Analysis of fog and inversion characteristics over sub-urban Bangalore

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सार – बेंगलुरु में कोहरे की घटना सर्दियों की एक विशेषता है, एक प्रक्रिया जो मानव स्वास्थ्य के साथ कई आर्थिक क्षेत्रो को प्रभावित करती है। इस अध्ययन में जनवरी 2009 से दिसंबर 2019 तक 11 वर्षों की अवधि के कोहरे के विश्लेषण जैसे- कोहरे की आवृति, कोहरे के घंटों की संख्या, शुरुआत / फैलाव का समय, उच्च घनत्व अंतरा-प्रति घंटा डेटा (अक्टूबर से मार्च) की तीव्रता के लिए एक व्यापक दृष्टिकोण अपनाया गया है। साथ ही दो संगामी मौसम घटनाओं के बीच संबंध स्थापित करने के लिए निशा प्रतिलोमित प्राचलों (प्रतिलोमित बेस की ऊंचाई, टॉप, डेप्थ और स्ट्रेंथ) और कोहरे / बिना कोहरे के दिनों की जांच की गई। अध्ययन की समय सीमा में दिसंबर में 129 और जनवरी में 126 कोहरे की घटनाएं दर्ज की गई, जबकि अक्टूबर, नवंबर, फरवरी और मार्च में क्रमशः 33, 96, 44, 11 रिपोर्ट की गई। इसी तरह, दिसंबर और जनवरी में अधिकतम कोहरे के घंटे रिपोर्ट किए गए। 80% से अधिक कोहरे की घटना 2200 से 0200 यूटीसी के बीच रिपोर्ट की गई जिनमें 0100-0129 यूटीसी स्लॉट में अधिकतम (74) और 0000-0400 यूटीसी के बीच रही। तीव्रतावार उथले कोहरे की सबसे अधिक आवृति (51%) रही जबकि मध्यम, घने, बहुत-घने की क्रमशः 29%, 19.6% और 0.4% की आवृति रही। बेंगलुरु में, पूरे वर्ष में एलीवेटेड - प्रतिलोमन आम घटनाएँ हैं जबकि सतह प्रतिलोमन सर्दियों में अधिक होते हैं। इस अध्ययन से पता चला कि कोहरे-प्रतिलोमन युग्मन के अनुसार, एलिवेटेड - प्रतिलोमन प्राचल कोहरे और बिना कोहरे के दिनों की तुलना में स्पष्ट अंतर दर्शाते हैं।

ABSTRACT. The occurrence of fog in Bengaluru is a perennial feature observed during winter, a phenomenon that affects several economic sectors and human health. This study takes a comprehensive approach for the analysis of fog attributes *viz.*, frequency of occurrence, numbers of fog hours, time of onset/dispersal, intensity with high-density intra-hourly data (October to March) for a period of 11 years from January 2009 to December 2019. Also, the characteristics of nocturnal inversion parameters (Height of Inversion Base, Top, Depth and Strength) have been examined on the days with/without fog to establish a relationship between the two concurring meteorological phenomena. In the studied time frame December reported 129 and January 126 fog events while October, November, February and March reported 33, 96, 44, 11 events respectively. Similarly, December and January accounted for maximum fog hours. More than 80% of fog events were reported between 2200 to 0200 UTC with maximum (74) in 0100-0129 UTC slot and dispersed between 0000-0400 UTC. Intensity wise Shallow fog is most frequent (51%) while Moderate, Dens, Very-Dense have a frequency of 29%, 19.6% and 0.4% respectively. In Bengaluru, Elevated-Inversions are common occurrences throughout the year while Surface-Inversions are more frequent in the winter. In the study, Elevated-Inversion parameters produce a clear distinction when compared in regards to foggy and Non-foggy days emphasizing on the Fog-Inversion coupling.

Key words – Fog characteristics, Intensity fog, Atmospheric inversions, Fog-inversion coupling.

1. Introduction

Fog is the suspended condensate (water droplet or ice crystals) formed due to the cooling of water vapor in humid air near the surface (Gultepe *et al*., 2017). The blanket of this condensate can take various forms as Fog, Mist, or Haze all with different densities and spatial/ temporal extent depending on the regional topology and atmospheric conditions. According to the India Meteorological Department (IMD), the distinction between Fog, Mist and Haze is done based on visibility (and relative humidity in the case of mist/Haze). Dense fog events where visibility drops below 200 meters have high potential to disrupt the normal functioning of an urban region by hindering economic activities and causing pernicious ramifications for human health (Pagowski *et al*., 2004). To mitigate the Fog predicament, it has become imperative to undertake a scrupulous study of the meteorological processes about fog formation and analyze the factors directly/indirectly abetting the spread and persistence of such events.

Fog occurrence is the direct result of physical processes regulating the heat transfer between the land

surface and the adjacent atmosphere in a high humidity scenario. Hence, the way a landmass (or water-body) absorbs and releases heat and how that heat interacts with aerosol particles and vapor in the upper air, determines the nature of the fog (Tardif and Rasmussen, 2008; Meyer and Lala, 1990).

Bengaluru mainly observes radiative fog which occurs during the wee hours of the day and disperses with the sunrise (Bhowmik *et al*., 2004; Kutty *et al*., 2019). It persists for a maximum of 3-4 days at a time during winter/post-monsoon months and has entirely different characteristics from the fog observed over north India. Radiation fog is one of the most common fog types and as the name suggests, radiative cooling (convective and evaporative transfer of heat) in the early morning abets condensation and consequently formation of fog/dew near the land surface (Duynkerke, 1991).

