Analysis of fog and inversion characteristics over sub-urban Bangalore

ARNAV SHUKLA and GEETA AGNIHOTRI
Meteorological Centre, India Met. Department, MoES, Bangalore – 560 001, India
(Received 8 May 2020, Accepted 13 October 2020)

e mail : arnav576@gmail.com

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 2020. 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 0100-0200 UTC slot and dispersed between 0000-0400 UTC. Intensity wise Shallow fog is most frequent (51%) while Moderate, Dense, 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 (Bhownik 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 & Thulasidas, 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. RS/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
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\(_{\text{SI}}\) hereafter), Only-Elevated (soundings which reported only EI, O\(_{\text{Elev}}\) 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).

\[
N_{\text{inv}} = N_{\text{Osi}} + N_{\text{Oelev}} + N_{\text{Both}} \tag{1}
\]

\[
F_{\text{Osurf}} = N_{\text{Osi}} / N_{\text{inv}} \tag{2}
\]

\[
F_{\text{Oelev}} = N_{\text{Oelev}} / N_{\text{inv}} \tag{3}
\]

\[
F_{\text{Both}} = N_{\text{Both}} / N_{\text{Both}} \tag{4}
\]

\[
F_{\text{All}} = N_{\text{inv}} / N_{\text{Sound}} \tag{5}
\]

where, \(N_{\text{Sound}}\), \(N_{\text{inv}}\), \(N_{\text{Osi}}\), \(N_{\text{Oelev}}\) and \(N_{\text{Both}}\) are the number of total soundings, soundings which reported inversions, soundings with \(O_{\text{SI}}\), soundings with \(O_{\text{Elev}}\) and soundings reporting both, respectively. \(F_{Osurf}\), \(F_{Oelev}\), 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 \(N_{\text{Osi}} + N_{\text{Both}}\), similarly, for EI, the total would be given by \(N_{\text{Oelev}} + N_{\text{Both}}\). 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
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 occur 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 R² 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 | 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.
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
700 hPa). These 1629 inversions constituted of 331 O\textsubscript{e}, 1022 O\textsubscript{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\textsubscript{e} is maximum in October followed by March whereas O\textsubscript{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\textsubscript{Elev} were recorded in summer (O\textsubscript{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 3(a) | Onset timings of fog |
|-------------|----------------------|
| Time (UTC) | Oct 0000 0030 0100 0130 0200 0230 0300 0330 0400 0430 0500 0530 0600 0630 0700 0730 0800 0830 0900 0930 1000 1030 1100 1130 1200 1230 1300 1330 1400 1430 1500 1530 1600 1630 1700 1730 1800 1830 1900 1930 2000 2030 2100 2130 2200 2230 2300 2330 2359 Total Oct 3 8 5 4 1 0 0 0 0 0 0 0 0 0 0 0 1 0 2 0 3 3 31 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 3 9 15 13 126 Feb 7 5 14 2 4 0 0 0 0 0 0 0 0 0 0 1 0 4 4 144 Mar 2 1 2 3 2 0 0 0 0 0 0 0 1 0 0 0 1 11 | TABLE 3(b) | Dissipation of fog |
|-------------|----------------------|
| Time (UTC) | Oct 0000 0030 0100 0130 0200 0230 0300 0330 0400 0430 0500 0530 0600 0630 0700 0730 0800 0830 0900 0930 1000 1030 1100 1130 1200 1230 1300 1330 1400 1430 1500 1530 1600 1630 1700 1730 1800 1830 1900 1930 2000 2030 2100 2130 2200 2230 2300 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 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 | TABLE 3(c) | Wind speed distribution |
|-------------|----------------------|
| WS (m/s) | 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 |
TABLE 4

Monthly inversion frequencies

| Month | N_{Osi} | N_{oce} | N_{both} | N_{rev} | N_{band} | F_{Osi} | F_{oce} | 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      | 89.1  |
| May   | 25     | 113    | 24       | 162    | 187      | 15.4   | 69.8   | 19.4     | 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 inductive 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
Fig. 3 (a-d). (a) HIB analysis, (b) inversion depth analysis, (c) inversion top (ceiling) analysis and (d) inversion strength analysis.

Fig. 4 (a&b). Vertical profile of (a) temperature (b) relative humidity on 22nd, 23rd January, 2019 and had corresponding RS data available. Here the number of $O_{\text{sh}}$, $O_{\text{elev}}$ 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.
3.8. Comparison of inversion Profiles on 22\textsuperscript{nd} 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 21\textsuperscript{st} 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 22\textsuperscript{nd} 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 lapse 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.

