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Micro-climatic study and trend analysis of fog characteristics at IGI airport New Delhi using hourly data (1981-2005)

RAJENDRA KUMAR JENAMANI

India Meteorological Department, New Delhi

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e mails : rjenamani1@yahoo.co.in/rjenamani@hotmail.com

सार – इंदिरा गाँधी अंतर्राष्ट्रीय हवाई अड्डा, नई दिल्ली शीत ऋतु के दौरान सघन कोहरे की घटनाओं के कारण अत्यंत संवेदनशील होता है, जहाँ प्रतिदिन औसतन लगभग 675 उड़ानें आती हैं। इस शोध पत्र में इंदिरा गाँधी अंतर्राष्ट्रीय हवाई अड्डे में रिकॉर्ड किए 25 वर्षों (1981–2005) के घंटेवार दृश्यता आँकड़ों के आधार पर दिसंबर और जनवरी के लिए तीव्रता पर आधारित कोहरा जलवायविक सूचना तंत्र विकास करने का प्रयास किया गया है यदि किसी प्रकार की विविधता और प्रवृति रही तो उनके तीव्रता वाले वर्षों और उनकी तारीखों के साथ–साथ उनका विश्लेषण भी किया गया। इस प्रवृति में जलवायविक उतार चढ़ाव का पता लगाने के लिए 1964 में अब तक के आँकड़ों का भी उपयोग किया गया जिसमें बिना कोहरे की स्थितियों की विभिन्न अधिकतम दृश्यताओं को भी शामिल किया गया। इस अध्ययन में माध्यम से विमानन में उपयोग के लिए तैयार की गई विभिन्न महत्वपूर्ण कोहरा जलवायविकी सूचनाओं के अलावा, अत्यन्त महत्वपूर्ण बात यह है कि 1960 में प्रेक्षित किए गए दृश्यता में अधिक घंटों में असामान्य रूप से तेजी से कमी आई, जो घंटों के एक तीसवें से एक पचासवें भाग तक कम रहे, की तुलना में 1960 से अब तक दोनों महीनों में घने कोहरे (<200मी.) में तेजी से वृद्धि की प्रवृति देखी गई है जो 10 से बीस गुना तक अधिक है। इस प्रकार इंदिरा गाँधी अंतर्राष्ट्रीय हवाई अड्डा विश्व का एक ऐसा हवाई अड्डा बन गया है जहाँ इन दोनों महीनों में अच्छी दृश्यता (>5000मी.) की स्थिति मुश्किल से देखी जा सकती है। एयर ट्रैफिक और यात्रियों की संख्या में तीस प्रतिशत की अप्रत्याशित बड़ी वार्षिक वृद्धि को देखते हुए जो वर्तमान में भूमंडलीय औसत के 6 प्रतिशत है, इस प्रकार की दृश्यता की प्रवृति यह भी पुष्टि होती है कि यदि कैट–III ILS को पूरी तरह से कार्यान्वित नही किया गया तो शीत ऋतु में वर्तमान की तुलना में उड़ानों में देरी और यात्रियों की परेशानियाँ आने वाले दिनों में तेजी से बढ़ने वाली है। अंततः इस शोध पत्र में हमने विमानन और कोहरा पूर्वानुमान में उपयोग के लिए विभिन्न तीव्रताओं पर आधारित कोहरे के शुरू होने और कोहरे के खत्म होने के बेहतर अनुकूल जलवायविकी समय, कोहरे के लगातार रहने के घंटे, कोहरे की अवधि का भी आकलन किया है।

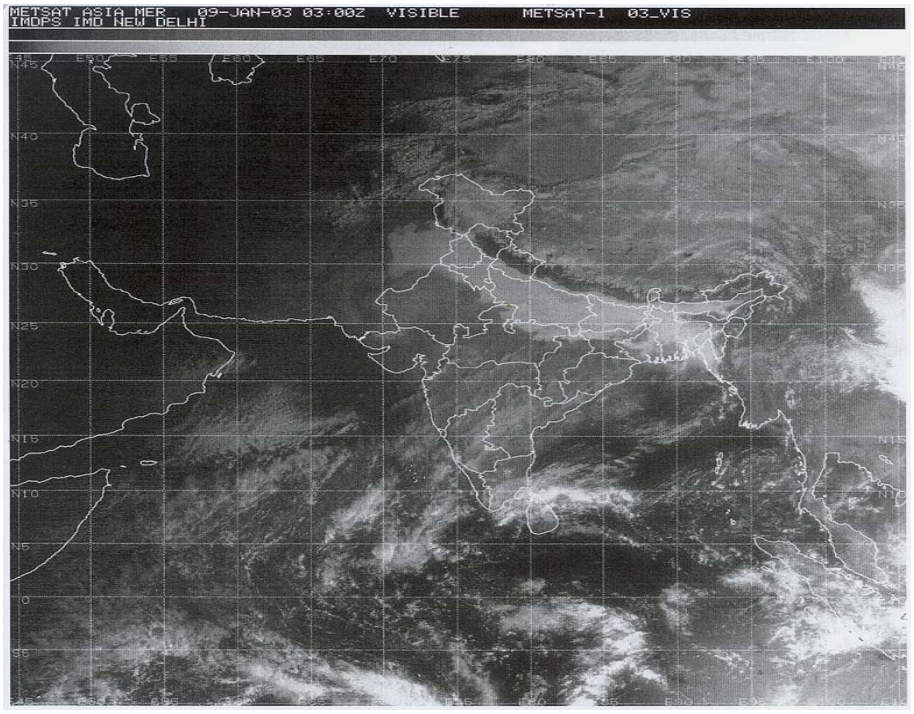
ABSTRACT. Indira Gandhi International (IGI) airport, New Delhi where near about 675 flights on an average depart and arrive daily, is highly susceptible to dense fog occurrences during the winter season. In the present paper, an attempt has been made for development of an intensity based fog climatological information system for December and January based on hourly visibility data of 25-years (1981-2005) recorded at IGI airport. Variations and trends if any were also analyzed along with their extreme years and dates of occurrences. Data since 1964 were also used to find climatic jumps in the trend which includes various higher visibilities of no fog conditions. Besides various vital fog climatological information generated through the present study for use in aviation, the most important finding is the alarming increasing trend of the dense fog (< 200m) occurrences in both the months up to as high as 10-20 times from 1960s in contrast to unusual drastic reduction of higher visibility hours to as low as one thirtieth to one fiftieth of hours which were observed in 1960s. Thus, finally making IGI airport, a unique airport in the world which hardly experiences good visibility conditions (>5000m) in both the months. By considering the unexpected huge annual growth of 30% in both air traffic and passengers that India including IGI has presently been experiencing against the global average of 6%, such visibility trend also confirms that present flight disruptions and passengers sufferings in winter will be aggravated more severely in days to come unless CAT-III ILS implemented fully. Finally, we have computed further number of consecutive hours, spell periodicity, most favorable climatological timing of fog onset and fog dispersal based on various intensities for use in aviation and fog forecasting.