The phenomenon of radiative cooling also results in the formation of inversion layers (specifically during winters), which can affect fog characteristics through the regulation of atmospheric stability (Suresh *et al*., 2007). An inversion is a situation when the ambient temperature increases with height (opposed to the expected decrease within the troposphere), its characteristics are defined by the mode of heat transfer between two thermodynamically separate entities (Baumbach, 2003). Inversions can be classified into two categories based on the height at which layers are formed, as Surface (formed at ground level, SI hereafter) and Elevated-Inversion (base is above ground, EI hereafter). Inversions are known to increase the atmospheric (thermal) stability resulting in the localization of particulate-matter/vapor in the atmosphere (Wahab *et al*., 2003). As aerosol/vapor concentration is a determining factor in fog formation and affects its density, it is reasonable to hypothesize that the behavior of EI & SI can have some influence on the fog occurrence and its properties.

The current study is aimed at understanding the association between fog and inversion occurrences by first analyzing characteristics of each phenomenon separately and then in tandem. Previous studies regarding the fog phenomenon in Bengaluru utilized hourly data sets and mainly focused on meteorological parameters such as ambient temperature, Relative humidity, Wind speed, soil moisture, etc. (Kutty *et al*., 2019; Mohapatra & Thulasi Das, 1998). Such an approach skipped the intra-hourly changes in the fog density limiting the sensitivity of the analysis. Also, the association of inversion and fog occurrence has not received much attention from the researchers. To develop a robust forecasting model, apprehension of the processes involved in transportation/ localization of vapor, heat and aerosol is essential and on

the same note, this study focuses on fog phenomenon and its relationship with inversion attributes.

Here Authors took a 2-step approach for data analysis: Step 1 is the analysis of fog and Radiosonde (RS) data separately followed by combined analyses of the two data sets for apprehending any overlap of inversion and fog events (and their features).

2.   Data and methodology

2.1. *Surface data*

The high frequency (Intra-hourly) surface climatological data for a period of 11 years from January 2009 to December 2019 has been collected from current weather books of Aerodrome Meteorological Office (AMO), Bengaluru (Station ID 43293). Fog day represents a day when at least one observation reported visibility <1000 m starting from 0000 UTC and a Fog event is characterized as a situation when visibility below 1000 m persists for at least 5 minutes. Here, Fog hours represents the cumulative time for which fog events occurred.

Fog events were further classified into four categories based on visibility as Very Dense, Dense, Moderate and Shallow (Jenamani *et al*., 2012).

(*i*)   Very Dense (< 50 m).

(*ii*)   Dense (≥ 50 and < 200).

(*iii*)   Moderate (≥ 200 and < 500).

(*iv*)   Shallow (≥ 500 and < 1000).

Based on the above classification month-wise Fog parameters, *viz*., frequency, duration, onset and dissipation times were calculated.

2.2. R*S/Upper air data*

Bengaluru (Station ID 43295) is an upper air station hence the data on the vertical profile of the atmosphere is available for two time-steps (0000 and 1200 UTC) for each day of ascension. This data was downloaded from the University of Wyoming website (http://weather.uwyo. edu/upperair/sounding.html) from January 2009 to December 2019.

For the inversion analysis, four parameters were selected, *viz*., Height of Inversion Base (HIB), Top (ceiling), Depth and Strength. Where HIB is the height at which temperature inversion starts, Top is the height at which it ceases, the Depth is the difference between the
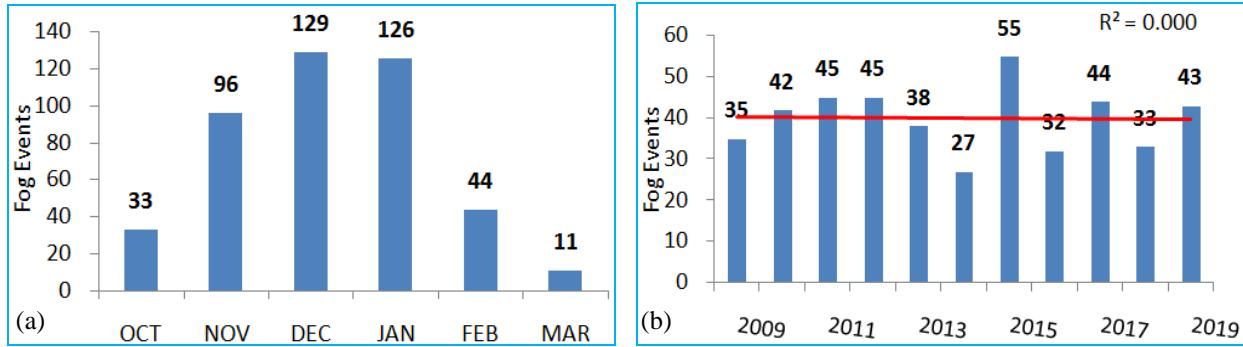
Figs. 1 (a&b). (a) Month-wise fog events and (b) year-wise fog events

top and HIB and Strength is defined in terms of the temperature difference between HIB and Top.

As mentioned earlier, using HIB inversions are classified into two categories as SI with HIB at 921 m AMSL and EI. Here inversions were also categorized based on unique/simultaneous occurrence as Only-Surface (soundings reporting only SI, O_{si} hereafter), Only-Elevated (soundings which reported only EI, O_{Elev} hereafter) and both (soundings which reported both SI and EI).

