*, 2021; Ghude *et al.*, 2017). Table 1 shows the observations from 1991-2020 (30-years) at IGI Airport, Delhi, for December and January; it summarizes the average fog hours and the number of fog days for different intensities. The long-term mean indicates that around 52 days have Visibility < 1000 m (fog), and 18 days have Visibility < 200 m (dense fog) at least for two hours in Delhi during each winter season.

3. Observational site, data and methodology

To understand the fog genesis and favorable conditions for its development over the IGP region, the Ministry of Earth Sciences, India, initiated the multi-institutional WiFEX campaign in 2015. From December

2015 to January 2016, December 2016 to January 2017, and December 2017 to January 2018, the winter fog experiment was successfully carried out (Ghude *et al.* 2017). These field observations are conducted at IGI Airport (28.56 °N, 77.09 °E, MSL 229 m). Fig. 1 shows the geographical location of the WiFEX site and the well-calibrated state-of-the-art instrument setup, installed on the northern side of the airport ~ 400 m from the runway (east-west direction).

The observational site is a wide-open area, typically prone to frequent fog formation during the winter season. A detailed description and overview of the WiFEX campaign and the specifications of instruments were mentioned in Ghude *et al.* (2017). In this study, a comprehensive analysis of very dense fog events (visibility < 50m) observed during the three phases of the