Key words – Fog, Intensity, Extremes, Trends, Consecutive hours, Onset, Dispersals.

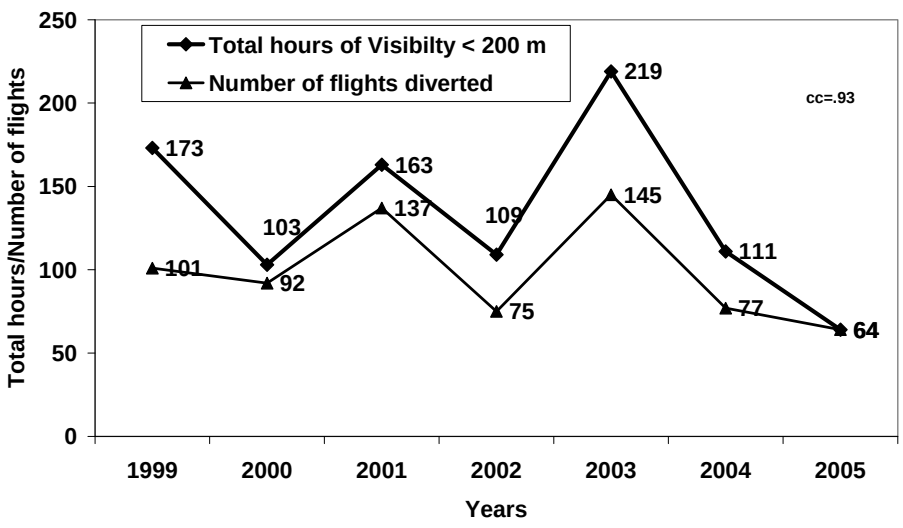
1. Introduction

Occurrence of dense fog during late in the night or early in the morning over northern parts of India is very common in winter. These fog occurrences many times remain so prolonged and well organized with large spatial extension over the region that it can be easily detected in satellite morning visible pictures as a very big white patch up to 1130 hrs (IST) [Figs. 1(a)] which may be rare in any other part of the world if one considers its unique larger spatial coverage. In every winter, flight take off/landing over the various airports of the region including at Indira

(a)



(b)



Figs. 1(a&b). INSAT pictures showing dense fog over part of North India (a) 0300 UTC, 9 January, 2003 and (b) Dense fog hours *vis-à-vis* flight diversion

Gandhi International (IGI) airport, New Delhi, which alone handles around 650 domestic and international flights are severely affected by their occurrences [Fig. 1(b)] for total number of flight diverted *vis-à-vis* total dense fog hours observed]. It also forces the authority at IGI airport during some occasions to close the airport for traffic in case very dense fog conditions prevails and visibility reaches to almost zero. With IGI airport handling an overcrowded traffic of average one flight at each 2-3 minute, by the time the sky opens up, return back to normalcy also takes few days because of the clearing of the huge backlog and waited passengers. Besides aviation, it also causes severe disruption to the ground transport, train services, damages winter crops, horticulture etc. Prolonged and frequent fog spells also cause the day temperature remains below 13° C

consecutively many days through obscuring the sky like clouds *e.g*., January 2003 and hence also hazardous to human health.