Inversion frequencies for each category were deduced with the equations given by Kahl *et al*. (1990).

$$N_{Inv} = N_{Osi} + N_{Oelev} + N_{Both} \qquad (1)$$

$$F_{Osurf} = N_{Osi} / N_{inv} \qquad (2)$$

$$F_{Oelev} = N_{Oelev} / N_{inv} \qquad (3)$$

$$F_{Both} = N_{Both} / N_{Both} \qquad (4)$$

$$F_{All} = N_{Inv} / N_{Sound} \qquad (5)$$

where, N_{sound}, N_{Inv}, N_{Osi}, N_{Oelev}, N_{Both} are the number of total soundings, soundings which reported inversions, soundings with O_{si}, soundings with O_{elev} and soundings reporting Both respectively. F_{Osbi}, F_{Oelev} and F_{Both} are the frequencies of the corresponding inversion types and F_{all} represents the frequency of inversion (all) occurrence. Since the Both category is not an actual (physical) inversion type, the total number of soundings which reported SI would be $N_{Osi} + N_{Both}$, similarly, for EI, the total would be given by $N_{Oelev} + N_{both}$. As fog occurs within the boundary layer, the calculations for inversion parameters were restricted to 700 hPa meaning, HIB and Top of EI were capped at 3080 m and 3500 m AMSL. Also, Isotherms have not been considered as a separate class and have been clubbed in the Surface or Elevated

category, besides isotherms of depth less than 10m and greater than 500 m were not included in the analysis.

It is important to note that two data stations under consideration namely, KIA and IMD Bangalore are about 30 km apart, still the rationale behind using such data sets for the comparative analysis is that these two stations have similar topographic characteristics associated to a semi-urban region with a considerable amount of greenery alongside built-up sectors. Moreover, as the RS balloon ascends, it drifts with the wind creating a vertical profile of the atmosphere corresponding to a region rather than a point (Fig. 5).

There are significant omissions in the availability of RS data and since Bengaluru observer's fog primarily in Jan and Dec, only these two months were considered for the analysis of inversion parameters on FG and NF Days, also for frequency analysis only years with full data sets were selected. Radiative fog mainly occurs at night hence, only 0000 UTC ascension data was included in the analysis. Atmospheric conditions can change rapidly during 0000 UTC, to maintain the fidelity of the results, only those RS ascension days were examined when fog event occurred or persisted within ±1 hour of 0000 UTC, also to ensure concurrence of the fog and RS readings, upper-air data from the same dates were considered if the fog event occurred between 0000-0100 UTC whereas if the fog event was reported between 2300-0000 UTC reading of the next day was selected.

3. Results and discussion

3.1. *Monthly and yearly frequencies of fog days, events and hours*

Table 1(a) indicates that a total of 439 fog events were reported in 470 foggy days (Figures in brackets are the number of fog-events). There is a difference between the number fog days and consequent fog events (days
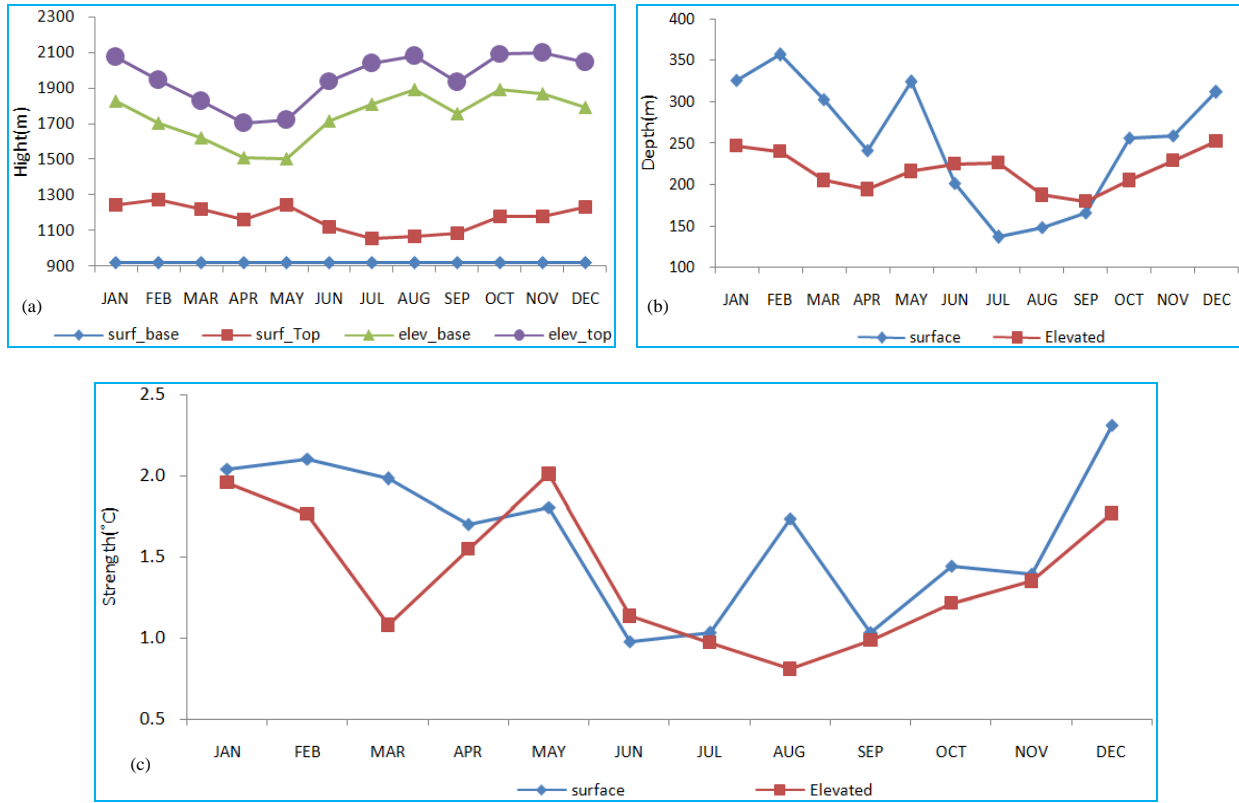
Figs. 2 (a-c). (a) Monthly inversion heights, (b) Monthly inversion depth and (c) Monthly inversion strength

