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An analysis of fog events in respect of winter season 2021-2022 using model reanalysis & INSAT-3D/3DR satellite data

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सार – **अध्ययन का उद्देश्य दोहरा था** (*i*) **अंतरिक्ष अनुप्रयोग केंद्र (एसएसी) भारतीय अंतरिक्ष अनुसंधान केंद्र (इसरो) द्वारा विकसित इन्सैट**-3**डी**/3**डीआर रात के समय कोहरे का पता लगाने वाले चैनल डिफरेंसिंग (एमआईआर- टीआईआर**1**) योजना की समीक्षा, जिसका शीत ऋतु में विकिरण कोहरा एक समान नहीं होता है और भारतीय क्षेत्र में भौगोलिक रूप से भिन्न होता है और** (*ii*) **एनसीईपी पुनर्विश्लेषण और ईआरए** - 5 **डेटा सेट से विसंगतियों (तापमान, हवा, नमी, उलटा, भू-संभावित ऊंचाई इत्यादि) का उपयोग करके** 2021-2022 **के शीत ऋतु में कोहरे की परिघटनाओं का विश्लेषण किया गया।** 2021-2022 **में प्रेक्षित कोहरे की परिघटनाओं में सराहनीय कमी देखी गई, जबकि मॉडल पुनर्विश्लेषण और इन्सैट**-3**डी**/3**डीआर डेटा ने शीत ऋतु** (2021-2022) **में कोहरे की परिघटनाओं को बहुत अच्छी तरह से दर्शाया गया। हालाँकि, भारत के विभिन्न क्षेत्रों के इन्सैट डेटा के आधार पर रात के समय कोहरे की सीमा निर्धारित करने और हाल के दिनों में कोहरे की परिघटनाओं में संतोषजनक कमी के लिए लंबी अवधि के डेटा के साथ अधिक संख्या में कोहरे के मामलों के लिए इसी प्रकार के अध्ययन करने की आवश्यकता है।**

ABSTRACT. The objective of the study was twofold (*i*) Review of INSAT-3D/3DR night time fog detection channel differencing (MIR- TIR1) scheme developed by Space Application Centre (SAC) Indian Space Research Organisation (ISRO) thresholds which were not uniform for winter season radiation fog and vary geographically over Indian domain & (*ii*) An analysis of Fog events of 2021-2022 winter season using the anomalies (temperature, wind, moisture, inversion, geo-potential height etc.) from NCEP reanalysis and ERA-5 data sets. The fog events observed with 2021-2022 were found to show an appreciable reduction, whereas model reanalysis and INSAT-3D/3DR data captured the winter fog occurrences very well. for winter season (2021-2022). However, to quantify the night time fog thresholds based on INSAT data of different regions of India and appreciable reduction of fog events in the recent past there is a need to carry out similar study for more number of fog cases with long period of data.

Key words – Fog, INSAT, National Centre for Environmental Prediction (NCEP), ERA-5.

1. Introduction

The Winter Season (December to February) is generally affected with low visibility episodes like radiation fog, mist, haze and air pollution, especially Indo Gangetic Plains (IGB) of North West India. In general, the meteorological pre-conditions of the occurrence of the radiation fog are clear sky, calm wind, night time cooling and moist air (humidity more than 80 %) over the area. In terms of the magnitude, the fog may be categorized spatially as slight, moderate, intense and extremely intense depending on the horizontal visibility. Generally, during foggy days the horizontal visibility should be less than 1000m and if it is further reduced then it will be termed as moderate, intense, extremely intense category. The formation, persistence and dissipation depend on many factors like boundary layer characteristics, inversion near the surface, radiation and turbulent mixing near the surface etc. Fog coverage during day and night can be monitored through high resolution satellite images. During day time many operational customized INSAT-3D/3R Imager derived satellite imagery products are available, *e.g.*, RGB images, day time microphysics, visible imageries and for night time, the Night time microphysics, channel difference products are available to monitor the fog.

The low level winds speed have an important role of mixing of moisture at lower levels and can enhance the fog activity. But if the wind speed is high then this enhancement in wind speed can affect advection as well as mesoscale mixing which sometimes causes evaporation of fog. Chaurasia *et al*., 2011, developed a night time fog detection scheme for monitoring and operational utilization of fog. The same scheme is tested with different brightness temperature thresholds (Ahmed *et al*., 2014) and found that other thresholds also contribute significantly.

Banerjee, *et al*., 2020 have studied spatiotemporal variability for winter fog over Indo Gangetic Basin (IGB) using INSAT-3D and comparison with surface visibility and aerosol optical depth. It has been observed that almost all types of fog events (very dense, dense and moderate) along with spatiotemporal variability with generated maps of fog images are captured well by INSAT-3D data. Das *et al*., 2015 conducted an integrated campaign to investigate the radiative effects over IGB during winter season December-2013 to February-2014. The contribution of anthropogenic aerosols (Srivastava *et al*., 2012) was relatively higher in summer as compared to winter and therefore increased the dust loading over the station. In the 4th assessment report of Intergovernmental Panel on Climate Change (IPCC) shows that aerosols have migrated effects of cooling as well as other regions have warming and estimated to be about 20 % increase of Green House Gases (GHGs) from pre-industrial era (Forster *et al*., 2007) and solid suspended particles can cause atmospheric heating over the Indian Ocean (Pilewskie, 2007). Gray, P Ellrod, 1995 used Geostationary Operational Environmental Satellites (GOES) multispectral technique used channel differencing of GOES 3.9- and 10.7–11.2-µm wavelength channels to depict the depth of fog by utilizing cloud-top heights reported by aircraft. Theoretically and operationally the sensitivity of INSAT satellite derived brightness temperature difference (BTD) in response to changes in fog depends on surface emissivity, temperature, droplet concentration and liquid water content (Dey, 2018; Ahmad *et al*., 2.014). Recently, C. Castillo *et al*., 2022, and I. Bartoková, *et al*., 2015 developed a new method for fog detection using Machine Learning (ML) regression based approach for low visibility prediction of airports. Occurrences of the Low visibility phenomena over IGB plains are well known weather hazards, which affect every year especially over North West India. Recently IIT Mumbai developed a satellite based fog monitoring system using Moderate Resolution Imaging Spectroradiometer (MODIS) flown on Aqua and Terra Satellite of National Aeronautics Space Administration (NASA) data. This will support government agencies for, *e.g*., Air, rail and water transport sectors in their decision making.