Since fog has very high damage potential to various sectors especially to aviations at IGI airport, it is very much necessary to develop an intensity and duration based fog micro-climatological information system for understanding fog occurrences at daily, monthly time scale, etc. at IGI at various visibility intensity ranges using their homogeneous longer period data. This will help various users *e.g*., Airport operator, Airlines, ATC etc., for understanding the vulnerability of the airport to various fog conditions *e.g*., shallow, moderate, dense fog etc., for implementing a better prepared mitigation plan *e.g*., CAT-III-ILS at various RWYs, winter special fog scheduled, making more pilot to be trained for CAT-III ILS, etc., before the start of each fog season. Various authors *e.g*., Singh *et al*. (1999), Singh and Kant (1999), Bhushan *et al*. (2003), Jenamani *et al*. (2004), Bhowmik *et al*. (2004), Singh and Kant (2006), Singh *et al*. (2007) etc. have attempted to study various aspects of fog occurrences over Delhi and adjoining North India during winter using either airport weather data or satellite data. But, there has not been any in-depth micro-climatic study/trend analysis of different fog climatological characteristics on the basis of its various visibility intensity ranges using standard longer period homogeneous visibility data. An attempt has been made in the present study, by analyzing hourly current weather data recorded at IGI airport for the main winter months of December and January for the 25-years period of 1981-2005, to prepare different micro-climatological characteristics of fog which are required for fog forecasting and aviation purposes. The main objective of the present study is to derive a complete intensity based fog climatological information system based on hourly visibility data. Their year to year variations and trend if any were also discussed along with their extreme values. Climatic jumps in the trends were also analyzed by considering 5-yearly averages using further longer period data available since 1964 which also include various higher visibilities of no fog conditions. Meteorological office at IGI Airport has responsibility to issue 6-hourly fog forecast, an outlook with validity for next 12 hours, landing type trend forecast with validity period of 2 hours, bulletins for LVP (low visibility procedures) to be used by IGI airport authority for making different CAT ILS available to pilots. These forecasts comprises of possibility of fog formation during the period, time of occurrence and time of dissipation of fog along with intensity etc. Since there is no accurate objective method available for forecasting of these characteristics of fog at IGI, we have further analyzed the present data for finding other micro-climatology features of fog *e.g*., number of consecutive hours, spell periodicity, timing of fog onset and fog dispersal on day-to-day at various visibility intensity ranges which may be used by the forecaster as climatological tips while writing the fog forecast for the airport.

2. Data and methodology

Current weather registers for the 25-years period of January 1981 till December 2005 of IGI airport archived in Regional Meteorological Center, New Delhi were collected and then hourly general visibility data are directly punched to the computer. Fog has been classified into following categories of different intensities as per visibility conditions of a particular hour: *General Fog* : If visibility <1000 meters; *Shallow Fog* : If visibility <1000 meters but ≥500; *Moderate Fog* : If visibility <500 meters but ≥ 200; *Dense Fog* : If visibility <200 meters but ≥50; *Very Dense Fog* : If visibility <50 meters. It may be noted that these different ranges of visibility classifications have been defined by keeping different CAT visibility range conditions as defined by ICAO which also allows implementation of different instrument guiding landing systems to the aircraft from the ATC as per gradual visibility reduction at the airport due to prevailing fog of different intensity.

A day is called as a foggy day *i.e*., a general fog day if at least one observation has reported visibility <1000 meters out of all hourly data of 24 observations a day starting from 0000 UTC of a date till 2300 UTC. Similarly, number of hours of a particular fog has been counted for day to day as per number of hours of reporting of visibility at a particular range as defined before. Only data of two months each *i.e*., 1992 and 1995 of December and 1995 and 1996 of January were not available. Some of these registers have been either misplaced or ceased due to official reasons. So total number of months for which all hourly data are available are 23 months for the December and January respectively *i.e*., a huge data record of $31 \times 23 \times 24 = 17112$ for each month. To find the impacts of these fog hours on flight operations, flight diversion data were also collected from AAI for both months for the period of 1999-2005. Correlation was calculated between monthly flight diversion data with frequency of occurrences of dense and very dense fog hours. It shows very high correlation of 0.93 between them with exactly year-to-year variation matching in both the curves in Fig. 1(b). Hence, these fog climatological data are very accurate which can be applied to aviation for various uses.

For determination of how many onset or dispersals have been taken place up to a particular time from evening to late nights or even upto early mornings starting from 1200 UTC onwards, we have computed cumulative % of total number of occurrences as per accumulated number of

TABLE 1

Monthly climatology of fog for the period 1981-2005 (S.D. is in bracket)

Month		General Fog visibility <1000 meters	Shallow Fog visibility <1000 meters but ≥500	Moderate Fog visibility <500 meters but ≥ 200	Dense Fog visibility <200 meters but ≥50	Very Dense Fog visibility <50 meters
Mean Days	December	23(5.4)	23(5.4)	10(5.9)	4(4.3)	5(4.1)
	January	24(4.7)	24(4.7)	13(6.4)	7(6.1)	8(5.3)
Mean Hours	December	233(95.6)	158(55.5)	41(29.2)	10(12.4)	24(32.6)
	January	221(100.4)	130(47..5)	40(30.7)	14(14.8)	36(31.8)

TABLE 2

Extreme occurrences of fog hours per day for the period 1981-2005 (Years and Dates are in the bracket)