being higher or lower compared to events) since certain days reported multiple fog events whereas some fog events persisted over more than one day. Here the maximum number of fog days (events) were reported in December (D) followed by January (J). During the 11 years, 142(136), 132(126) and 101(91) fog days (events) were reported in D and J and November respectively. Mohapatra and Thulasi Das (1997) used similar (but hourly) surface data for the period 1983-1993 and found that a total of 194 fog events occurred in the decade where maximum occurrences were in January followed by December. The considerable increment in fog frequency from 1983-93 to 2009-19 is expected and follows the trend of urbanization and land-use change, yet Linear trend analysis of the yearly fog data (within the decade; 2009-2019) shows a slight negative slope. Since the R^2 value is statistically insignificant [Figs. 2(a-c)] it can be inferred that there is no notable change in the decadal fog pattern but yearly fluctuation (specifically after 2013) does point towards the mercurial nature of fog events. In the studied period, total fog-events accounted for 894 hours and 45 minutes. Table 1(b) shows the number of hours of fog recorded each year. Fog hours are maximum in December followed by January.

3.2. *The intensity of fog*

In this section, fog is studied in terms of intensity which is differentiated into four categories as mentioned in Section 2. Table 2(a) shows year wise fog events in terms of intensity. Visibility can vary considerably within one fog event (Lasker *et al.*, 2013) hence it can contain several Intensity fog-events. Frequencies of such events are compiled in Table 2(b). Table 2(a) also represents that the maximum number of fog events have occurred in the year 2015 and the minimum in 2014, also Very-Dense fog is rare in Bengaluru reported only 5 times (events) in the years 2011 and 2013. Intensity wise shallow fog is the most frequent (51%) while Moderate, Dense and Very-Dense fog reported frequency of 29%, 20 and 0.4% respectively. December accounts for the highest number of Intensity fog events (33%) which are predominantly shallow (50%).

As compared to north India (Indo-Gangetic plane) where a fog-event can persist for several hours or even over multiple days Bengaluru mostly observes such events in short successions. The number of events during which fog persisted continuously for more than or equal to 4 hours is shown in Table 2(c), December and January

TABLE 1(a)

Total fog days (events)

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Total
Oct	2(2)	3(3)	6(6)	5(4)	2(2)	3(2)	9(9)	0(0)	1(1)	2(2)	3(2)	**36(33)**
Nov	13(15)	10(12)	8(6)	10(8)	11(8)	7(6)	7(7)	6(6)	9(7)	13(10)	13(11)	**107(96)**
Dec	10(11)	12(13)	15(14)	16(12)	12(10)	8(6)	16(18)	10(11)	18(17)	8(8)	11(9)	**136(129)**
Jan	7(7)	6(6)	14(14)	12(11)	17(15)	11(12)	14(13)	9(8)	13(12)	11(10)	18(18)	**132(126)**
Feb	0(0)	8(7)	5(5)	9(8)	3(3)	1(1)	5(5)	4(3)	8(7)	4(3)	3(2)	**50(44)**
Mar	0(0)	1(1)	0(0)	2(2)	0(0)	0(0)	3(3)	5(4)	0(0)	0(0)	1(1)	**12(11)**
Total	**32(35)**	**40(42)**	**48(45)**	**54(45)**	**45(38)**	**30(27)**	**54(55)**	**34(32)**	**49(44)**	**38(33)**	**49(43)**	**473(439)**

TABLE 1(b)

Total fog hours

Hr:Mn	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Total
Oct	2:04	3:20	7:03	5:01	0:37	4:11	11:21	0:00	2:56	2:09	4:07	**42:49**
Nov	35:20	11:08	12:21	21:15	19:21	11:42	16:55	10:38	16:49	18:41	18:03	**192:13**
Dec	18:21	40:07	47:06	34:59	24:31	13:07	47:03	24:17	32:04	15:12	16:24	**313:11**
Jan	13:15	10:40	29:33	19:23	37:17	15:59	23:06	17:03	26:42	20:22	43:38	**256:58**
Feb	0:00	16:13	5:50	10:22	6:00	0:46	7:23	7:27	12:43	6:54	2:20	**75:58**
Mar	0:00	1:30	0:00	1:49	0:00	0:00	1:33	8:26	0:00	0:00	0:18	**13:36**
Total	**69:00**	**82:58**	**101:53**	**92:49**	**87:46**	**45:45**	**107:21**	**67:51**	**91:14**	**63:18**	**84:50**	**894:45**

witnessed 28 and 12 such events respectively. The longest continuous fog event was recorded on 11th December, 2012 which persisted for 8 hours (from 2000 UTC on 11th to 0400 UTC on 12th).

3.3. *Onset and dissipation of fog*

Data on fog onset and dissipation is represented in half-hourly time-steps in Tables 3(a&b). More than 60% of the fog events started between 2300-0200 UTC (most of which, 74 occurred in 0100-0129 UTC time-step coinciding with the sunrise) followed by 0000-0029 and 0030-0059 UTC. Similarly, most dispersals were reported between 0300-0329 UTC. More than 80% of onset and disappearance happened in the 2200-0200 UTC and 0000-0400 UTC range respectively, supporting the radiative characteristics of fog over Bengaluru.

It is essential to note that the number of fog events suddenly dips just after 0129 UTC, also 50% of the fog events disappear between 0200-0329 UTC, which means that there is a small window of approximately 2 hours providing favorable condition for fog

formation starting just before the sunrise and ending soon after.

