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Application of Ground based Microwave Radiometer in Aviation Weather Forecasting in Indian Air Force

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Highlights

- Efficacy of MWR in nowcasting thunderstorm and dense fog.
- Comparison of MWR and radiosonde observations to ascertain variation in respective profiles.
- Thermodynamic indices inferred from both are not correlated / have moderate correlation.
- Superepoch technique of lagged composite for thermodynamic indices / parameters on the time series could not determine any pattern to predict thunderstorm and dense fog with lead time of 2-4 hours.

GRAPHICAL ABSTRACT
Abstract

Time and intensity specific very short-term forecasting or nowcasting is the biggest challenge faced by an Aviation Meteorologist. Ground-based Microwave Radiometer (MWR) has been used for nowcasting convective activity and it was established that there is a good comparison between thermodynamic parameters derived from MWR and GPS radiosonde observations, indicating that MWR observations can be used to develop techniques for nowcasting severe convective activity. In this study, efforts have been made to bring out the efficacy of MWR in nowcasting thunderstorms and fog. Firstly, the observations of MWR located at Palam, New Delhi, India have been compared with the nearest radiosonde (RS) data to ascertain the variation in respective profiles. Large differences were found in Relative Humidity (RH) whereas temperatures from MWR were found to be close to RS observed temperature upto 3.5 Km. Subsequently, the scattered plots and correlation coefficient of thermodynamic indices / parameters indicated that most of the parameters are either not correlated or have moderate correlation only for 1200 UTC profiles. The superepoch technique of lagged composite for various thermodynamic indices / parameters to obtain a combined picture of all the thunderstorm and dense fog cases on the time series could not determine any pattern to predict thunderstorm and dense fog with lead time of 2-4 hours. MWR profile for a case of occurrence of thunderstorm was analyzed. No significant variation was observed in most of the indices (as calculated from MWR observed parameters) prior to the occurrence of thunderstorm. RH at freezing level and between 950 and 700 hPa levels were the only parameters which increased four hours prior to the occurrence.

Keywords: Radiosonde, Microwave Radiometer, nowcasting, superepoch analysis
Resumen

El pronóstico a muy corto plazo o el pronóstico inmediato específico de tiempo e intensidad es el mayor desafío al que se enfrenta un meteorólogo aeronáutico. El radiómetro de microondas terrestre (MWR) se ha utilizado para realizar predicciones inmediatas de la actividad convectiva y se estableció que existe una buena comparación entre los parámetros termodinámicos derivados de MWR y las observaciones de radiosondas GPS, lo que indica que las observaciones de MWR se pueden utilizar para desarrollar técnicas de predicción inmediata de condiciones convectivas severas. actividad. En este estudio, se han hecho esfuerzos para resaltar la eficacia de MWR en tormentas eléctricas y niebla de pronóstico inmediato. En primer lugar, las observaciones de MWR ubicadas en Palam, Nueva Delhi, India, se han comparado con los datos de la radiosonda (RS) más cercana para determinar la variación en los perfiles respectivos. Se encontraron grandes diferencias en la Humedad Relativa (RH), mientras que las temperaturas de MWR se encontraron cercanas a la temperatura observada de RS hasta 3.5 Km. Posteriormente, los gráficos de dispersión y el coeficiente de correlación de los índices / parámetros termodinámicos indicaron que la mayoría de los parámetros no están correlacionados o tienen una correlación moderada solo para los perfiles de 1200 UTC. La técnica de superepoch de composición rezagada para varios índices / parámetros termodinámicos para obtener una imagen combinada de todos los casos de tormenta y niebla densa en la serie de tiempo no pudo determinar ningún patrón para predecir tormentas y niebla densa con un tiempo de espera de 2-4 horas. Se analizó el perfil de MWR para un caso de ocurrencia de tormenta. No se observó una variación significativa en la mayoría de los índices (calculados a partir de los parámetros observados de MWR) antes de que ocurriera la tormenta. La HR a nivel de congelación y entre 950 y 700 hPa fueron los únicos parámetros que aumentaron cuatro horas antes de la ocurrencia.
1. Introduction