Aviation services need on route and around the airfield area forecast of low clouds and low visibility phenomena information for navigation aids or at the departure/destination/alternate airfields. Elevated haze or dust can mislead the pilots to correctly access the runway and this type of situation sometimes extends up to pre-monsoon season (March to May). As a requirement of continuous service enhancements of such low visibility phenomena efforts have been made by various authors (Bendix, 2002, Fischer *et al*., 2004, Nowak *et al*., 2008, Oliver, 1973, Egli *et al*., 2018, Cemark *et al*., 2008, 2009, Andrews, *et al*., 2018, Kim *et al*., 2019, Shimizu Akihiro, 2020, WMO, 2012, Andrews & Bright, 2018). Connection of Global wind circulation, evolution of Western Disturbances (WD’s), prevailing teleconnections, La Nina conditions, anthropogenic activities, urbanization, reducing aerosol loading etc.) are responsible for decreasing the intensity and persistence of the fog. Recent developments in numerical weather prediction modelling capabilities captures well the dynamic processes of mixing, turbulence, subsidence, thermodynamic properties, moisture fluxes and microphysical properties of Cloud Condensation Nuclei (CCN) in quite high resolution modes (Fernando *et al*., 2021).

The fog scheme developed by SAC, ISRO was recently modified based on the feedback from the end users, various stakeholders and forecasters. The modified scheme is now working in the operational chain of recently installed Multi Mission Data Reception and Processing System (MMDRPS), satellite division Mausam Bhawan, New Delhi. Most of the queries were related to dawn & dusk time issues and clear cut demarcation of fog and stratus cloud pixels contaminations. Most of the issues were resolved in the new modified scheme, however the issues related to fog and low cloud pixels still persist (Chaurasia *et al*., 2011). This issue can be minimized by incorporating a correction factor or masking criteria based on new instruments (like ceilometer etc.) data. The datasets required for this purpose should be at sufficiently dense locations to make suitable corrections in the satellite algorithms. In a similar way, next generation should have the multi-spectral and hyper spectral imaging capabilities with better resolution can improve further the fog detection scheme. This paper also highlighted such issues like night time channel differencing thresholds (which is normally kept fixed at 1.5 for all places) verification based on the actual occurrence of fog over the areas.

It is seen that this difference during night time vary significantly at different geographical locations and we cannot universally set a uniform threshold for all cases (Shang *et al*., 2017). Second, an important point of changing behaviour of fog formation is also analysed with the help of model reanalysis ERA-5 and NCEP Reanalysis data sets. It is known that the formation, intensification and dissipation of fog during the winter season is very complex in nature. It depends on boundary layer interactions to upper air system interaction through various mechanisms of land, air, sea interactions.

The data sets mean sea level pressure and anomalies of temperature and geopotential height NCEP and ERA-5 acts an additional supplement to diagnose the synoptic as well as mesoscale weather events which are responsible for fog occurrences and their persistence.

Therefore, the association of current satellite derived products (night as well as day time) with recently generated ERA-5 (25 km × 25 km) data sets will be very useful in diagnosing and predicting the fog occurrences. Similar type of work with larger data sets can further improve the forecasting capabilities and its lead time of prediction by matching the analogues behaviour of the past. The trained data heuristic program can further help to develop the fog vulnerable pockets over the Indian domain.