3.4. *Analysis of surface parameters*

It has been widely reported that Wind Speed and Relative Humidity significantly affect the characteristics of fog (Kutty *et al*., 2019; Sarkar & Goswami, 2017). Hence the same was studied to develop a better signature for the local fog. Taking advantage of the Intra-hourly data set, fog "Instances" were considered rather than "Events". Here an Instance implies any reporting less than 1000 m (a fog event can contain several reportings/Instances). In the time under consideration 3030 reportings were made out of which 16 were Very-Dense fogs, 1099 were Dense, 649 Moderate and 1266 were of Shallow category. Since the correlation between low Wind Speed (WS), high Relative Humidity (RH) and Fog has been already established by numerous studies (Pick *et al*., 1931; Ryznar *et al*., 1977), only RH & WS characteristics were determined concerning different fog densities.

TABLE 2(a)

Year-wise intensity fog events

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Total
VD_FOG	0	0	2	0	3	0	0	0	0	0	0	**5**
D_FOG	20	22	32	25	26	13	34	20	21	16	20	**249**
M_FOG	18	38	37	40	41	20	45	22	40	24	44	**369**
S_FOG	45	62	64	62	56	43	84	44	66	50	71	**647**
Total	**83**	**122**	**135**	**127**	**126**	**76**	**163**	**86**	**127**	**90**	**135**	**1270**

TABLE 2(b)

Month-wise intensity fog events

	Oct	Nov	Dec	Jan	Feb	Mar	Total
VD_FOG	0	0	2	3	0	0	5
D_FOG	7	49	83	79	24	7	249
M_FOG	17	71	118	115	41	7	369
S_FOG	41	148	201	176	65	16	647
Total	**65**	**268**	**404**	**373**	**130**	**30**	**1270**

TABLE 2(c)

Number of fog events persisting for ≥ 4 hours

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Dec	1	5	6	2	1	0	3	3	3	1	1
Jan	0	1	3	1	1	1	0	0	1	1	3

3.4.1. *Relative humidity*

RH data reflected that more than 92 percent (2805 out of 3030) of the fog instances occurred alongside 100% RH making it the most favorable category (irrespective of the density) besides, this trend reflects that there is minuscule variance in the RH values. Minimum RH was reported as 50%, which occurred on 15th October, 2009 (15 instances with RH < 90% were recorded, mostly associated with shallow fog). 2900 fog instances occurred between 98 and 100 percent RH range. It is interesting to note that within the same RH range multiple Fog Intensities were observed.

3.4.2. *Wind speed*

The same data set was used to determine the characteristics of wind speed. More than 90% of the fog Instances were reported when the wind speed was less than 3 m/s. Still, fog events occurred outside the 3 m/s mark, mostly dominated by shallow fog incidents. Very-Dense fog was found to have the smallest tolerance for WS in the category and was only reported when WS was less than 2.58 m/s. Maximum, Minimum and Mean values of the WS [Table 3(c)] denote that there is a considerable overlap among the categorical fog events and hence density wise distinction cannot be made solely based on the WS (and RH) values. It also suggests that some other mechanism (aerosol concentration) is also involved in determining the fog density, requiring further investigation.

3.5. *Inversion frequency*

The results of the monthly inversion frequency analysis are presented in Table 4. A total of 2327 soundings were conducted in the studied time frame, out of which 1629 soundings reported inversions (under

TABLE 3(a)

Onset timings of fog

Time (UTC)	0000 0029	0030 0059	0100 0129	0130 0159	0200 0229	0230 0259	0300 0329	0330 0359	1830 1859	1900 1929	1930 1959	2000 2029	2030 2059	2100 2129	2130 2159	2200 2229	2230 2259	2300 2329	2330 2359	Total
Oct	3	8	5	4	1	0	0	0	0	0	0	0	0	0	2	4	0	3	3	**33**
Nov	10	11	15	3	2	0	0	0	0	1	1	4	4	5	3	11	11	7	8	**96**
Dec	12	15	18	10	1	2	0	0	2	0	1	2	3	12	10	10	12	9	10	**129**
Jan	16	12	20	8	7	3	2	0	0	1	0	2	0	2	7	9	9	15	13	**126**
Feb	7	5	14	2	4	0	0	0	0	0	0	0	0	0	0	1	0	4	7	**44**
Mar	2	1	2	3	2	0	0	0	0	0	0	0	0	0	0	1	0	0	0	**11**
Total	**50**	**52**	**74**	**30**	**17**	**5**	**2**	**0**	**2**	**2**	**2**	**8**	**7**	**19**	**22**	**36**	**32**	**38**	**41**	**439**

TABLE 3(b)

Dissipation of fog

Time (UTC)	0000 0029	0030 0059	0100 0129	0130 0159	0200 0229	0230 0259	0300 0329	0330 0359	0400 0429	1830 1729	1930 1959	2000 2029	2030 2059	2100 2129	2130 2159	2200 2229	2230 2259	2300 2329	2330 2359	Total
Oct	3	0	6	5	8	4	3	0	0	0	0	0	0	0	0	0	2	0	2	**33**
Nov	3	4	4	11	17	16	16	3	2	0	1	0	1	2	2	3	3	5	3	**96**
Dec	6	3	7	12	20	16	22	10	8	3	1	1	0	1	2	3	4	4	6	**129**
Jan	6	3	5	4	15	25	29	21	1	0	1	0	0	0	3	3	2	5	3	**126**
Feb	4	0	2	5	9	9	12	2	1	0	0	0	0	0	0	0	0	0	0	**44**
Mar	0	0	1	1	4	2	3	0	0	0	0	0	0	0	0	0	0	0	0	**11**
Total	**22**	**10**	**25**	**38**	**73**	**72**	**85**	**36**	**12**	**3**	**3**	**1**	**1**	**3**	**7**	**9**	**11**	**14**	**14**	**439**

TABLE 3(c)

Wind speed distribution

WS(m/s)	Mean	Max	Min	SD
VD Fog	1.32	2.57	0	0.7
D Fog	1.32	4.12	0	0.92
M Fog	1.58	4.63	0	0.94
S Fog	1.62	4.62	0	0.98

700 hPa). These 1629 inversions constituted of 331 O_{si}, 1022 O_{Elev} and 276 both sub-categories. Data revealed that EI is the dominant type throughout the year in Bengaluru whereas SI primarily prevails between October and March.