1.1 Radiosonde and Need of Real time Profiling

Information about the vertical atmospheric profile plays an important role in weather prediction. Radiosondes have been one of the most reliable means of retrieving these profiles. It is common practice to examine the temperature and humidity profiles measured by radiosonde and its derived thermodynamic indices / parameters in nowcasting convective weather events. Meteorologists have estimated the wind gust based on the temperature, humidity and wind measurements (Lee, 2007). However, the radiosonde profiles are discrete in nature and are available twice a day in general. On the other hand, weather instances are due to continuous changes in the atmosphere and these changes are more dynamic in pre-monsoon season especially in tropical region. This necessitates use of an equipment capable of continuous profiling to support nowcasting. MWR is one such equipment which provides vertical profile of the atmosphere high temporal resolution. Ground-based Microwave Radiometer (MWR) is a passive sensor which provides continuous atmospheric profile from surface to 10 Km. It measures the radiation intensity at different frequencies in the microwave spectrum which are dominated by the absorption / emission of atmospheric water vapour, cloud liquid water and oxygen (Rose et al, 2003).

1.2 Earlier Studies using MWR

As per Leena et al (2015) analysis of MWR-measured temperature (specific humidity) has a warm (wet) bias below 3 km and cold (dry) bias above that altitude. However, correlation of stability indices estimated from radiometer and radiosonde showed fairly good correlation, with a correlation coefficient greater than 0.5 with 95% significance. Madineni et al (2013) studied MWR profile over Indian region and depicted that, MWR observations show warm (cold) bias in the temperature, except at 0.5 km, when compared to radiosonde observations below (above) 3–4 km, assuming latter as a standard technique. In case of water vapor, MWR observations show wet (dry) bias below (above) 2–3 km depending on the time. Ratnam et al. (2013) reported warm (cold) bias in the temperature below (above) 3-4 km height when compared with radiosonde measurements. They also noticed a wet (dry) bias in specific humidity for 6-8 g/kg below (above) 2-3 km. Chan PW (2009) brought out that MWR does
not cater for the scattering effects of rain in the given frequency and hence to be used with caution during the actual occurrence of precipitation.

1.3 **MWR in the Indian Air Force**

Indian Air Force (IAF) is in possession of 21 MWRs evenly distributed across the country. These are MP-3000A series passive radiometers which provide continuous thermodynamic profile of PBL and above up to 10 Km. The equipment measures brightness temperature in both water vapour and oxygen bands and produces atmospheric sounding similar to that of radiosonde every minute. The system scans 21 K-band frequencies (22-30 GHz) and 14 V-band frequencies (50-59 GHz) which are dominated by absorption of water vapour and oxygen molecules, respectively. Retrievals are broadly classified into two domains i.e Zenith and off-Zenith (20°) to mitigate heavy precipitation. The intensities thus received are converted to temperature and moisture profile by applying Radiative Transfer Equation (RTE), historical soundings of nearby station and artificial neural network.

1.4 **Nowcasting using MWR**

In the field of aviation, thunderstorms and dense fog are considered as most dangerous aviation weather hazards. Very short-range forecasting of convective weather incidents were historically based on the extrapolation of radar reflectivity echo. However, the accuracy of these predictions decreases very rapidly in first 30 min because of short life span of convective cells. For forecasts period beyond 20 min, techniques for predicting the initiation, growth and dissipation of convective storms are essential (Hering et al, 2004). Similarly, significant changes occurring within the PBL are most important to be trapped to predict the occurrence or dissipation of dense fog. MWR has the advantage of continuous monitoring of atmosphere and can play an important role in nowcasting these events. A comprehensive study by Chan PW (2009) discussed the importance of MWR profile in nowcasting of intense convective weather over Hong Kong. Later in 2011, he elaborated the importance of MWR derived indices and their usage in nowcasting by correlating derived variables with the lightning activity. Madhulatha et al (2013) presented the superepoch analysis to bring out the changes in various thermodynamics indices in pre-convective environment.
1.5 Thermodynamic Indices of MWR and RS

Thermodynamic indices are considered as predictors for forecasting aviation weather hazards. The thresholds values of indices calculated from radiosonde observations may not be the same as calculated with the MWR profiles, as both equipment have different working principles. MWR data is to be validated against the nearest radiosonde profile to understand the degree of variation. This paper presents validation of profiles of the MWR installed at Palam, New Delhi, India Vis-a-Vis nearest radiosonde station of India Meteorological Department (IMD) at Safdarjung, New Delhi. Efforts have also been made to study the correlation between the various thermodynamic indices generated by MWR and radiosonde data sets. These indices have been studied further on the temporal scale to bring out the usage of MWR in nowcasting thunderstorm and fog events over Delhi.