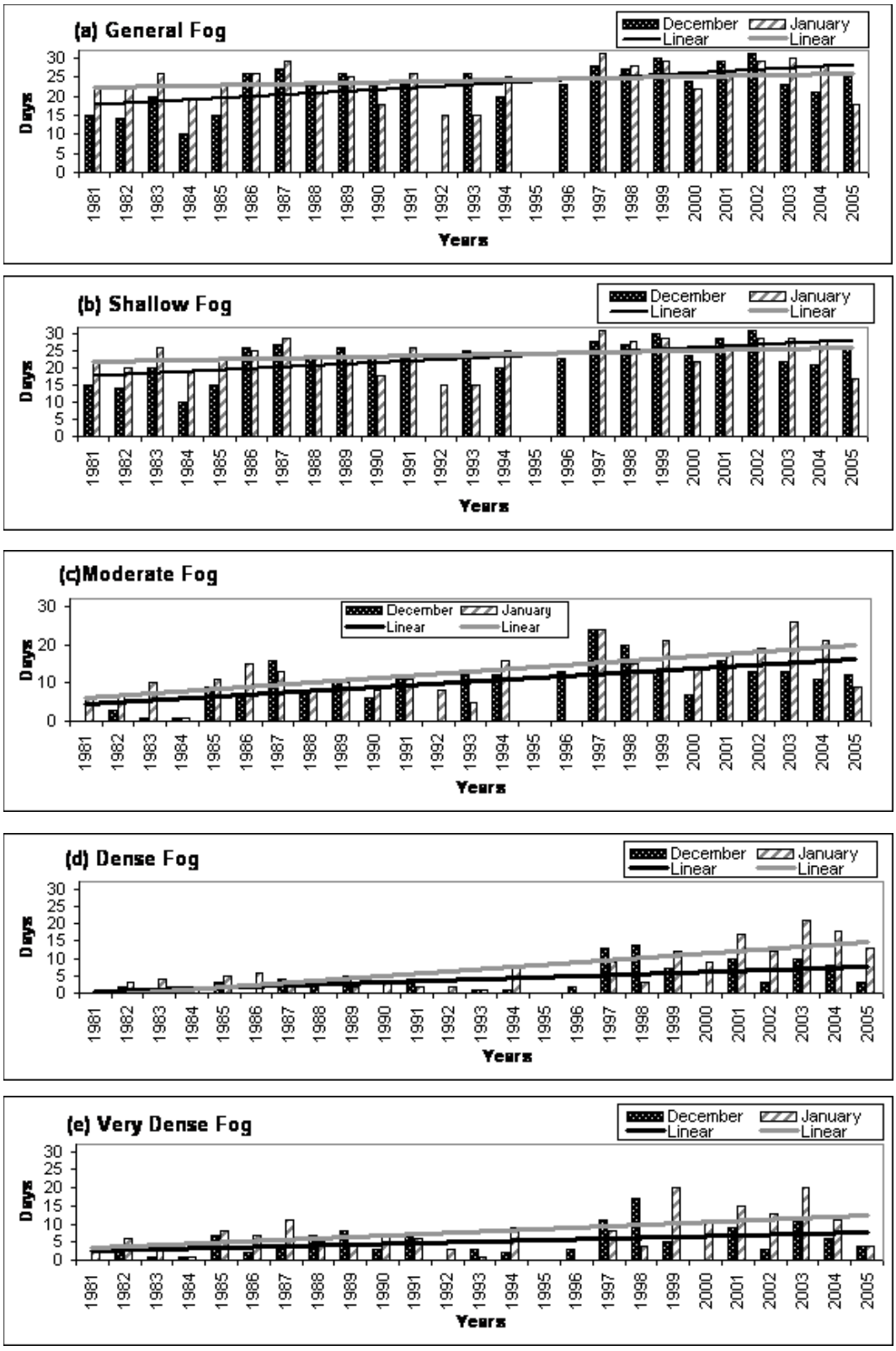
Month	General Fog	Shallow Fog	Moderate Fog	Dense Fog	Very Dense Fog
December	24 [1997(27, 28) ; 1998 (16, 19); 1999(31); 2001(28); 2003(27); 2005(23)]	20 [2005 (16)]	14 [1987(26)]	8 [2003(24)]	15 [1998(27); 1999(31)]
January	24 [1998(7,8); 2000(2,4,5); 2002(1); 2003(7,18)]	23 [2000(9)]	13 (1997(15)]	6 [2001(17); 2002(9); 2004(2, 25)	17 [2000(2)]

onset/dispersals takes place up to that time out of total number onsets/dispersals taken place in the considered data period. The most favorable time of onset/dispersals of fog is defined as a time when highest number of onset have taken place compared to their values of all other timings. Also, the favorable time period of onset/dispersals of fog is defined as time period during when cumulatively more than 85% of onset/dispersal of fog were completed. Fog normally starts setting over the airport at 2nd half of the day starting from evening till very early morning of next day as per local IST *i.e*., between 1200 UTC - 2300 UTC and dissipate at the 1st half of the days at early morning till noon of local IST *i.e*., between 0000 UTC - 1100 UTC. So for determination of climatological timing of fog onsets on a day, numbers of all new occurrences between 1200 UTC - 2300 UTC are calculated hour-wise by considering hourly frequencies of fog occurrences of all days of the month in December and January separately from 1200 UTC onwards till 2300. For determination of most favorable climatological timing of their dissipation, first the hour having highest number of their occurrences is determined from daily hourly occurrences between 0000 UTC - 1100 UTC and then their subsequent numbers of occurrences are subtracted from it to get the number of fog occurrences dissipated at that particular time. The method is repeated for subsequent hours till 1100 UTC or the hours when no fog reported. We did not consider fog of various intensities separately which we discussed before while discussing their onset or dispersal timing. However, except general fog, we have also considered onset of those fog types cumulatively which reduces the visibility at IGI to less than 500m and 50m corresponding to moderate to very dense and very dense fog respectively and *vice-versa*. For analyzing IGI airport's vulnerability to persistent fog coverage of various types which also includes dense and very dense fog, we have computed their consecutive hours by re-arranging their hourly visibility data on day to day from 1200 UTC of 1st till 1200 UTC of 2nd December, 1200 UTC of 2nd till 1200 UTC of 3rd December and so on to know how many hours the fog event of a particular intensity of that day has been continued from evening till forenoon of next day.