January reported the highest number (~90%) soundings with inversions. Soundings with the least number of inversions were observed between July and September (~46%). The frequency of O_{si} is maximum in October followed by March whereas O_{Elev} attained maxima in May. Both (category) inversions are most frequent in October and March. As mentioned earlier EI are dominant throughout the year and maximum frequencies of O_{Elev} were recorded in summer (O_{Elev} + Both).

3.6. *Inversion parameters*

Mean Heights of Base and Top of the respective inversions (excluding base of SI which is fixed at 921 m) almost create a mirror image in the monsoon (June, July, August and September) season where EI reported maximum and SI minimum values [Fig. 2(a)].

TABLE 4

Monthly inversion frequencies

Month	N_{Osi}	N_{Oelev}	N_{Both}	N_{Inv}	N_{Sound}	F_{Osi}	F_{Oelev}	F_{Both}	F_{All}
Jan	15	89	45	149	166	10.1	59.7	30.2	89.8
Feb	34	78	27	139	156	24.5	56.1	19.4	89.1
Mar	47	62	21	130	170	36.2	47.7	16.2	76.5
Apr	28	94	8	130	197	21.5	72.3	6.2	66.0
May	25	113	24	162	187	15.4	69.8	14.8	86.6
Jun	15	93	18	126	188	11.9	73.8	14.3	67.0
Jul	15	64	11	90	182	16.7	71.1	12.2	49.5
Aug	15	79	9	103	208	14.6	76.7	8.7	49.5
Sep	27	81	18	126	254	21.4	64.3	14.3	49.6
Oct	58	76	34	168	227	34.5	45.2	20.2	74.0
Nov	29	82	28	139	194	20.9	59.0	20.1	71.6
Dec	23	111	33	167	198	13.8	66.5	19.8	84.3

These results are in agreement with the study conducted by Abdul-Wahab and Sabah (2003). In winters calmer ambient conditions allow SI to occur, whereas strong advection and turbulent mixing in the summer season resists the same.

Depth and Strength [Figs. 2(b&c)] also support the pattern of strong SI characteristics during the colder months. An interesting observation can be made from the Fig. 2(b), EI Depth remains relatively constant compared to the fluctuations in the SI Depth which attains 3 maxima in January, May and December. SI parameters are particularly prolific in May. As Bengaluru doesn't observe any fog this time of the year it becomes clear that only inversion attributes cannot explain the whole scheme of fog formation.

3.7. *Analysis of inversion characteristics in regards to fog events and comparison between foggy and non-foggy days*
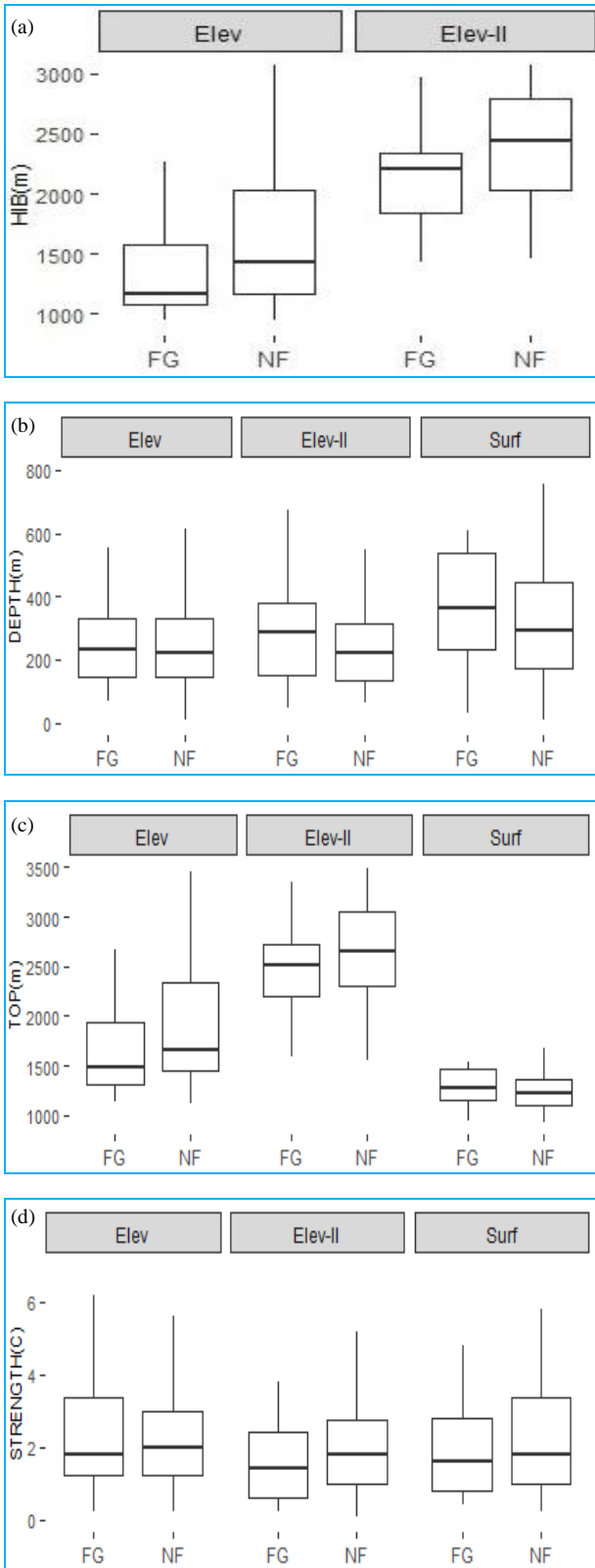
The key to establishing a relationship between inversion properties and fog formation lies within the common mechanism radiative cooling governing saturation of the air and vapor condensation.