2. Instrumentation and Methodology

2.1 Instrumentation over Area of experimentation

2.1.1. The radiometer installed at Palam {Lat/Long: 28.5°N / 77.1°E & elevation: 237 m Above Mean Sea Level, (AMSL)}, Delhi measures radiation intensity at water vapour (22-30 GHz) and oxygen channel (50-59 GHz) to obtain the temperature and humidity profile. MWR generates profiles in every two minutes with 50 m vertical resolution up to 0.5 km, 100 m resolution from 0.5 to 2 km and 250 m resolution from 2 to 10 km. A total of three retrieval are available for a given time period i.e one zenith and two off-zenith on either side at 20° angle. An average of all the three profiles for each time frame is also made available to the users. However, for the present study only zenith scan has been utilized. Retrieval of temperature and humidity profiles from the radiation intensity is done by applying RTE and artificial neural network to historical sounding data. The accuracy of temperature and relative humidity sensor of MP-3000A series radiometer is claimed to be 0.5°K and 2% respectively which is at par with radiosonde observation.

2.1.2. Radiosonde data of nearest India Met Department (IMD) observation station, Safdarjung (Lat/Long: 28.5°N / 77.2°E & elevation: 216 m AMSL), Delhi is used as the base profile to carry out the comparative study. The observations are available twice (0000 & 1200 UTC) a day. Both the profiles have been studied separately in this paper for 08 cases of
Thunderstorm and 03 cases of dense fog events over Delhi. Occurrence, cessation and variation in the intensity of weather events were studied through half hourly Aerodrome Routine Meteorological Report (METAR). Convective events were further substantiated by Lightning Detection System (LDS) of IAF, Doppler Weather Radar (DWR) at IGI airport, Delhi and INSAT-3D IR1 images of the relevant time period. Various cases of the significant weather events considered in present study are shown in Table I.

2.2 Methodology

2.2.1 In first part of the study, validation of MWR data is undertaken with nearest radiosonde profile. Thereafter, a total of 09 parameters i.e. K-Index (KI in °C), Total Totals Index (TTI in °C), Vertical Total Totals Index (VTT in °C), Cross Total Totals Index (CTT in °C), MEAN_RH (950-700 hPa) in %, RH at Freezing Level (FL) in %, TEMP_DIFF (950-700 hPa) in °C, TEMP_DIFF (700-400 hPa) in °C, TEMP_DIFF (400-300 hPa) in °C have been studied to bring out the correlation between both the derived profiles. P value for each set of indices has been calculated using t-test to bring out the probability of variation between the datasets.

2.2.2 K index (KI) is a measure of thunderstorm potential based on the vertical temperature lapse rate, and the amount and vertical extent of low-level moisture in the atmosphere and calculated as $\text{KI} = \text{T}(850 \text{ hPa}) + \text{TD}(850 \text{ hPa}) - \text{T}(500 \text{ hPa}) - \text{DD}(700 \text{ hPa})$. VTT represents static stability or the lapse rate between 850 and 500 hPa and calculated as $\text{VTT} = \text{T}(850 \text{ hPa}) - \text{T}(500 \text{ hPa})$. Whereas, The CTT includes the 850 hPa dewpoint and represented as $\text{CT} = \text{TD}(850 \text{ hPa}) - \text{T}(500 \text{ hPa})$. The Total Totals Index consists of two components, the Vertical Totals (VTT) and the Cross Totals (CTT). As a result, TTI accounts for both static stability and 850 mb moisture but would be unrepresentative in situations where the low-level moisture resides below the 850 mb level. TTI can be calculated as $\text{TTI} = \text{VTT} + \text{CTT}$. Mean RH between 950-700 hPa and at Freezing Level (RH_FL) along-with temperature differences at three distinct levels were calculated to derive the moisture availability and lapse rate in the atmosphere. Last part of the study deals with plotting and studying the temporal variation of stability indices in pre-convective environment. The superepoch analysis is carried out with the aim to comment upon the utility of these indices in nowcasting thunderstorm and dense fog events over Delhi.
3. **Results and Discussion**