2. Data and methodology

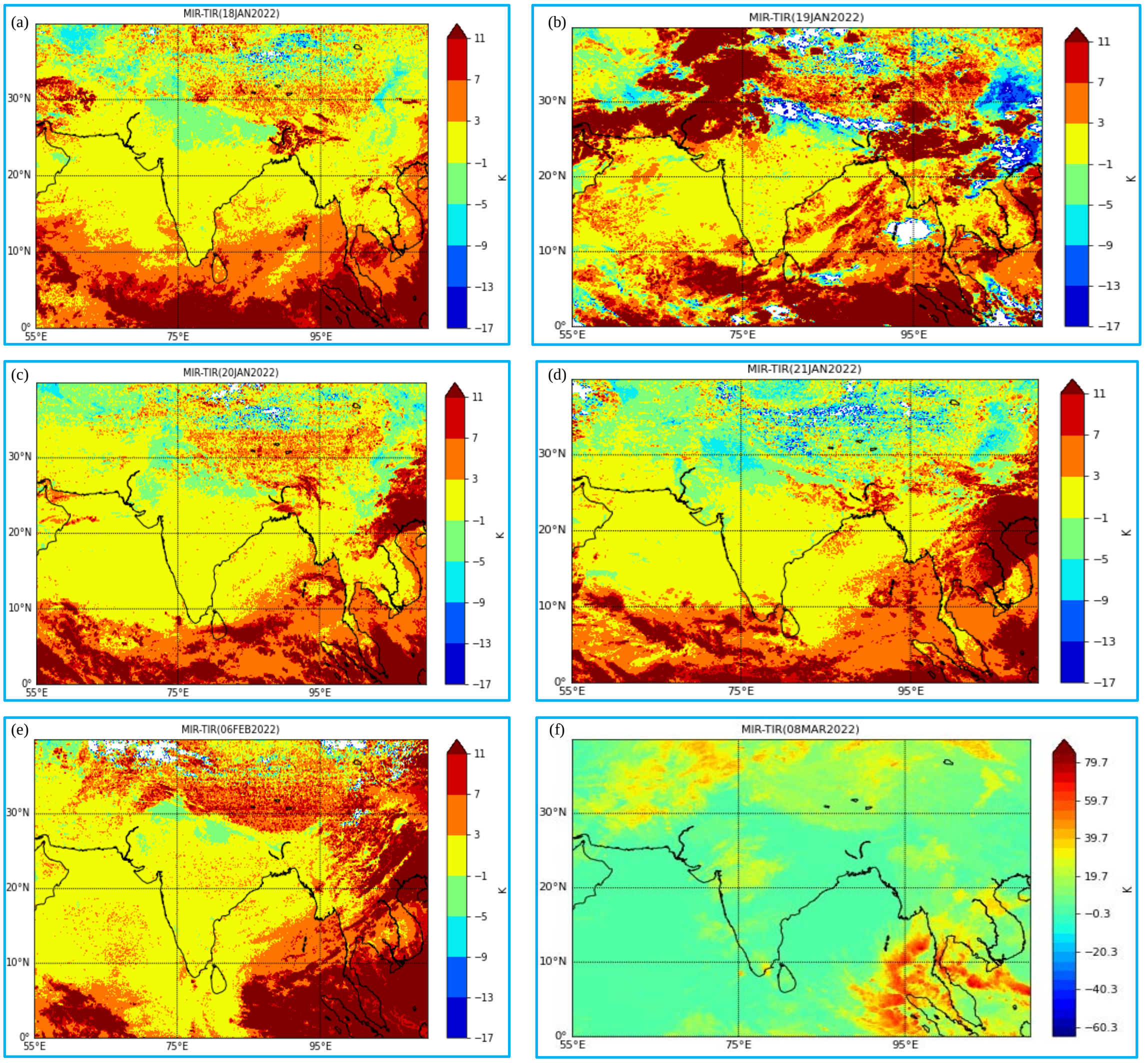
In this work INSAT-3D/3R satellite L1B data (HDF-5) of Thermal Infrared -1 (TIR-1) & Mid Infrared (MIR) IMAGER channels is utilized. Both the data sets are available every half an hour but for detection of night time fog events data sets from 1400 UTC to 0000 UTC have been taken from satellite division of India Meteorological Department (IMD). During night time Thermal Infrared (TIR) Channels of IMAGER are unable to capture precisely the fog events because these channel radiances have almost same emittance reached to the satellite and same texture is seen in satellite images over the fog area. There is no clear distinction seen with TIR images due to almost uniform illumination over fog areas. To overcome this fact, the channel differencing method (TIR1-MIR) has been utilized with a suitable threshold limit of this difference. A customized application code is written using PYTHON script, to capture night time fog events from INSAT-3D/3R satellite images, which is being utilized for operational purpose at satellite division of IMD. Data from NCEP /NCAR (at 2.5° × 2.5°) and ERA-5 (0.25° × 0.25°) reanalysis of European Centre for Medium Range Weather Forecasting (ECMWF) has been taken to generate anomalies in pressure, temperature and geo-potential to investigate the surface and upper air characteristics of fog occurrences.

3. Results and discussions

Satellite division of IMD receives and processes INSAT-3D/3R satellite images in 6 channels almost every half an hour. In the current operational status, IMD is processing Imager data in staggering mode and we are getting images for operational use every 15 minutes. MMDRPS system images & derived products are also available through Real-time Analysis of Product and Information Dissemination (RAPID) tool for day to day analysis which is developed by SAC, ISRO. This web based analysis tool is available in public domain globally and used extensively by the forecasters and end users for day to day weather forecasting in every season. Recently upgraded RAPID has many new additional features of handling other datasets and it can easily be operated through mobiles phones. Through this new RAPID tool we can visualize and analyze RADAR, Numerical Weather Model outputs, surface and upper air data for any weather event. During winter time (December to February) at instances the widespread fog disrupts services like railway, highways, aviation, navigation and many other sectors of the society. Satellite based fog monitoring is done through RAPID as well as a dedicated website of IMD. The customized program code generates an image of night time fog with all possible cases of brightness temperature thresholds (BTDs) and seen in a different grey shades in the image. Therefore, this application of INSAT-3D/3R satellite data will help the forecasters and end users to monitor the fog events during night time more appropriately. INSAT-3D/3DR channel differencing algorithm developed by Space Application Centre (SAC), Indian Space Research Organisation ISRO) is equally capable to detect and predict the marine as well as advection fog occurrence during night. Radiation fog generally occurs when wind is calm, sky is clear, plenty of moisture (relative humidity > 80-90 %) available and atmospheric layers near the grounds are stable, inversion at lower layers and air have a tendency just to condense. The other operation classification of fog as per IMD criteria is the visibility should be < 1000 m (fog), 1000-2000m (mist) and haze (2000-5000m) and on the lower side of visibility the condition of thick and dense fog is when visibility reduces up to 500 meter and less than 50 meter respectively.