3. Results

3.1. *Monthly climatological features*

Table 1 shows monthly climatological occurrences of number of days and total hours of occurrences of various fog types along with variances in the month of December and January. It shows number of occurrences of 23 and 24 days of general fog as well as shallow fog in the month of December and January respectively while in case of very dense fog their occurrences substantially reduced to 5 and 8 days for respective months. Table 1 shows the number of total hours of occurrence of general (233 hours) and shallow fog (158 hours) are higher in December compared to January (221 and 130 hours respectively) in contrast to number of days as discussed



Figs. 2(a-e). Variation & linear trend of total number of days of fog of various intensities for the period 1981-2005

before with nearly same number of total hours for moderate fog in both the months (41 and 40 hours) respectively. However, total hours of dense and very dense fog occurrences are higher in January (14 and 36 hours respectively) compared to December (10 and 24 respectively). One can also note from Table 1 that average total hours of occurrence of very dense fog per month at IGI airport is more than two times of dense fog per month.

In case of variances of both total number of days and hours in the month from Table 1, one can find standard deviations of all types of fog days remain same with in 4-6 days in contrast to their mean being highly different while in case of total number of hours of various fog types, respective standard deviations values differ much from 12 hours of moderate fog to 100 hours for general fog per month. But, variance of number of hours of fog of respective intensities remains same if compared for respective months. Hence, it shows that more is the intensity of fog, lesser is the number of fog days and their total hours with presence of very high variations relative to their corresponding mean values. The variance with respect to means in latter cases are so high that even the standard deviations of dense fog and very dense fog during both months are higher than mean in most of these cases (Table 1).

Table 2 shows extreme dates when highest number of hours, a particular fog was observed. In case of general fog, these were experienced throughout the day for complete 24-hours for 7 days among all days covering 23 months of data for December during 1981-2005 *e.g*., 31 December, 1999, 28 December, 2001, 27 December, 2003 etc. with one case was having fog for consecutive days *i.e*., 48-hours period *e.g*., 27 and 28 December, 1997. For January (Table 2), general fog was experienced through out the day for complete 24-hours for 8 days among all days covering 23 months of data for January during 1981-2005 with 2 events (7-8 January, 1998 and 4-5 January, 2000) were having fog for consecutive days *i.e*., 48-hours period like that of December. Similarly, one can note from Table 2 about the occurrences of extreme fog conditions at other intensity ranges. In case of very dense fog which caused disruption for aviation service most, Table 2 shows their occurrences for December were as high as 15 hours on both dates of 27 December, 1998 and 31 December, 1999 while the highest number of hours of occurrence for January was on 2 January, 2000 with 17-hours.

3.2. *Interannual variations*

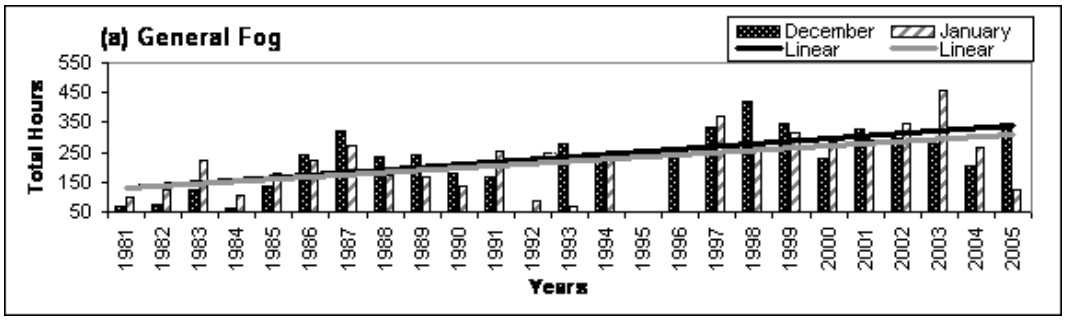
Figs. 2(a-e) and Figs. 3(a-e) show year to year variation of number of different categories fog days and their total hours along with linear trend analysis for December and January for the whole period. One can note the presence of very high increasing trends and year to year variability for almost all types of fog days and fog hours in Figs. 2 and 3. In Figs. 2(a-e), highest number of days of general, shallow, moderate, dense, very dense fog for the month of December for the period 1981-2005 are 31, 31, 24, 14, and 17 days in 2002, 2002, 1997, 1998, 1998 while their lowest values are 10, 10, 0, 0 and 0 days occurred during 1984, 1984, 1981, 1981(also in 1984, 86, 90, 2000), 1981 (also in 2000). Similarly in January, their highest values corresponding to various fog are 31, 31, 26, 21 and 20 days in 1997, 1997, 2003, 2003 and 2003 (also 1999) while lowest values are 15, 15, 1, 0 and 1 days in 1992 (also in 1993), 1992 (also in 1993), 1984, 1988, 1984 (also 1993) respectively.