3.1 **Validation of MWR Profile Using Radiosonde Data**

3.1.1 **Comparison of 0000 and 1200 UTC Profiles**

The temperature and relative humidity profile of MWR and nearest radiosonde (Safdarjung, Delhi) observations have been compared for all the 11 cases. Mean profiles of zenith scan of MWR for 0000 and 1200 UTC and radiosonde has been depicted in figure 1 and 2 respectively, Where Y axis is depicting altitude of comparison in meters AMSL. Temperature profiles for both (0000 & 1200 UTC) hours depict the close match up to the level of 3.5 Km (Fig. 1a and 2a). However, temperature has the variation of 1-2°C (RS based temperatures are higher as compared to MWR) at middle and upper levels as shown in the difference profile of figure 1c and 2c. MWR profiles are showing cold bias above 3.5 Km and the trend remains same with variation in quantity at various levels. Contrast in relative humidity (RH) profile was found to be large at different levels for both 0000 & 1200 UTC (Fig. 1b & 2b). Deviation is even larger at lower levels i.e below 3.5 Km. Figure 1c & 2c are depicting the difference plot of RH. It clearly showcases the presence of dry bias of the range of 30-50% up to 3.5 Km and thereafter wet bias of 20-30% at higher levels. The variations in RH were found to be higher (10-15% Appx) for the morning profiles.

3.1.2 **Variation in MWR-Radiosonde Profiles**

Chan and Hon (2011) brought out that, the measurement principle of the two instruments is different (volume integral above a fixed location on the ground for radiometer vs. point measurement of a drifting balloon for radiosonde), hence there are biases and spreads of the data, but the trend was found to be identical. However, the present case study reflects that only the temperature trend of both the profiles is matching. Whereas, the RH profile has variation, primarily till 3.5 Km.

3.2 **Correlation between MWR and Radiosonde based Indices**

3.2.1 **Comparison of 0000 and 1200 UTC Indices**
Correlation and p value (using t-test between) the MWR and RS based indices have been calculated separately for 0000 and 1200 UTC profiles (Table II). A total of nine indices / parameters of Zenith scan of MWR and nearest RS station have been studied. It revealed that none of these indices are correlated for 0000 UTC profile. However, moderate correlation in KI, VTT, TTI, MEAN_RH (950-700 hPa) and TEMP_DIFF (950-700 hPa) were observed for 1200 UTC profile. The scattered plots of one of the least correlated Index (KI of 0000 UTC) and best correlated Index (TEMP_DIFF between 950 & 700 hPa of 1200 UTC) are depicted in figure 3 and it substantiate the high variation in the parameters derived through MWR and Radiosonde profile. Best fit line along with the equation has been depicted over the plots. However, it cannot be utilized for prognostic purpose.

3.3 Case Study of Thunderstorm over Delhi on 07 Feb 19

3.3.1 Cases under the Study

A total of eight thunderstorm cases over Delhi have been studied. An elaborated analysis of a thunderstorm event occurred on 07 Feb 19 has been covered in this section.

3.3.2 Weather Sequence

Cyclonic storms associated with the mid latitude Subtropical Westerly Jet (SWJ), referred to as Western Disturbances (WDs), play a critical role in the meteorology of the Indian subcontinent. WDs embedded in the southward propagating SWJ produce extreme precipitation over northern India and are further enhanced over the Himalayas due to orographic land-atmosphere interactions (Dimri et al, 2015). Similar type of extra-tropical system moved across the northern region on 07 Feb 19. INSAT-3D (IR1) satellite imageries of 07 Feb 19 from 1030 UTC to 1330 UTC (Fig. 4) depicts the presence of multi-layered clouding embedded with intense convection in isolation over Delhi and adjoining area. METAR reports of Indira Gandhi International airport, Delhi reveals the commencement of thunderstorm activity with effect from 1130 UTC.

3.3.3 Movement of Convective Cells
MWR location is approximately 10 Km (areal) southwest of the IGI airport, Delhi. Max (z) product of DWR, installed at the airport has been placed in figure 5. It clearly indicates the presence of convective cell southwest of the MWR station at 1032 UTC with vertical extent up to 6.0 Km. This cell can be seen overhead at 1102 UTC with a new one developing in southwest direction at a distance of 20 Km. Second convective cell reached overhead by 1232 UTC. Reflectivity on both the occasion was more than 57.0 dBZ that substantiate the presence of intense convection.