3.1. *Fog events (17-20 January-2022 & 18-20 Febrary-2022)*

Generally, December to February months every year are affected by low visibility phenomena weather events and disrupts the normal public life especially in entire IGP



Figs 1(a-f). Channels (MIR-TIR1) of INSAT-3R brightness temperature difference ((in °K) 18th January-2022 (2100 UTC) (b) same as (a) for 19th January-2022 (c) same as (a) for 20th January-2022 (d) same as (a) for 21st January-2022 (e) same as (a) for 06th February-2022 (2100 UTC) (f) same as (a) for 08th March-2022 (0600 UTC)

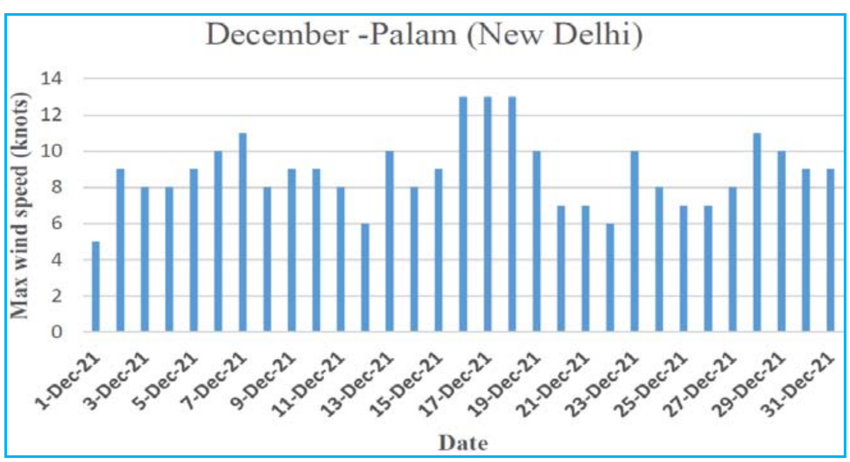


Fig. 2. Maximum wind (average-2100-UTC) reported at Palam Airport-New Delhi during the month of December-2021 [For radiation fog formation the wind speed should be light ~02-03 knots]

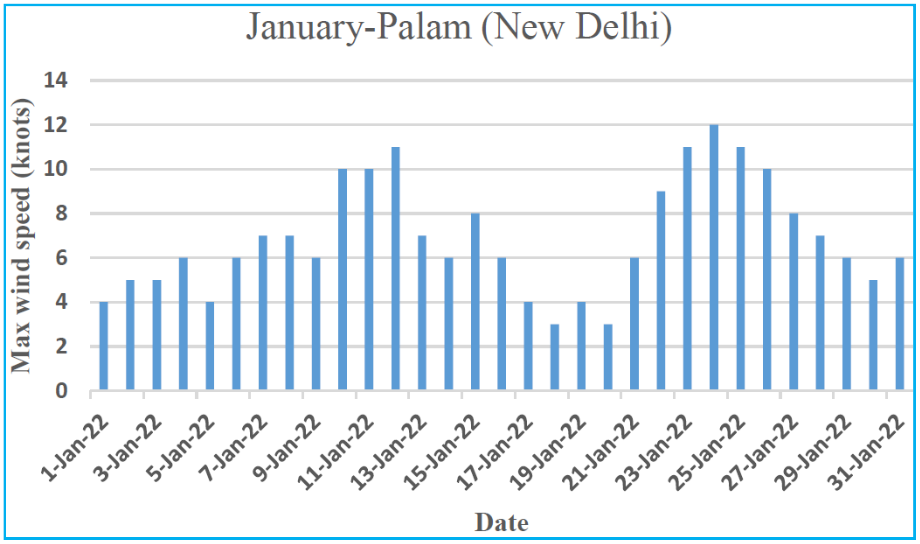


Fig. 3. Maximum wind (average-2100-UTC) reported at Palam Airport-New Delhi during the month of January-2022 [For radiation fog formation the wind speed should be light ~02-03 knots]

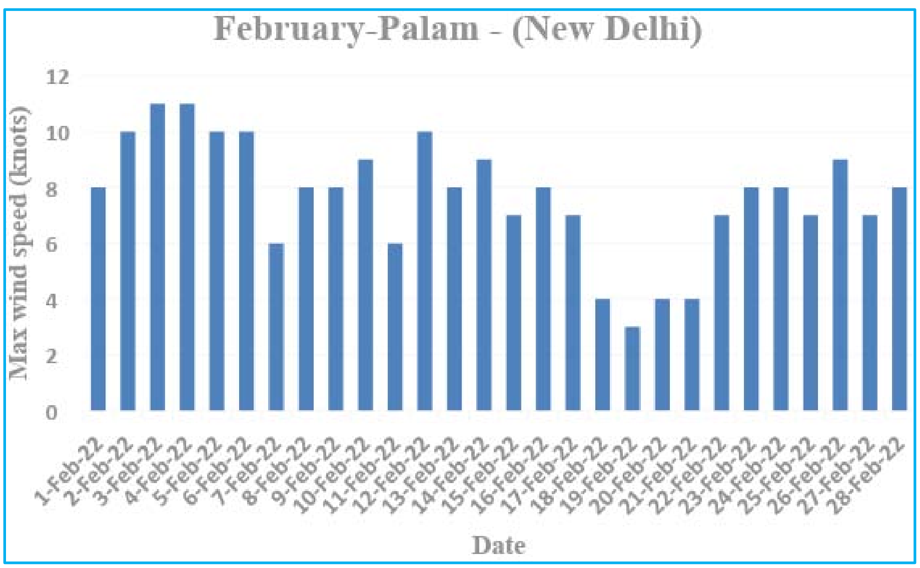


Fig. 4. Maximum wind (average-2100-UTC) reported at Palam Airport-New Delhi during the month of February-2022 [For radiation fog formation the wind speed should be light ~02-03 knots]

plains and Delhi NCR regions. Apart from fog the pollution levels also getting rising up from November inwards. This type of situation continues day and night and for a week or more. These events are not showing linier trend, in the year 2022 very few episodes of fog events were noticed. During the month of December - 2021 we do not have a single fog episode. Brightness Temperature Difference **(**BTD) of INSAT -3D/3DR (MIR-TIR1) Figs. 1 (a-f) has been generated to check the spread of for over Indian region (especially over IGP plains). The conditions like calm winds and relatively higher concentration of particulate matter were not noticed during entire December-2021 months, accepts a few number of days (Figs. 2&5). The BTDs range (-1 to -5 °K or °C) is found to be more suitable in capturing the night time fog extents. Some of the areas are attributed to low cloud contaminations and also showing the false signature of the fog. Some of such masking features are incorporated by Arun *et al*., 2018 in their new modified algorithm and BTDs thresholds are converged in much shorter domain as observed by Ahmad *et al*., 2014. Although it supports the finding that BTD thresholds will