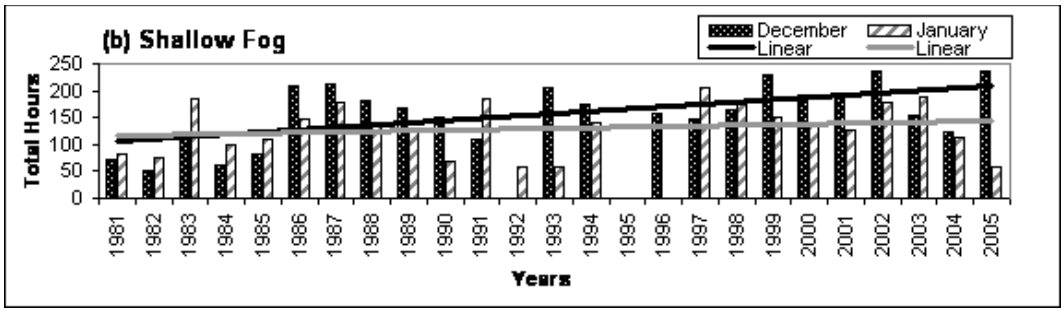
In case of year wise total number of hours of occurrences of various fog plotted in Figs. 3 (a-e) for both months, one can also note very high variability as highest number total hours of general, shallow, moderate, dense, very dense fog for December are 419, 238, 101, 41, and 158 hours in 1998, 2002, 1997, 1997 and 1998 while their lowest values are 64, 51, 0, 0 and 0 during 1984, 1982, 1981, 1981 (also in 1984, 86, 90, 2000), 1981(also in 2000). Similarly in January, their highest values corresponding to various fog are 459, 207, 119, 50 and 127 hours in 2003, 1997, 1997, 2001 and 2003 while lowest values are 70, 58, 2, 0 and 1 hour in 1993, 1992 (also in 1993, 2005), 1984, 1988 and 1984 respectively. From such huge difference of their extremes, one can note why the variability of fog from month to month at IGI airport could be very high in main winter months.

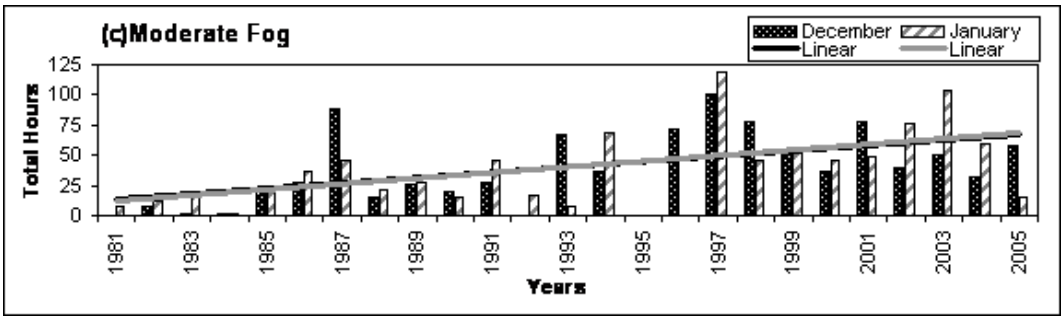
In case of total hours of very dense fog in Figs. 3(e), it may be noted that occurrence of higher values of very dense fog hours for both months are very much higher than dense fog hours [Fig. 3(d)]. Hence it shows fog intensifies quickly to become very dense fog once dense fog set in over IGI airport and remains for prolonged period than dense fog hours. It is very interesting to note from Figs. 2(a-e) and Figs. 3(a-e) about the presence of high linear increasing trend in almost all types of fog conditions during both of December and January for various fog types whether one considers their total days of occurrences or hours of occurrences since 1981 after fitting of linear trend lines for the period 1981-2005. We have discussed more about such trend characteristics in the following section.

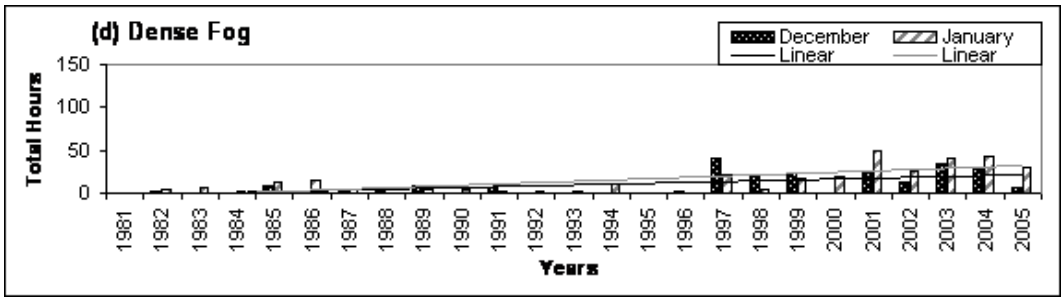
3.3. *Trend analysis for various Fog and higher visibility conditions*

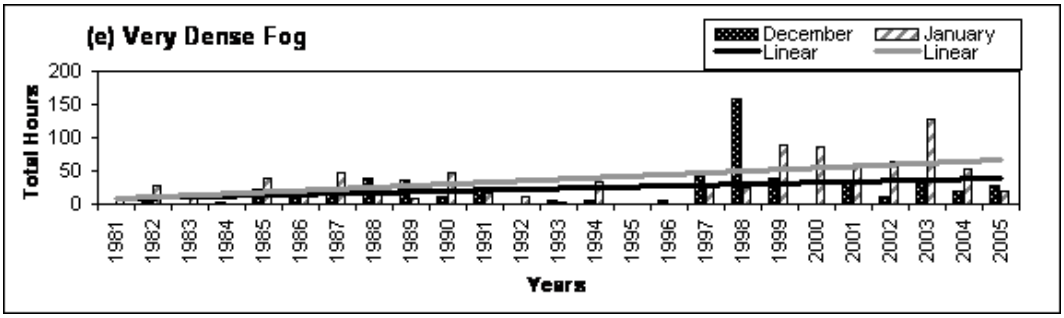
Using data from 1980s : Since increasing trends have been noticed in frequencies of occurrences of all most all types of fog conditions as has been indicated from Figs. 2(a-e) and Figs. 3(a-e) before, it is very much