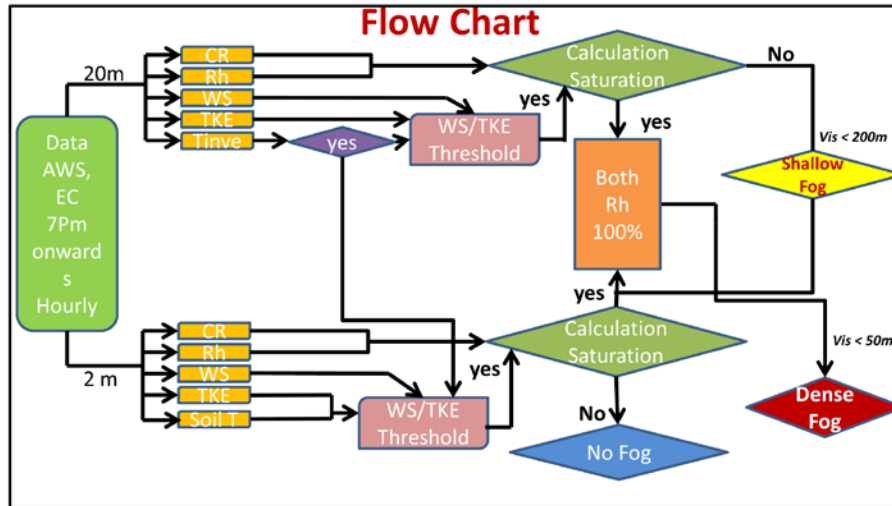


Fig. 2. Flow chart of decision tree based on the observational data

TABLE 2

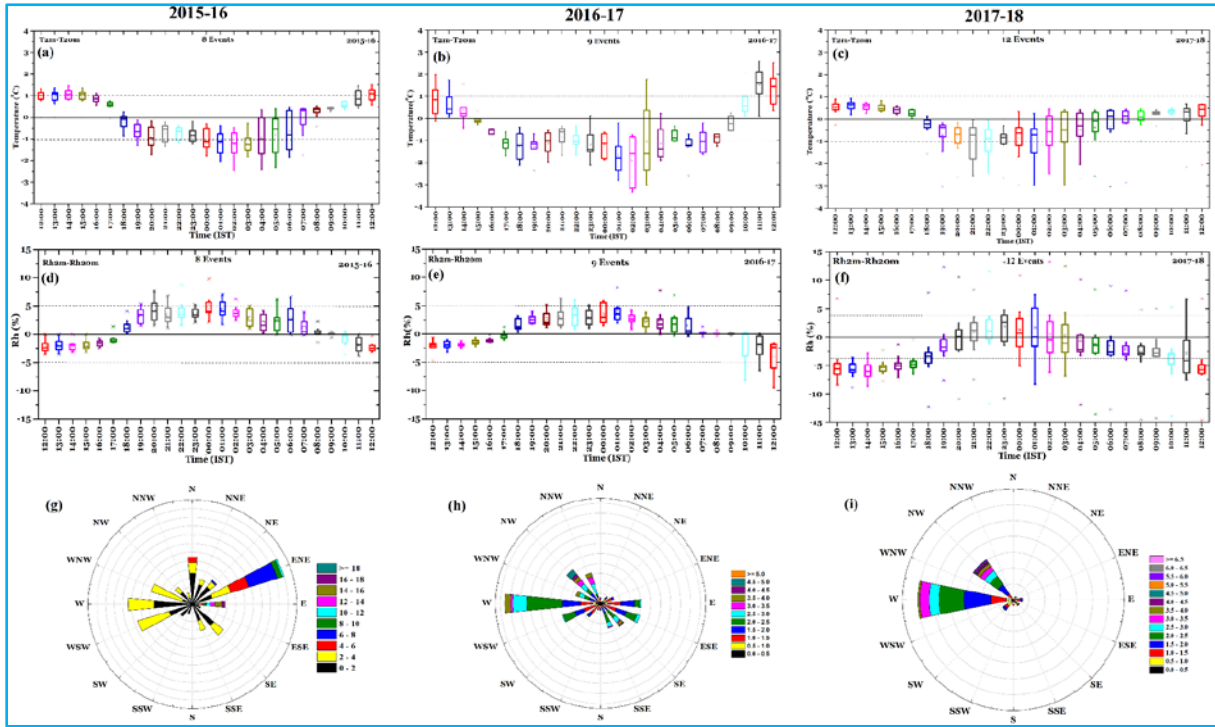
List of instruments deployed at IGI Airport, New Delhi, during WiFEX campaigns

Instruments	Parameters	Resolution
Multicomponent weather sensors (WXT520, VaisalaOyj, Finland; on a 20-m tower)	Barometric pressure, air temperature, relative humidity (RH), wind speed, and direction	1 min
Temperature and RH sensor (HMP45C, VaisalaOyj, Finland; on a 20-m tower)	Air temperature and RH	1 min
EC system consisting of fast-response 3D sonic anemometer thermometer (Windmaster Pro, Gill Instruments, Inc., UK) and a CO ₂ /H ₂ O infrared gas analyzer (IRGA model: LI-7200 enclosed path CO ₂ /H ₂ O analyzer, Licor Inc., USA; on 20 m tower)	Measurement of surface fluxes of heat, water vapor, momentum, CO ₂ , and Turbulent Kinetic Energy	10 HZ, 30 min averaged fluxes
Integrated soil temperature and moisture probes (5TM, Decagon Devices, Inc., USA) were placed at 0, -2, -5, -10, -20, -30, -50 cm depths.	Soil temperature, volumetric water content	1 min

WiFEX campaign is analyzed to develop an observation-based algorithm to accurately nowcast the dense fog events before 3 hours of actual fog. Multicomponent weather sensors like an all-in-one sensor (air temperature, relative humidity, and wind vector), and 2D sonic anemometers were installed at different heights on a 20m mast at IGI airport. All-in-one weather sensors have been calibrated at the India Meteorological Department (IMD) calibration facility. An Eddy covariance sensor was installed at the exact location for turbulence and surface flux measurements at 12.5 m above ground level. Table 2 describes accurate information on the sensors installed during different phases of the WiFEX campaign. In addition, we have utilized hourly visibility data from Aviation Routine Weather Reports (METAR).