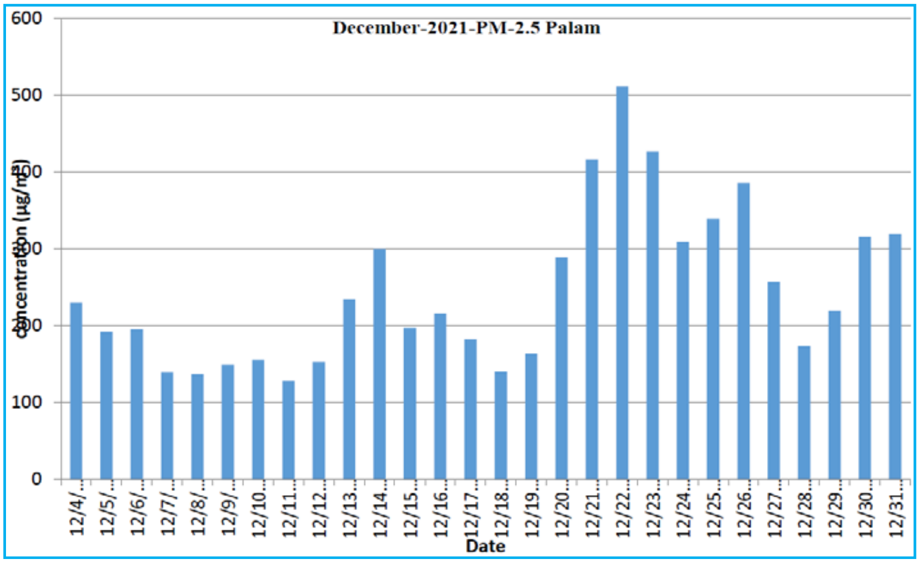


Fig. 5. $PM_{2.5}$ Air pollution data of Palam for the month of December-2021 (Particulate matter concentration (μg/m³) will be high during low visibility days)

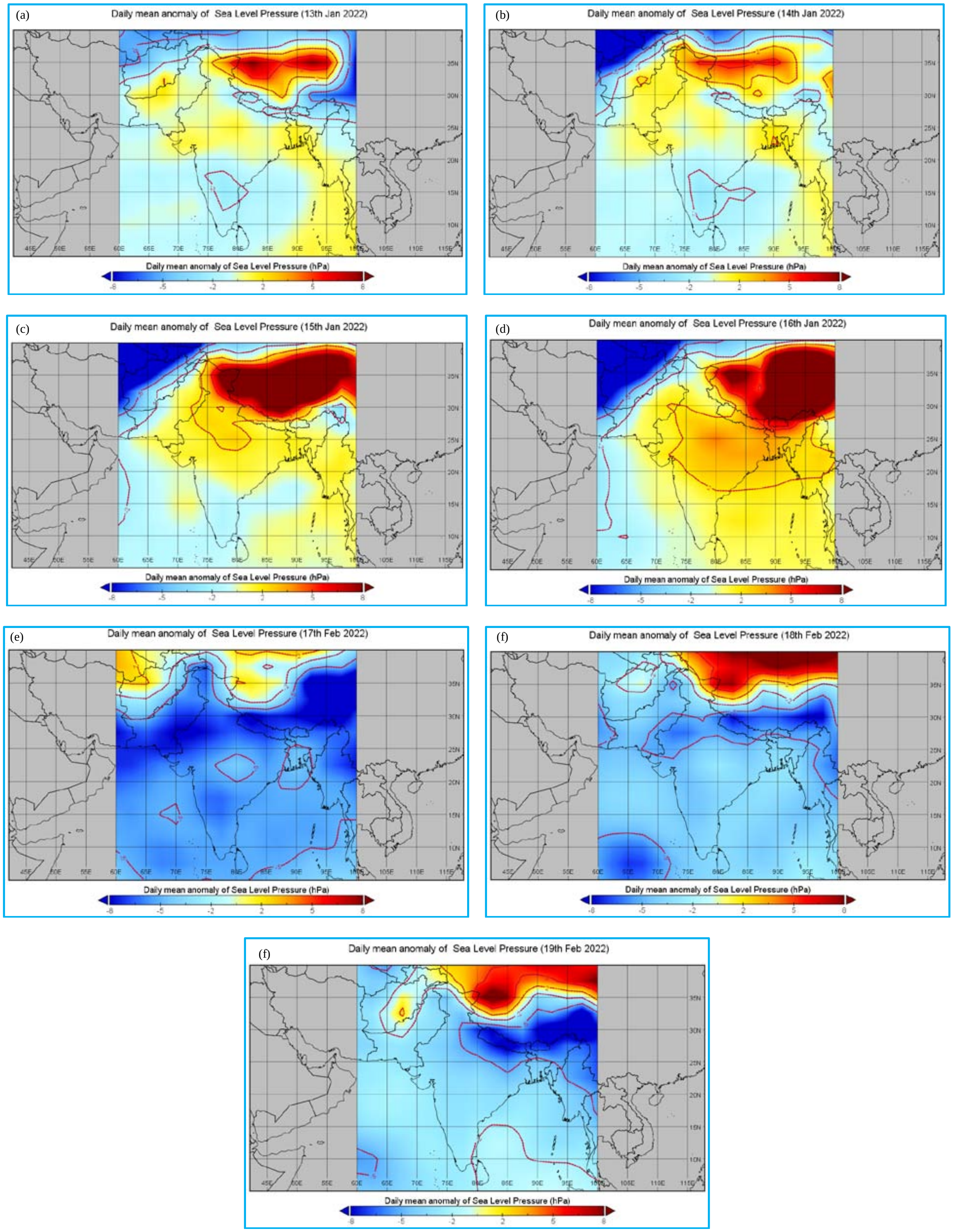
be different at different regions of India for night time depiction of fog. The BTD data of 8th March -2022 (0600 UTC) was also processed as seen in Fig. 1(f) and no negative departure is seen and hence during day time the scheme works well. For the months of January and February at the time of fog event the average wind speed over Delhi is around 3-5 knots or 1.54 to 2.57 m/sec which is supportive for mixing the boundary layer moisture and helps in fog formation as well its persistence (Figs. 3&4). Most of the other days of the months January and February the average wind speed for Delhi was quite high and may be one of the factor of formation of no fog. Figs. 1 (a-d) fog occurrence was associated with surface as well as passage of mid latitude systems known as Western Disturbances. The quasi-persistent sinking motion from mid latitudes aloft around Indian region generates the favourable conditions of fog at surface. These features have been brought out clearly from NCEP reanalysis and ETA-5 models reanalysis data. The less frequent fog events in the recent past indicates the absence of such type of scenario in the mid and upper troposphere. Sometimes the local features also develops shallow fog conditions if sufficient moisture is available in the lower layers and other conditions like radiative cooling etc are also available as observed on 6th February-2022 [Fig. 1(d)]. The surface and upper air analysis is given in subsequent section of this work.