Figs. 3 (a-e). Same as Figs. 2(a-e) but for their total number of hours

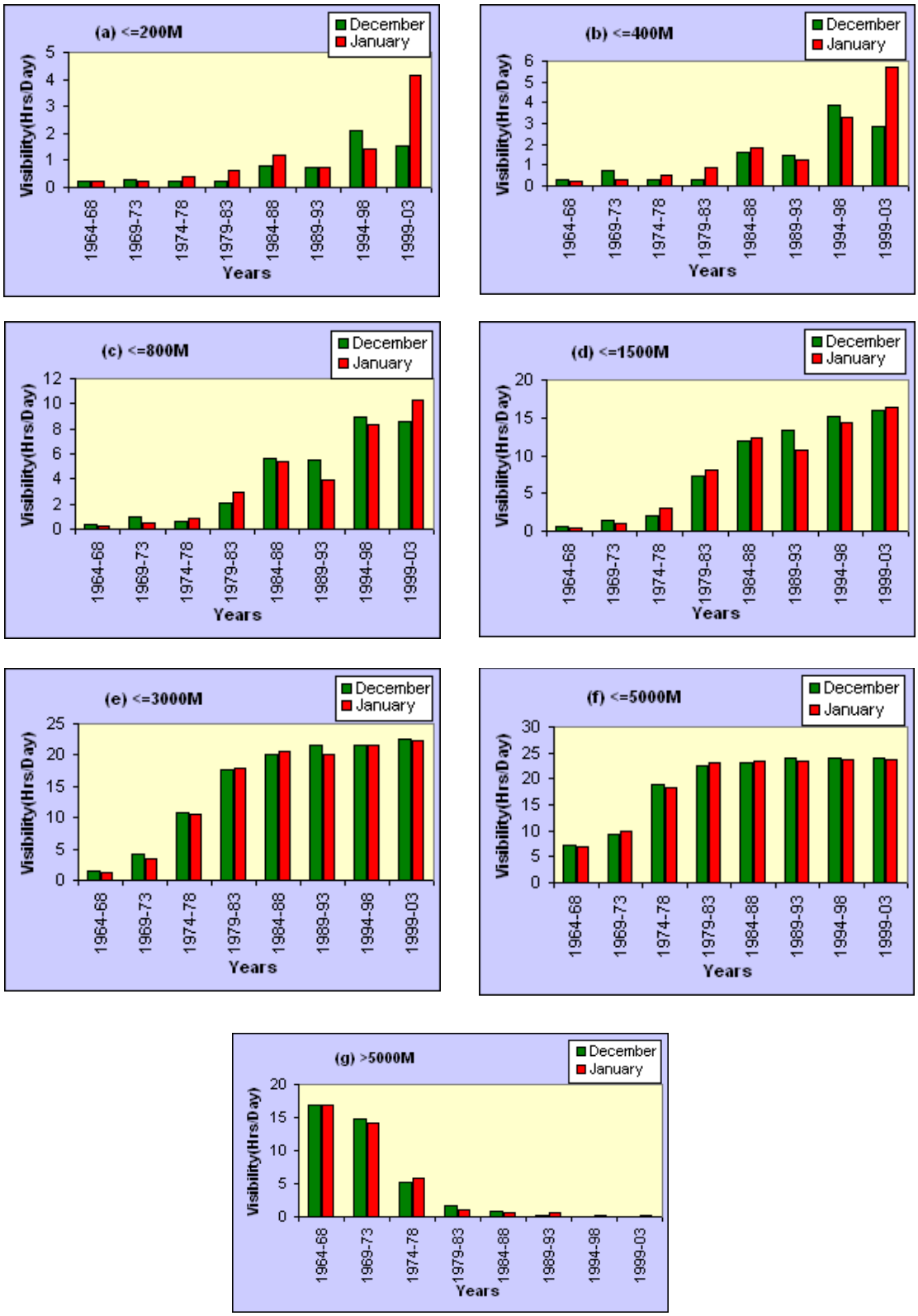
TABLE 3

Linear trend values for all types of fog for 1981-2005 (* denotes high /bold-low)