3.3.4 **MWR Profile of the Episode**

Pre and post convective environment of 07 Feb 19 were also studied in the light of MWR based profile. Timeline of temperature, RH and vapour density variations are depicted in figure 6. It clearly brings out that, temperatures in vertical were insensitive to pre-convective environment and sharp changes could only be seen during the actual occurrence of the weather event i.e at 1130 UTC. High RH % (> 90%) was seen at lower level (upto 1.5 Km) at 0900 UTC and the same reduced thereafter till the time of occurrence. RH was seen increasing gradually from 0900 UTC onwards in between 3 and 6 Km levels. However, the quantity reduced significantly to 70% just prior to the occurrence. Absolutely saturated atmosphere is depicted during the time of occurrence of both the spells. Vapour density (VD) also showed gradual increase prior to the occurrence wherein the values reached from 1.0 g/m$^3$ to 7.0 g/m$^3$ in between 2 and 3 Km levels. At lower levels the gradient was more with the jump of approximately 8.0 units. Maximum contours in the values are coinciding with the time of occurrence. VD is the only parameter showing significant changes in pre convective environment. Rise in VD is indicative of increase in saturated water content at different levels of the atmosphere conducive for convective build-up.

3.3.5 **Lightning Counts and MWR Indices**

The case was further analyzed by calculating and studying the variation of MWR based indices. For the purpose, pre and post convective hourly values of the various indices / parameters have been plotted against the total number of lightning flashes sensed by the IAF LDS within 50 Km of the MWR location. Figure 7 shows the variation in different indices with respect to number of lightning flashes on the day of occurrence. Left Y-axis depicts the number of Lightning (LT) flashes, CT & VTT and right Y-axis depicts the variation of RH,
TTI, KI and temperature differences of various levels. X-axis represents the timeline with “0” as time of occurrence (1130 UTC) and “- / +” values to depict pre/post convective hours respectively. Analysis portrays the significant increase in RH% at freezing and in between 950-700 hPa levels wherein the values reach to 98% as compared of NIL recorded three hours prior to occurrence. Decreasing trend in the CT, VTT (Fig. 7a), TTI and KI (Fig. 7b) indices were noticed prior to the time of occurrence of thunderstorm. Feeble fall (~3°C) in the temperature difference of 950 and 700 hPa (Fig. 7b) level recorded one hour prior to the occurrence of thunderstorm. Temperature variations in middle (700-400 hPa) and upper (400-300 hPa) levels were found to be insignificant (Fig. 7b).

3.4 Superepoch Analysis

3.4.1 Time Lag Analysis

Madhulatha et al (2013) suggested the technique of superepoch analysis for obtaining a composite picture of all the thunderstorms events vis-à-vis variation of different indices / parameters on the time series. To examine the temporal variations of various thermal indices lagged composite of all the nine parameters are calculated and depicted in figure 8. The time of occurrence of thunderstorm is considered as lag 0 and lag -6 corresponds to environment six hours before the thunderstorm occurrence. Similarly, lag +6 denotes the environment six hour after the occurrence of thunderstorm. In the current depiction the storm occurrence in considered as zero.

3.4.2 Amalgamated Depiction of Thunderstorm Cases

For this technique, nine parameters were calculated for all the eight thunderstorm cases. Pre and post environment was superimposed to give a composite picture of each case and thereafter all the cases were merged to present an average variation in the indices / parameters. The average variation is depicted in bold lines whereas the vertical bars showcase the range of deviation.

3.4.3 Rajeevan et al (2012) mentioned that, observing the variation of the composite time series of thermo dynamical parameters can explain the prerequisites necessary for the genesis of thunderstorm activity. The similar concept has been implemented in the superepoch
analysis where the MWR based indices / parameters are being studied to bring out the nowcasting of thunderstorm events. VTT remained almost constant with the value of 28°C (Fig. 8a) prior to the thunderstorm occurrence. CTT, TT and KI indices (Fig. 8a) were showing sinusoidal pattern with a marginal fall prior to occurrence. KI during the time of occurrence came out to be around 20°C which is far low as compared to 42°C as brought out by Madhulatha et al (2012). Lapse rate in layers 900-700 hPa (Figure 8b) and 700-400 hPa (Fig. 8b) was of 1°C and 3°C respectively. However, a feeble variation of 0.1°C was seen in the lapse rate of 400-300 hPa (Fig. 8b). The other two parameters which displayed gradual variation four hours prior to the occurrence were mean RH in between 950 and 700 hPa (Fig. 8b) and relative humidity at freezing level (Fig. 8b). Rise in RH at freezing level was close to 36% whereas that of mean RH in between 950 and 700 hPa was almost 20%.