3.2. *Synoptic as well as surface analysis based on model reanalysis data*

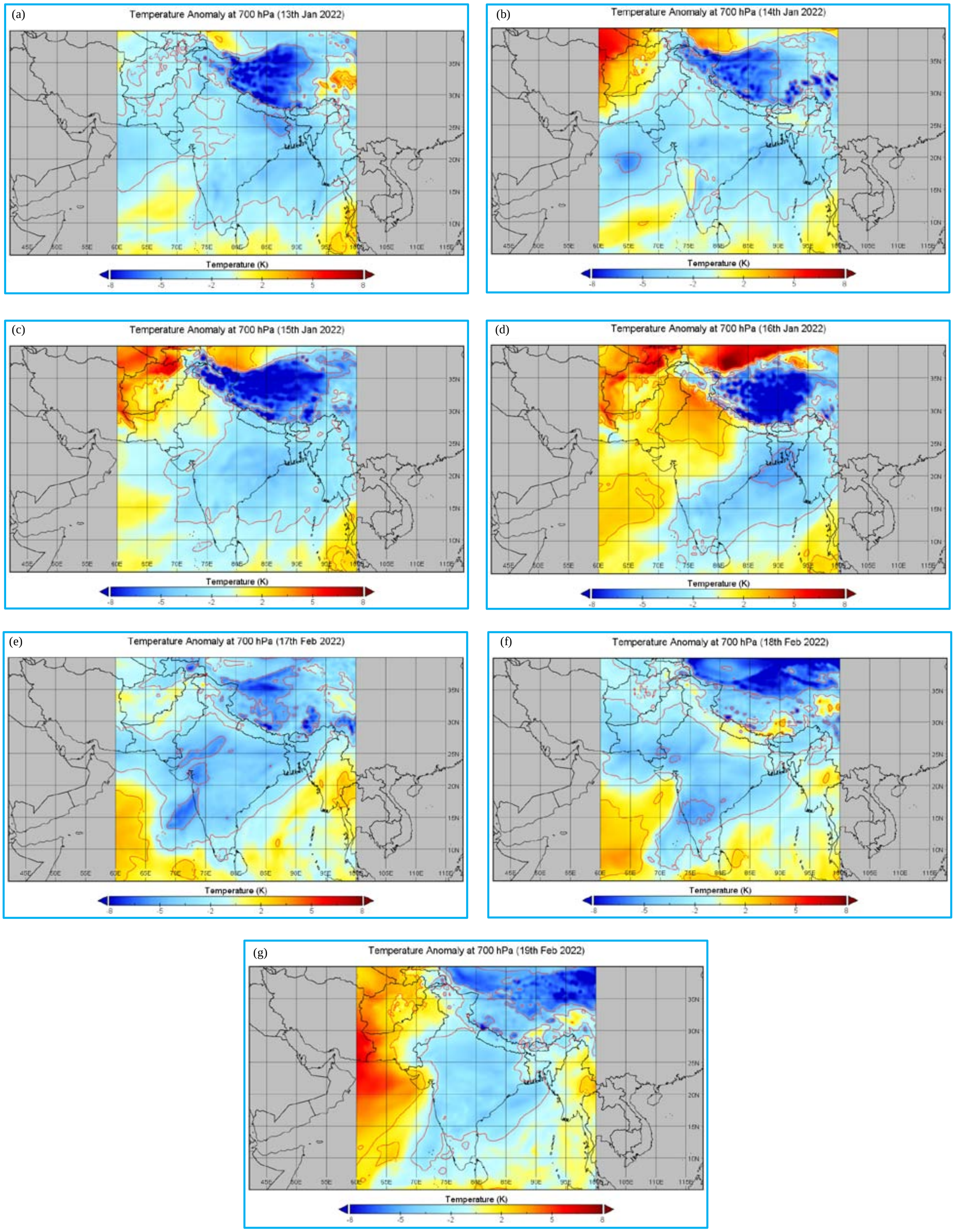
During cold season the influence of local, mesoscale conditions on the fog distribution may vary daily, monthly and seasonal scale It has been found that similar conditions are not always true for the existence of fog at one location due to complex geographical or terrain conditions especially over IGP.