3.1. Flow chart of decision tree

Based on the micrometeorological observation of the three WiFEX campaign, a simple decision tree was developed considering the parameters like temperature, lapse rate, relative humidity, soil temperature, turbulent kinetic energy, and wind speed. Fig. 2 shows the flow chart of the decision tree approach fortified with the performance of influencing parameters during the dense fog period to predict the dense fog at IGI Airport, New Delhi. Hourly mean values of the temperature and relative humidity from the 2m and 20m weather sensors were used to deduce the cooling rate at respective heights. The output of the cooling rate (Temperature difference and last hour relative humidity) gives the theoretical value of



Figs. 3(a-i). Observed values of the temperature, relative humidity, and wind vector of dense fog events during (a, d, g) 2015-16, (b, c, h) 2016-17, and (c, f, i) 2017-18

TABLE 3

Three-year WiFEX campaign fog classification based on the visibility scale (numbers must be in digit format throughout the manuscript)

WiFEX campaign Year	0 m < Vis < 50 m	50 < Vis < 200 m	200 m < Vis < 500 m
2015-16	8 Events	12 Events	29 Events
2016-17	9 Events	15 Events	24 Events
2017-18	12 Events	3 Events	17 Events
Total	29	30	70

saturation (relative humidity) based on the previous hour’s cooling rate kept constant. It is revealed by Dhargar *et al.* (2021), that to trigger dense fog (visibility < 50m), saturation must be equal at both heights (2m and 20m). This condition is necessary to predict dense fog events and other weather parameters. Inversion of temperature and relative humidity between 2m and 20m was analyzed during the dense fog events. In addition, wind speed, turbulent kinetic energy, and soil temperature have been considered in the decision tree.

Additionally, the following equation (1) has been developed based on 3-year data of temperature and relative humidity data. We assume that the difference

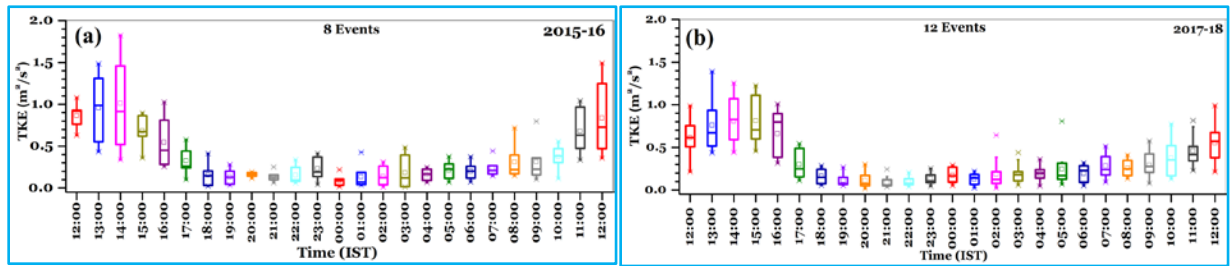
between the relative humidity of the previous hour and the current hour is constant to determine the relative humidity for the next hour. One of the inputs in the decision tree is cooling rate calculation.

$$Rh_{cal} = \frac{V_{press_{t_0}}}{V_{press_{t_1}}} \times \frac{t_0}{t_1} \times Rh_0 \tag{1}$$

where,

Rh_{cal} is the calculated relative humidity,

Rh_0 is the current hour relative humidity,



Figs. 4(a&b). The composite structure of observed turbulent kinetic Energy of very dense fog events during (a) 2015-16 and (b) 2017-18

TABLE 4

Dense fog events with observed minimum visibility, onset, and dissipation times to verify the decision tree

Dense fog Events	Min. Visibility (m)	Onset (IST)	Dissipation (IST)
23-24 Jan, 2016	0 m	03:00	11:00
29-30 Dec, 2016	100 m	02:00	05:00
02-03 Jan, 2017	0 m	01:00	11:00
13-14 Dec, 2017	0 m	01:00	04:00
03-04 Jan, 2018	0 m	01:00	12:00
27-28 Jan, 2018	0 m	03:00	10:00

t_0 and t_1 are the previous and current hour temperature, respectively.