The wide range of visibility/intensity being reported in the same time frame reflects the dynamic state of the atmosphere and hence ambient meteorological parameters change rapidly around 0100 UTC every day.
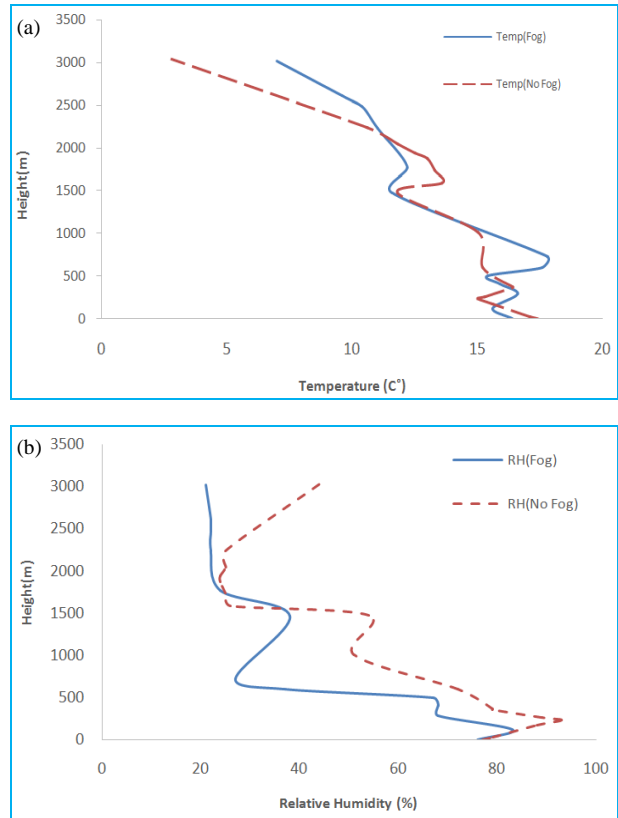
Inversions can induce atmospheric stability, trapping the vapor/aerosol content within the stagnated air parcel. This situation could be inducive for fog if the appropriate amount of liquid water content is available, if not the same situation can become detrimental by prohibiting moisture exchange (Sarkar and Goswami, 2017; Suresh *et al*., 2007).

Previous studies have addressed the issue and found that in most cases a combination of radiative cooling of the surface and turbulent mixing of adjacent air parcel was essential for the development of radiative fog (Roach *et al*., 1976; Nakanishi, 2000; Terradellas *et al*., 2008). As the land surface warms up at the time of sunrise, the nocturnal inversion is shattered by turbulent heat flux leading to a quasi-stable state of the atmosphere just above the landmass. This turbulence abets the mixing of vapor/aerosol content in the air parcel and when combined with latent heat flux causes saturation of air resulting in the formation of fog (Duynkerke, 1991). Here wind plays a crucial role as it can promote the mixing but only under specific intensity. Several studies have emphasized on the Light/Weak wind as a predominant condition related to radiation fog (Kutty *et al*., 2019; Sarkar and Goswami, 2017), the wind which is strong enough to abet the mixing but not too strong to remove moisture from the air parcel. The same has been reflected by the data analysis in section 3d.

Out of 255 fog events reported in Jan and Dec, only 68 occurred within the range of ±1 hour from 0000 UTC

Figs. 4 (a&b). Vertical profile of (a) temperature (b) relative humidity on 22nd, 23rd January, 2019

Figs. 3 (a-d). (a) HIB analysis, (b) inversion depth analysis, (c) inversion top (ceiling) analysis and (d) inversion strength analysis

and had corresponding RS data available. Here the number of O_{sbi}, O_{elev} and both were 6, 47 and 15 respectively. Since a single RS assent can observe multiple EI the category can further be reduced into subcategories of single EI (23) and two consecutive EI (24). It's evident from the data that EI (alone or in some combination of the abovementioned categories) plays a crucial role in the emergence and persistence of radiative fog.