NCEP/NCAR Reanalysis composite map for mean sea level pressure (MSLP; unit: hPa) for the fog days during the 2021-2022 winter season has been generated to highlight the high pressure belt above or around the fog area. Synoptic scale subsidence or warm advection over cool and moist air and radiation fog is associated with radiation cooling of the surface and associated low level heat exchange. Dew point inversion is also a contributed factor for the fog formation and such synoptic analysis already studied with NCEP/NCAR reanalysis (Kalney *et al*., 1996).

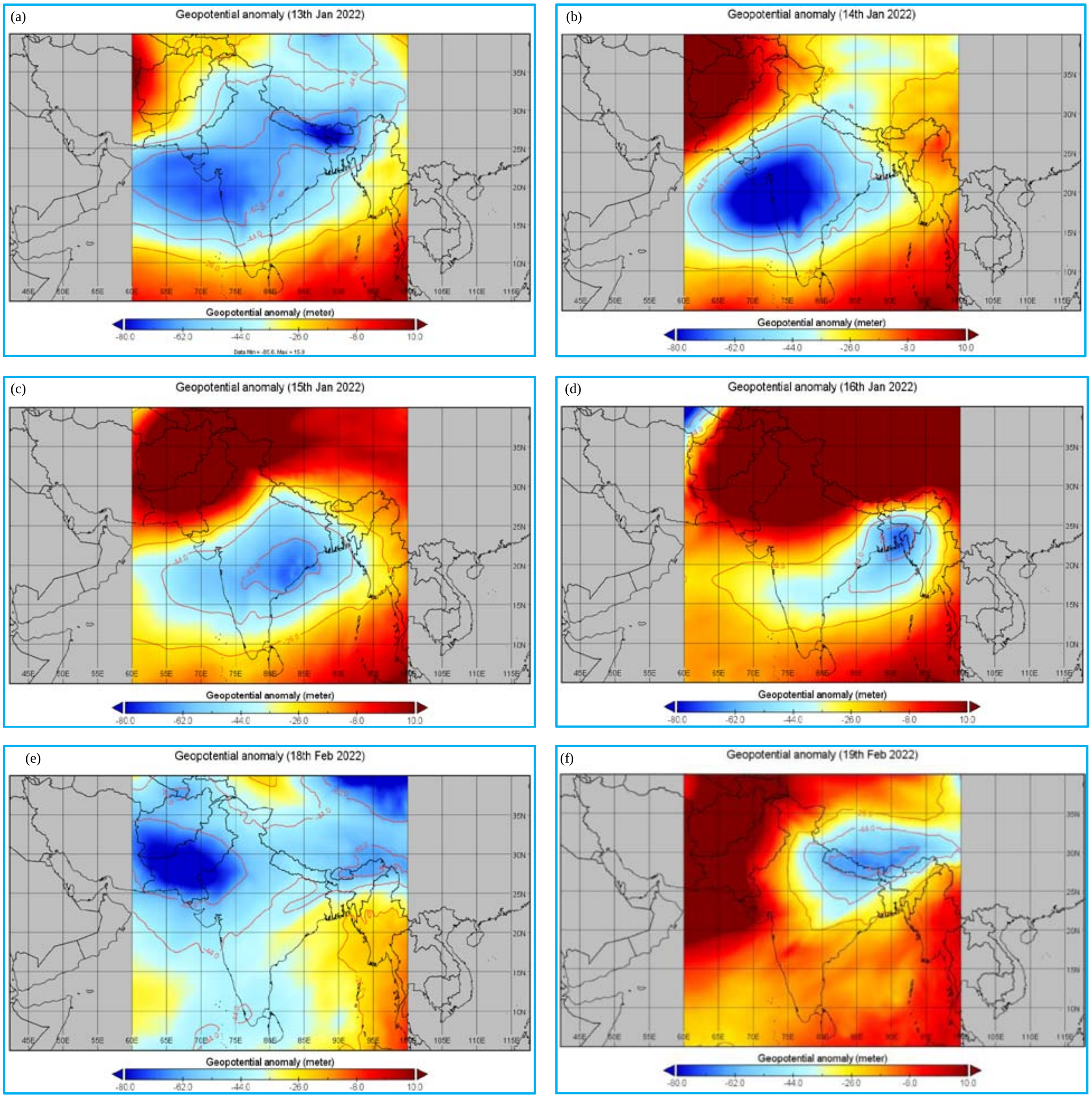
Surface high pressure lies between latitude 30° N - 35° N & 75° E - 95° E on 13th January-2022 and subsequently shift further eastward on subsequent days of 14th to 16th January-2022 till the entire domain have significant reduction of surface pressure over the region and this is conducive environment for fog formation. Therefore, this type of surface reduction prior to the fog occurrence will be the pre-requisite condition of fog formation Figs. 6 (a-d). In another event on February (16 to 19) the surface pressure pattern changes as per the movement of fog area depicted in Figs. 6 (e-g). Therefore, monitoring of surface pressure pattern from model reanalysis field over the domain 30° N - 35° N & 70° E - 100° E is very important pre-cursor of low visibility phenomena. Sometimes the areas of moisture source either from Arabian Sea or Bay of Bengal also



Figs. 6(a-g). (a) Mean sea level pressure anomalies from NCEP/NCAR reanalysis data - 13th January-2022 (b) same as (a) for 14th January-2022 (c) same as (a) for 15th January-2022 (d) same as (a) for 16th January-2022 (e) same as (a) for 17th February-2022 (f) same as (a) for 18th February-2022 (g) same as (a) for 19th February-2022