$$V_{prss_{t_0}} = \exp [(20.386 - 5132) \div t_0]$$

$$V_{prss_{t_1}} = \exp [(20.386 - 5132) \div t_1]$$

4. Results and discussion

4.1. The decision tree based on combined surface meteorology for 2m and 20 m during three campaigns

Fog is a unique phenomenon; the drivers of fog onset include changes to the synoptic-scale circulation, local land-use features, and feedback of the land-atmosphere within the boundary layer. The significant drivers of fog formation and its occurrence involve complex interactions of thermodynamic parameters and its feedback through many atmospheric processes that happen at different scales. During the first three phases of the WiFEX campaign (2015-16, 2016-17, and 2017-18), 70 fog events were observed with visibility between 200m and 500m based on the METAR visibility observation. Apart from this, 30 and 29 fog events were reported as dense and very dense fog cases. Table 3 presents a classification of fog events during the three-year WiFEX campaign based on

the visibility scale. Due to the poor visibility conditions, significant air traffic, delays in trains, and zero movement of vehicles on the road in the early morning hours occurs. In order to understand the characteristics of the fog, the sensitivity of meteorological parameters like the temperature, relative humidity, wind speed, wind direction, and total kinetic energy was analyzed, especially in very dense fog cases.

Box and whisker plots of the temperature and relative humidity of dense fog events at 2m and 20m during 2015-16, 2016-17 and 2017-18 are depicted in Fig. 3. Here, boxes indicate the lower and upper quartiles, while the horizontal line in each box represents the median temperature and relative humidity. A small square box indicates the mean temperature and relative humidity for each season. Vertical lines extending from each box represent the minimum and maximum temperature and relative humidity recorded for that particular hour. Points denote the outliers at the end of box whiskers of the specific hour. Figs. 3(a-c) show the difference between the 2m and 20m temperatures starting from the 1200 IST to the next day at 1200 IST. The difference was significant as the median of the box whisker was beyond 1 °C, indicating a positive gradient. The crossover occurred at around ~1800 IST during the very dense fog events, just after sunset. The difference becomes zero, and gradually it

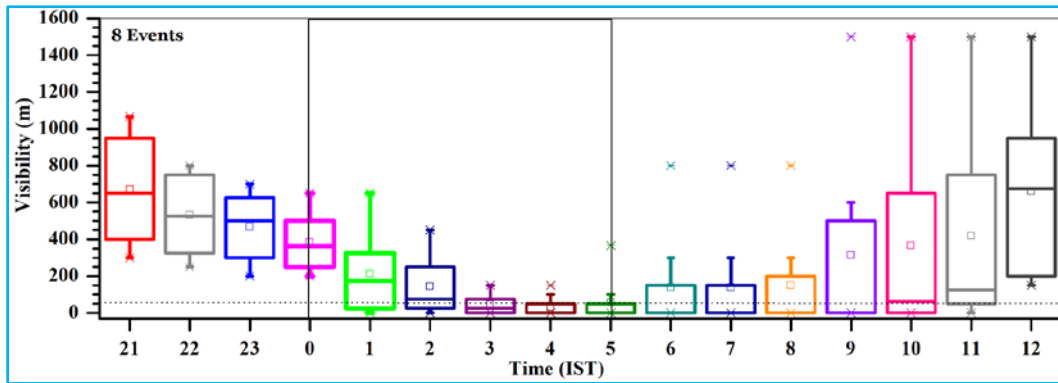


Fig. 5. Box and whisker plots of 6 very dense fog events in terms of observed visibility

attains negative gradient that indicates the fog onset. The difference becomes $-1\text{ }^{\circ}\text{C}$ for the fog period and ultimately sustained for the fog dissipation around ~ 0600 IST. The same pattern characterized the mean observed picture of temperature difference during the three campaigns.