3.4.4 **Superepoch Analysis of Fog Events**

Superepoch analysis was also applied for three cases of dense fog over Delhi, where the visibility dropped to zero in the morning hours (Fig. 9). However, the parameters studied were related to the moisture and temperature variations at the lower levels (in between 200 m and 500 m) only. Marginal rise of the order of 0.25°C in the lapse rate in between 500 m and 200 m was noticed prior to the occurrence of fog. Total vapour pressure in the similar levels was almost constant with the value of 40 g/m³. Nil variation was noticed in total liquid water with the values close to 0.3 g/m³. Gradual increase in mean RH was recorded at the lower levels with the jump of approximately 22%.

4. **Inferences and Conclusion**

Main objective of the study was to bring out the application of ground based Microwave Radiometer in Aviation Weather Forecasting in Indian Air Force. For this purpose, first the data of MWR was validated using radiosonde for the similar time period. It came out from the study that the temperature profile of MWR and radiosonde has minimal variation below 3.5 km for both 0000 and 1200 UTC. However, moderate deviation was noted at mid and higher levels.

Variation in RH profile was noticed with dry bias at lower and wet bias at middle and higher levels. Variation was even larger for 0000 UTC. It signifies that MWR generated
profiles (especially of 0000 UTC) are significantly different from the radiosonde profiles. Also, weak correlation and high p value between most of the datasets signifies a large variation in derived parameters of the MWR and radiosonde profiles.

Hence, the threshold values of indices or parameters developed with the studies of radiometer data cannot be explicitly implemented for forecasting through MWR profiles. Real time inputs received from MWR should not be used in isolation. These indices need to be correlated with the local forecasting hints and thereafter to be utilised for the nowcasting purposes. These huge variations may be attributable to the technique of neural network and quality of historical data being used to generate the MWR profile from raw data of brightness temperature. After the neural upgrade of MWR, the profile sensitivity needs to be established against thunderstorm and fog events. Refinements in the threshold values of thermodynamic indices for MWR based prediction may also be carried out on large historical dataset.

Similarly, correlation between different indices generated through MWR and radiosonde profile were calculated. It came out that, the parameters of 0000 UTC have no correlation. However, a total of 05 parameters showed moderate correlation for 1200 UTC profiles. It depicts that, RH% variation has a profound impact on most of the indices and they cannot be implemented for nowcasting purpose in isolation.

As per Madhulatha et al (2013), the superepoch analysis suggested that many thermodynamic parameters, lower-level relative humidity, stability index at different levels, lapse rate of equivalent potential temperature showed useful signals at least 3 h before the storm occurrence. Their analysis showed sharp changes in the thermodynamic parameters associated with the storms. There are appreciable differences in the variations between thunderstorm and non thunderstorm cases. However, in present superepoch analysis most of the parameters under study remains insensitive prior to the occurrence of severe weather phenomenon. At the same time standard errors were huge. Parameters like total liquid (500 m - 200 m), temperature difference (500 m - 200 m) and Total vapour density (500 m - 200 m) have given no indication to predict dense fog events. Steep variation in the MWR profiles for the similar weather events is making it difficult for the forecaster to select any reliable nowcasting indices to predict thunderstorm and dense fog events.
Atmospheric instabilities, mainly convection, depend on temperature distribution and moisture availability (P Leena, 2015), which are measured at very high resolution using MWR. However, based on the present study it can be inferred that, MWR can only be utilized as observation tool. Due to its inherent sources of error, MWR profiles cannot be exploited for the nowcasting purpose. There could be multiple reasons for this outcome of the study the most noticeable being the difference in retrieval / observations techniques of parameters from MWR and Radiosonde. However, the results may vary if more number of cases are studied, a better neural network is treated and also the off zenith profiles of MWR are considered for different geographical locations of the country.

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Data Availability

Due to the sensitive nature of the data used in this study, authors are not able to share the research data.