Figs. 7(a-g). (a) 700 hPa temperature anomalies from ERA-5 data -13th January-2022 (b) same as (a) for 14th January-2022 (c) same as (a) for 15th January-2022 (d) same as (a) for 16th January-2022 (e) same as (a) for 17th February-2022 (f) same as (a) for 18th February-2022 (g) same as (a) for 19th February-2022



Figs. 8(a-f). (a) 500 hPa geo-potential anomalies from ERA-5 data -13th January-2022 (b) same as (a) for 14th January-2022 (c) same as (a) for 15th January-2022 (d) same as (a) for 16th January-2022 (e) same as (a) for 18th February-2022 (f) same as (a) for 19th February-2022

shows reduction in surface pressures during the active phase of low visibility weather event.

3.3. *500 hPa Geopotential Height (m) composite mean*

ERA-5 Reanalysis v-5 data sets of European Centre for Medium Range Weather Forecasting (ECMWF) composite map for 500 hPa geopotential heights (unit: m) for the fog days during the 2021-2022 winter season.

Figs. 8 (a-f) of composite mean of geopotential height 500 hPa, shows ridge in the west and a deep trough ahead that prevents upper air systems from scouring cold air but sometimes it allows periodic intrusions of cold air from north to northwest.

3.4. *700 hPa Air Temperature (K) composite mean*

Similarly, ERA-5 Reanalysis v-5 data sets of European Centre for Medium Range Weather Forecasting

(ECMWF) composite map for 700 hPa air temperature (unit: K) for the fog days during the 2021-2022 winter season.

From the study it is found that for almost all the foggy days: large upper level ridge over IGP and persistence fog area. The average synoptic pattern is depicted in 500 hPa height referred above & 700 hPa temperature and mean sea level pressure patterns. These upper level changes upper level height and temperature modulates the system intensity and persistence and are the prime requisite of moisture flow and affected themselves by various other global interactions. Therefore, fog and similar low visibility phenomena still remain a great challenge. As such these events are interlinked surface boundary layer to upper troposphere local to global level. Therefore, synergy of all such actual and interconnections and their understanding which further leads to prediction in advance have great challenge.

Similar patters also seen in Figs. 7 (a-g) of 700 hPa temperature composite mean as upper levels warm and inverted conditions develop/redevelop depending on the upper level ridging patterns develop/redevelop and this allows relatively warm temperature aloft over west of IGP along with periodic intrusions of additional cold air. Hence, warm anomalies occur in the west and cold anomalies remains in the east. This pattern causes high pressure at surface with the intrusion of cold air during foggy days in winter over northwest India. This combination of stability at lower layers develops inversion over the area and sometimes persist over few days and therefore radiation fog disrupts the life common public (starts from early morning) under this high pressure at surface and clear sky conditions prevailed over night.

Station parameters (pressure, temperature anomalies) on a day to day basis show little change and therefore surface conditions effect is not as strong as upper air systems for the fog occurrences over the area. This interaction process varies from place to place and the exact nature of these mesoscale interactions are unclear.

The length of fog is variable and it has been found that fog occurrences near sunrise are more pronounced than with a minimum in the afternoon hours, especially in January and February months of 2022.

4. Conclusion

It is observed from the study that the BTD thresholds of night time fog events generally vary (-1 to -5 °K or °C) in most of the cases (~90 %) of 8 events occurring during December winter season 2021-22. Low cloud contamination issues in fog pixels yet need to be addressed and need more observational data of cloud base heights or hyperspectral imaging. For brevity, figures of two cases have been presented in this work. Therefore, BTD thresholds can be generated with a large number of data sets for many winter seasons over larger domains. This work is in progress to quantify the BTD thresholds over the Indian domain. Secondly, the surface and upper level features from model reanalysis data sets (NCEP/NCAR or ERA-5) needs to be carried out with larger data sets to quantify the surface pressure, 500 hPa geopotential height and 700 hPa temperature anomalies. The pattern or contour of these anomalies before, at the time and after the occurrence of fog or low visibility phenomena needs to work out for demarcation of regions of persistence of weather events.

The surface pressure anomalies migrated with time between latitudes 30° N - 35° N & 75° E - 95° E longitudes.

This migration decides how frequently develops /re develops in high to low pressure patterns from NCEP/NCAR data gives a clue for the spatial and persistency of the fog events. The other conditions of radiation fog like low or calm winds (~ 1 to 2 knots), high humidity (> 90 %), radiation cooling and sufficient concentration of particulate matter favours formation of fog and if deviates then fog events will be suppressed, like winter season 2021-22.

ERA-5 reanalysis 500 hPa geopotential height shows ridge in the west and a deep trough ahead that prevents upper air systems from scouring cold air but sometimes it allows periodic intrusions of cold air from north to northwest. If this scenario positively deviates in any season then occurrence of fog events and its impacts will be affected.

ERA-5 generated 700 hPa temperature composite mean as upper levels warm and inverted conditions develop/redevelop depending on the upper level ridging patterns develop/redevelop and this allows relatively warm temperature aloft over west of IGP along with periodic intrusions of additional cold air. In the recent past these weather patterns are less frequent and persistent, therefore the fog or low visibility phenomena are decreasing, On the other hand these interactions are interlinked from surface boundary layer to mid and upper troposphere local, regional and global levels. Thus this work objective was two fold, one was to examine the low occurrence of fog events during the winter season 2021-22 and other advanced BTD capability of INSAT-3D/3DR Imager thresholds variation at different regions of Indian domain.

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Disclaimer : The contents and views expressed in this study are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

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