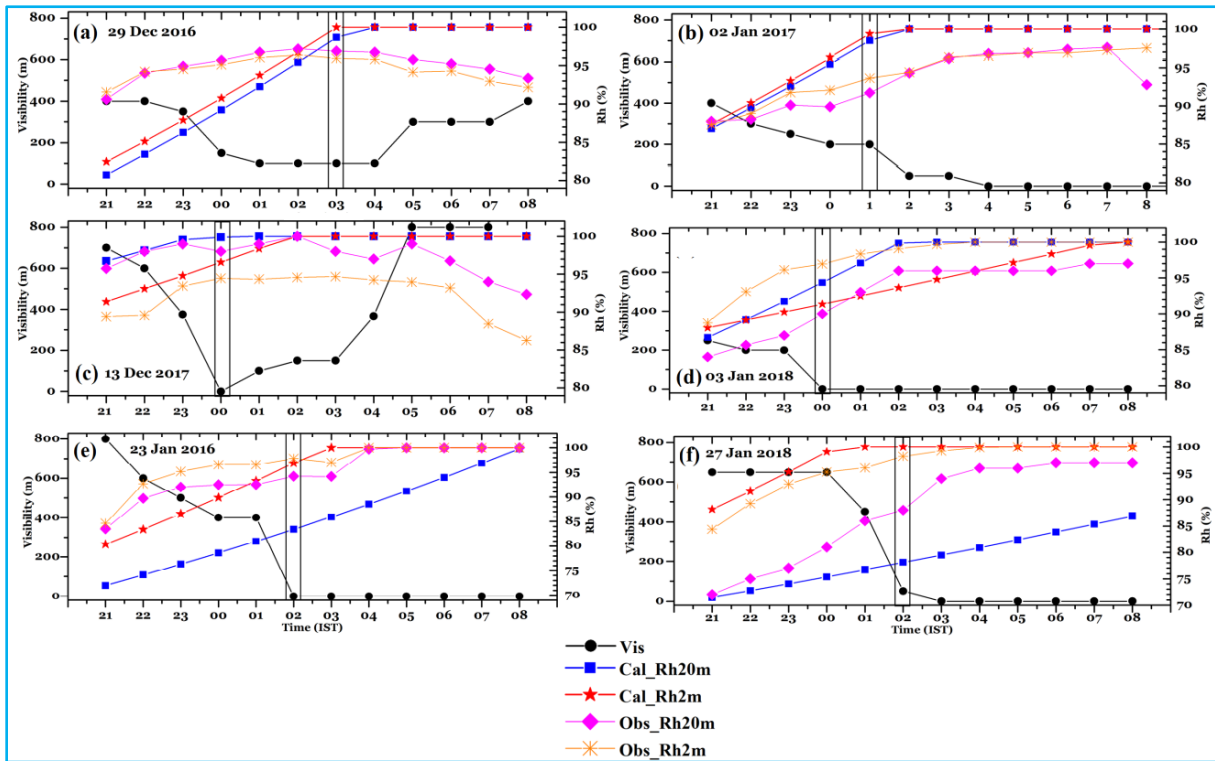
The value of the temperature difference oscillates between $-1\text{ }^{\circ}\text{C}$ and $+1\text{ }^{\circ}\text{C}$. Consequently, a relative humidity difference between 2m and 20m is shown in Figs. 3 (d-f). The low moisture at 2m and high moisture at 20m during the afternoon hours gives negative relative humidity difference. A moisture difference between 2m and 20m gradually becomes a positive difference after sunset. It suggests that the same amount of moisture was acquired between the two levels at the onset. A positive difference was maintained during fog, which was below 5%. In other fog events like moderate fog and haze, the difference was more than 5% during the fog. Since the dissipation starts after sunrise, it converts the moisture difference into negative. The value of moisture difference continuously oscillating between -5% to $+5\%$ was characterized during the all three fog campaigns. The winds were closely related to synoptic conditions, but we describe only the statistical characteristics of wind-based on-site observation. Figs. 3(g-i) shows wind distributions during the very dense fog periods for each of the three campaigns as a wind rose plot. It was noticed that the winds blow more frequently in a westerly direction (only feeble during the 2015-16 winter season), and the wind speed was weak, which was around $2\text{-}3\text{ m s}^{-1}$ in very dense fog cases.