Acknowledgement

We acknowledge the limitations of this study as several factors involved in the mechanism of fog occurrence were not addressed, this undertaking is aimed at a humble exploration of the possible interaction between the two above mentioned meteorological phenomenon and determine whether inversion parameters can influence fog occurrence and its characteristics. Both of the physical phenomena are dynamic processes that cannot be effectively compared based on a single time-step. We hope this study would open a door for further investigation of the Fog-Inversion coupling. Authors are also grateful for the invaluable feedbacks from the referees without which this publication wouldn't have been possible.

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.

References

Abdul Wahab, S. A., 2003, “Analysis of thermal inversions in the Khareef Salalah region in the Sultanate of Oman”, Journal of Geophysical Research : Atmospheres, 108, (D9).

Baumbach, G. and Vogt, U., 2003, “Influence of inversion layers on the distribution of air pollutants in urban areas”, Water, Air, & Soil Pollution : Focus, 3, 5-6, 65-76.

Bhowmik, S. K. R., Sud, A. M. and Singh, C., 2004, “Forecasting fog over Delhi-An objective method”, MAUSAM, 55, 2, 313-322.

Duynkerke, P. G., 1991, “Radiation fog: A comparison of model simulation with detailed observations”, Monthly Weather Review, 119, 2, 324-341.

Gultepe, I., Heymsfield, A. J., Gallagher, M., Ickes, L. and Baumgardner, D., 2017, “Ice fog: The current state of knowledge and future challenges”, Meteorological Monographs, 58, 4.1-4.24.

Jenamani, R. K. and Kalsi, A. R., 2012, “Micro-climatic study and trend analysis of fog characteristics at IGI airport New Delhi using hourly data (1981-2005)”, MAUSAM, 63, 2, 203-218.

Kahl, J. D., 1990, “Characteristics of the low-level temperature inversion along the Alaskan Arctic coast”, International Journal of Climatology, 10, 5, 537-548.

Kutty, S. G., Agnihotri, G., Dimri, A. P. and Gultepe, I., 2019, “Fog occurrence and associated meteorological factors over Kempegowda International Airport, India”, Pure and Applied Geophysics, 176, 5, 2179-2190.

Laskar, S. I., Roy Bhowmik, S. K. and Sinha, Y., 2013, “Some statistical characteristics of occurrence of fog over Patna airport”, MAUSAM, 64, 2, 345-350.

Meyer, Michael B. and Garland Lala, G., 1990, “Climatological aspects of radiation fog occurrence at Albany, New York”, Journal of Climate, 3, 5, 577-586.

Mohapatra, M. and Thulasidas, A., 1998, “Analysis and forecasting of fog over Bangalore airport”, MAUSAM, 49, 135-142.

Nakanishi, M., 2000, “Large-eddy simulation of radiation fog”, Boundary-layer meteorology, 94, 3, 461-493.

Pagowski, M., Gultepe, I. and King, P., 2004, “Analysis and modeling of an extremely dense fog event in southern Ontario”, Journal of Applied Meteorology, 43, 1, 3-16.

Pick, W. H., 1931, “A note on the relationship between fog and relative humidity”, Quarterly Journal of the Royal Meteorological Society, 57, 240, 288-295.
Roach, W. T., Brown, R., Caughey, S. J., Garland, J. A. and Readings, C. J., 1976, “The physics of radiation fog : I - A field study”, Quarterly Journal of the Royal Meteorological Society, 102, 432, 313-333.

Ryznar, E., 1977, “Advection-radiation fog near Lake Michigan”, Atmospheric Environment, 11, 5, 427-430.

Sarkar, S. and Goswami, P., 2007, “An Assessment of Forecast Skill of an Atmospheric Meso-scale Model in Simulating the Observed Contrasts in Meteorological Fields for Foggy and Non-foggy Days”, Pure and Applied Geophysics, 174, 7, 2827-2845.

Suresh, R., Janakiramayya, M. V. and Sukumar, E. R., 2007, “An account of fog over Chennai”, MAUSAM, 58, 4, 501-512.

Tardif, R. and Rasmussen, R. M., 2008, “Process-oriented analysis of environmental conditions associated with precipitation fog events in the New York City region”, Journal of Applied Meteorology and Climatology, 47, 6, 1681-1703.

Terradellas, E., Ferreres, E. and Soler, M. R., 2008, “Analysis of turbulence in fog episodes”, Advances in Science and Research, 2, 1, 31-34.