To further understand the effects of inversion on fog events, characteristics of inversion parameters were analyzed in tandem FG and NF days. Isothermal layers were not included in the analysis to ensure a clear description of the features. Several days reported more than one EI within the limits of 3500 m ceiling level, such inversions have been analyzed separately as Elev denoting 1st (or only EI) and Elev-II representing the second EI layer. Few days even recorded a third layer but their numbers were statistically insignificant to include a separate category. The results of the analysis are presented in Figs. 3(a-d). FG observed relatively lower mean values for HIB, Top and Strength (HIB reflecting most prominent distinction) whereas Depth was greater for FG than NF.
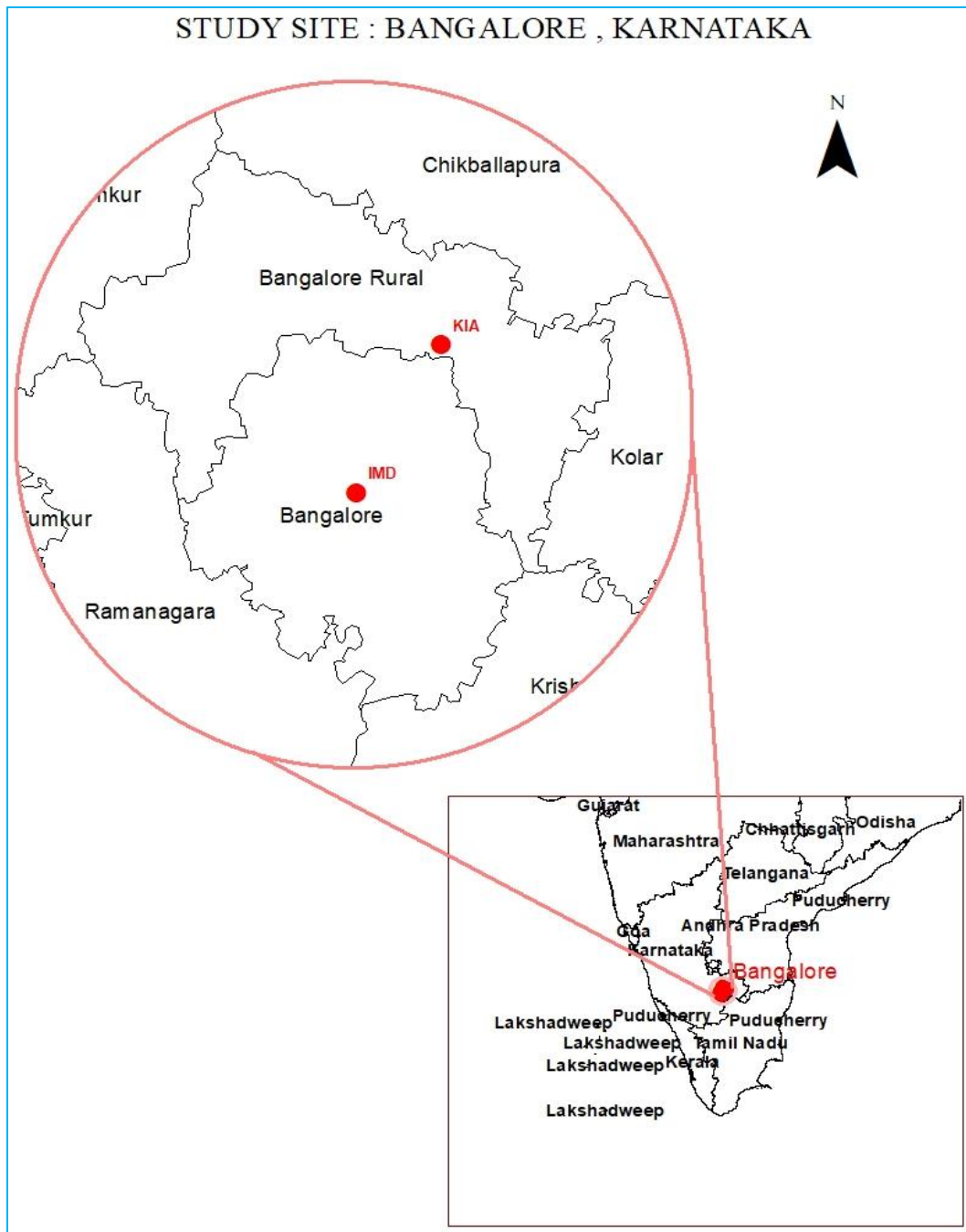
Fig. 5. Study site

3.8. *Comparison of inversion Profiles on 22ⁿᵈ January (FG) and 23 January (NF), 2019*

Vertical profiles w. r. t. temperature and RH for the dates under considerations are represented in Figs. 4(a&b) respective. On 21ˢᵗ January, 2019 Fog event was reported at 2312 UTC and Persisted for approximately 4 hours, till 0340 UTC of the next day. Hence for the analysis, RS data

of 22ⁿᵈ January, 0000 UTC was considered. Starting from 2312 UTC to 0100 UTC (±1 hr from RS ascension) visibility varied between 50 to 800 meters with RH (surface) remaining close to 100% and WS (surface) being reported under 2.5 m/s. On the Foggy Day two successive EI were observed under 1000 m, first (relatively weaker) beginning at 125 m (above ground level) with a Depth of 166 m and Strength of 1 °C, the second originated

at 501 m with Depth and considerable Strength of 223 m and 2.4 °C respectively. Such a combination of consecutive inversion profiles supports the hypothesis of quasi-stable atmospheric conditions being conducive to fog formation. In contrast, the non-foggy day witnessed single EI within 1000 m emerging at 233 m with a slight Depth of 139 m and Strength of 1.4 °C. Also, on 23rd (NF) the laps rate just before inversion was 10.30 °C/km whereas on 22nd (FG) the same was observed as 6.4 °C/km. RH curves also support the contrasting narrative between foggy and non-foggy days with RH (on 22nd) recording small increment coinciding with the advent of the first inversion followed by a sharp decrease at 600 m, on the contrary 23rd witnessed a sharp increment of RH at first accompanied by a relative gradual decrease with height.

4. Conclusions

Though the data available was not ideal some important assertions can be made from the results:

(*i*) December and January account for most of the Fog events in Bengaluru with the majority of them (76%) lasting for 0-180 min, some persisted for 5-6 hours. The longest duration fog event was reported on 11th December, 2012 (8 hours).

(*ii*) Intensity wise Very-Dense fog is rare and shallow fog is the most common type closely followed by Dense fog (in both, frequency and hours).

(*iii*) EI are common throughout the year while SI predominantly manifest during the winter season. They exhibit unique characteristics for each month.

(*iv*) For most days Bengaluru observes multiple inversions and most of the fog events coincide with EI (single/multiple layers).

(*v*) A viable distinction was observed in the characteristics of inversion parameters on FG and NF days validating coupling/interaction between the two phenomena, still further exploration is required to draw any robust conclusion.

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Disclaimer

The contents and views expressed in this research paper/article are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

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