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Table I. Cases of Occurrence of Thunderstorm and Fog

| Sl. No. | Weather   | Date          |
|---------|-----------|---------------|
| 1.      | Thunderstorm | 07 May 2018   |
| 2.      | Thunderstorm | 27 Jun 2018   |
| 3.      | Thunderstorm | 22 Jul 2018   |
| 4.      | Thunderstorm | 26 Jul 2018   |
| 5.      | Thunderstorm | 06 Sep 2018   |
| 6.      | Thunderstorm | 08 Sep 2018   |
| 7.      | Thunderstorm | 22 Jan 2019   |
| 8.      | Thunderstorm | 07 Feb 2019   |
| 9.      | Fog        | 01 Jan 2018   |
| 10.     | Fog        | 06 Jan 2018   |
| 11.     | Fog        | 29 Jan 2018   |

Table II. Correlation between MWR and Radiosonde based Indices of 0000 & 1200 UTC

| Sl No. | Indices               | Correlation Values (R)/p Value (0000 UTC) | Correlation Values (R)/p value (1200 UTC) |
|--------|-----------------------|------------------------------------------|------------------------------------------|
| 1.     | KI                    | 0.09 / 0.79                              | 0.49 / 0.12                              |
| 2.     | CTT                   | 0.09 / 0.79                              | 0.25 / 0.45                              |
| 3.     | VTT                   | 0.16 / 0.63                              | 0.49 / 0.12                              |
| 4.     | TTI                   | 0.16 / 0.63                              | 0.36 / 0.27                              |
| 5.     | MEAN_RH(950-700)      | 0.16 / 0.63                              | 0.49 / 0.12                              |
| 6.     | RH_FL                 | 0.04 / 0.90                              | 0.16 / 0.63                              |
| 7.     | TEMP_DIFF(950-700)    | 0.04 / 0.90                              | 0.81 / 0.002                             |
| 8.     | TEMP_DIFF(700-400)    | 0.09 / 0.79                              | 0.16 / 0.63                              |
| 9.     | TEMP_DIFF(400-300)    | 0.16 / 0.63                              | 0.16 / 0.63                              |
**FIGURES**

**Figure 1(a).** 0000 UTC composite profiles of temperature along with standard deviation observed for all the cases under study.

**Figure 1(b).** 0000 UTC composite profiles of Relative humidity % along with standard deviation observed for all the cases under study.
**Figure 1(c).** Difference between the radiosonde and MWR temperature (blue line) and relative humidity (red line) along with standard deviation of errors (0000UTC)

**Figure 2(a).** 1200 UTC Composite profiles of temperature along with standard deviation observed for all the cases under study.
Figure 2(b) 1200 UTC Composite profiles of Relative humidity % along with standard deviation observed for all the cases under study.

Figure 2(c) 1200 UTC Composite profiles of Difference between the radiosonde and MWR temperature (blue line) and relative humidity (red line) along with standard deviation of errors.
**Figure 3 (a).** Scattered plot of MWR – Radiosonde Indices generated through 0000 and 1200 UTC profiles. Scattered plot of KI in °C (0000 UTC) with one of the least correlations of 0.09

\[ y = 0.1553x + 16.45 \]

**Figure 3 (b).** Scattered plot of MWR – Radiosonde Indices generated through 0000 and 1200 UTC profiles. Scattered plot of temperature difference between 950 & 700 hPa in °C (1200 UTC) with best correlation of 0.81

\[ y = 0.7392x + 5.5604 \]
Figure 4. INSAT-3D (IR1) imageries of 07 Feb 19 from 1032 UTC to 1302 UTC
Figure 5. DWR Max (z) products of Delhi IGI airport of 07 Feb 19 from 1032 UTC to 1302 UTC
Figure 6. MWR generated profile of 07 Feb 19 displaying variation in temperature, relative humidity and vapour density wrt the genesis of thunderstorm.
Figure 7. Time series plot of various indices and parameters generated through MWR profile of 07 Feb 19 against the count of lightning (LT) flashes. X-axis depicts the ± 06 Hours of post/pre convective phase where x=0 depicts the time of maximum thunderstorm activity. (a) Left Y axis denotes the variation of CT, VT & lightning (LT) count and Right Y axis denotes the variation of RH at freezing level (RH_FL), Mean RH. (b) Left Y axis denotes the variation of lightning (LT) count and Right Y axis denotes the variation TTI, KI and temperature differences at various levels (TEMP_DIFFs).
Figure 8. Superepoch analysis of nine indices / parameters for eight thunderstorm cases, where x=0 depicts the time of maximum thunderstorm activity.
Figure 9. Superepoch analysis of four parameters for three dense fog cases, where x=0 depicts the time of maximum intensity of fog.