Fig. 4(a&b) and Fig. 5 indicates the observed turbulent kinetic energy and box and whisker plot in terms of observed visibility of very dense fog events during the WiFEX (2015-16) and WiFEX (2017-18). The findings by Dhangar *et al.* (2021) reveal that the TKE is $<0.1\text{ m}^2\text{s}^{-2}$ before the fog onset and can reach $0.5\text{ m}^2\text{s}^{-2}$ during the fog. Results from the composite structure of observed

turbulent kinetic energy of very dense fog events during 2015-16 and 2017-18 were in good agreement with Dhangar *et al.* (2021). The mean value of TKE was maintained at less than $0.2\text{ m}^2\text{s}^{-2}$ during very dense fog events. Low wind speed values and TKE were suggestive of the stable atmosphere near the surface. In addition, it was one of the precursors considered for the preparation of the decision tree. The data from the eddy covariance system during WiFEX (2016-17) could not be converted into the actual TKE values. Therefore, threshold values of wind speed, TKE, and soil temperature at the first level (-2 cm) considered during the initial stage of the decision tree were $2\text{-}3\text{ m s}^{-1}$, $0.2\text{ m}^2\text{s}^{-2}$, and $10\text{ }^{\circ}\text{C}$, respectively.

4.2. Verification of dense fog events using decision tree

For verification of the dense fog cases, we have compared the predicted relative humidity at 2m and 20m with observations. The predicted relative humidity at 2m and 20m from the decision tree utilized the corresponding measurements of the meteorological variables at the same heights. Even though there was no systematic relative humidity bias in all dense fog events, the onset was predicted accurately in several cases shown in Figs. 6 (a-c). The onset of fog was predicted accurately on 29-30 December 2016 at 03 IST, 02-03 January 2017 at 01 IST and 13-14 December 2017 at 0000 UTC, respectively. The skill of the decision tree in predicting dense fog cases is 66%. However, the given decision tree completely failed to capture fog onset on 03-04 January 2018 shown in Fig. 6(d). Here, it was observed that both 2m and 20m relative humidity value is $<95\%$ (not saturated) even if the dense fog evolved. Fig. 6(e) represents the onset of the dense fog event at 02 IST on 23-24 January 2016 by raising relative humidity above 95% (saturation) and declining horizontal visibility below 50m. Interestingly, the relative humidity trend at 2m (20m) is significantly (reasonably) captured in the decision tree. A similar finding was noticed during the



Figs. 6(a-f). Represents the particular event verified with respect to observed visibility, the output of the decision tree at 2m and 20m

27-28 January 2018 dense fog event, where relative humidity at 2m shows >95% value close to actual fog onset compared to the relative humidity at 20 m shown in Fig. 6(f). In an individual analysis of the relative humidity at 2m and 20m, it was noticed that the predicted relative humidity at 2m has better skill in fog onset prediction (approximately 83%) than relative humidity at 20m (approximately 50%). This could suggest that onset of fog was different at different heights due to vertical variability in fog.

5. Conclusions

The present study was comprehensively carried out based on an indigenously developed decision tree to predict very dense fog events. For this study, we used the threshold values of the thermodynamics and dynamical features of fog from the three years of WiFEX campaigns during 2015-16, 2016-17 and 2017-18. This approach was applied directly to the six episodes of very dense fog. The study concluded that the decision tree is capable of nowcasting very dense fog events during midnight. This is sensitive to weak and robust temperature inversion between 2m and 20m, ultimately controlling relative humidity at corresponding defined levels. The nowcasting approach directly follows the initial state of the atmosphere that prevailed during the previous hour.

Eventually, the cooling rate (air saturation at both levels) was critical in predicting dense fog events. The nowcasting approach shows good agreement in nowcasting fog onset time with 66% accuracy (now cast of three very dense fog events out of six events). Further, the skill could be improved by multiple iterations on the initiation of every alternate hour after sunset. The current version of the nowcasting approach was only focused on predicting the fog onset, so further improvement is necessary to indicate the fog dissipation in the future.

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not have any commercial or associative interest that represents a conflict of interest with the work submitted.

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