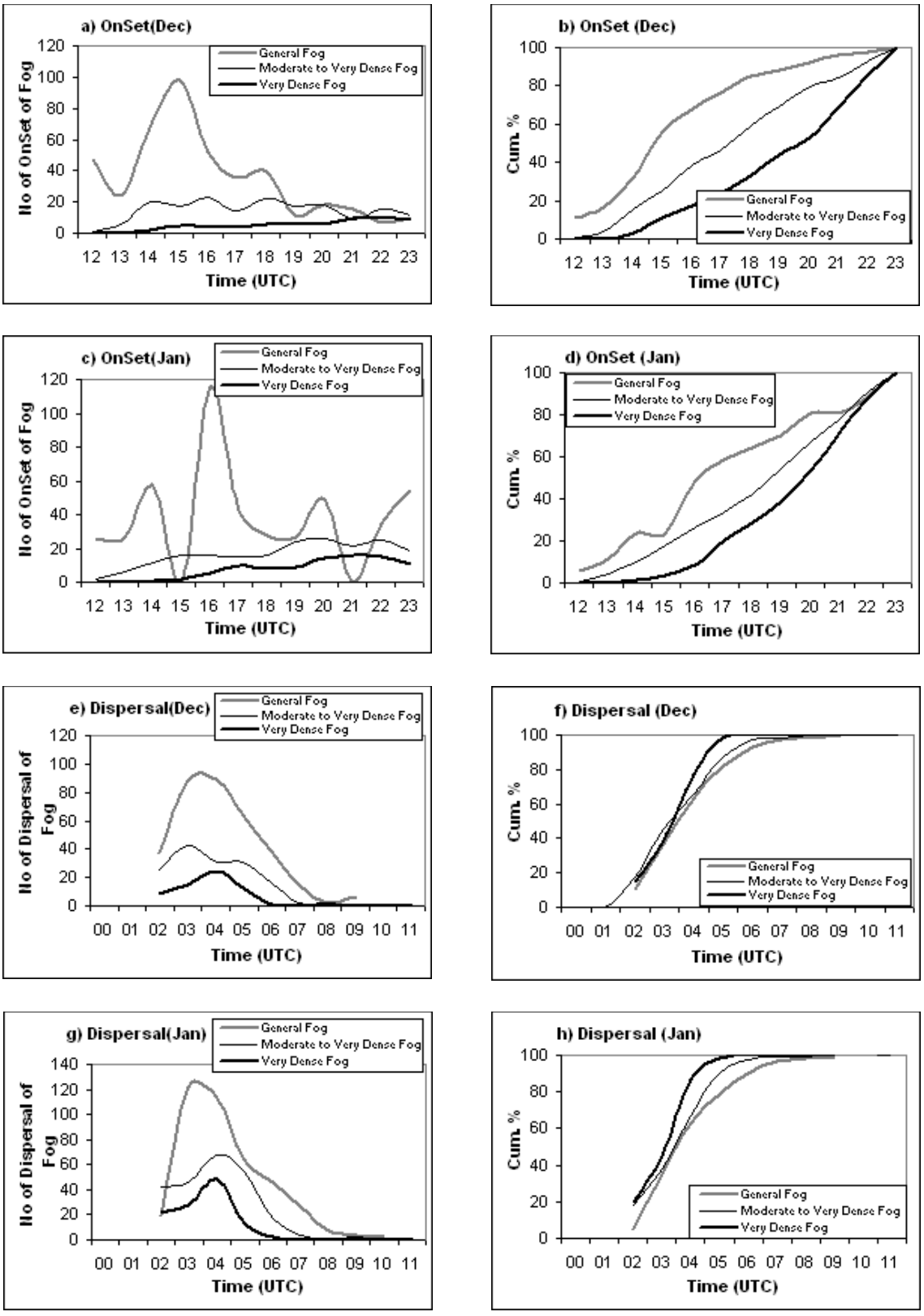
Fog category	Total trend				Trend per year			
	Days		Duration		Days		Duration	
	Dec	Jan	Dec	Jan	Dec	Jan	Dec	Jan
General Fog	10.5	4	205	180	0.46	**0.17**	8.91*	7.83*
Shallow Fog	10	4	100	25	0.43	**0.17**	4.35*	1.09
Moderate Fog	11.5	14	54	40	0.5	0.61	2.35	2.09
Dense Fog	7	15	22	33	**0.3**	0.65*	0.96	1.43
Very Dense Fog	4.5	9	28	63	**0.2**	0.39	1.22	2.74*

necessary to compute and compare their total trend or trend per year quantitatively to find which types of fog have highest trends and *vice-versa* which we have shown in Table 3. It shows high total trend values of 15 and 14 days in case of dense and moderate fog days for January respectively and 11.5 days for moderate fog occurrences in December with lowest total trend of 4 days in general and shallow fog days of January respectively. In case of total hours of occurrence of a particular type of fog in Table 3, it shows highest total trend values of 205 hours in case of general fog for December followed by 180 hours of general fog for January, 100 hours of shallow fog for December and 63 hours of very dense fog hours for January respectively with lowest total trend 22 hours of dense fog for December. Similarly, when we consider rate of trend from Table 3, it shows an increasing rate of trend of 1.22 and 2.74 hours per year for very dense fog hours and 0.96 and 1.43 hours per year for dense fog hours for the month of December, and January respectively which are a very much alarming for the future as landing and take off flights are likely to be affected more in coming years if the present rate of trend will continue. Analysis for foggy days of higher intensities *i.e.*, dense and very dense fog days and their total hours in both the month in Figs. 2(d&e) and Figs. 3 (d&e) which cause problems in aviation shows their less occurrence in contrast to presence of very higher occurrences of less intense fog categories (moderate and shallow fog) before 1996 in Figs. 2(a&b) and Figs. 3 (a&b) while corresponding intense fog occurrences are very much higher after 1996. Hence, it may be the case that the during the period of 1996-2002, flight operation must have been severely affected in the mornings for 15-20 days with every days averages of 3-4 hours per day due to occurrence of such very dense fog as visibility came down below 50 meters.

Using data available since 1960s - A comparison with trend of no fog hours : The present climatic study and trend analysis of fog in winter based on its intensity till now have considered hourly visibility data from 1981 as available with authors. It has been further re-analyzed on the basis of different visibility categories as classified in Singh *et al*., 1999 under different poor visibility limits of 200m, 400m, 800m, 1500m, 3000m, 5000m etc. called SPECI limits as used in aviation Meteorology whose 5-yearly average number of hours of occurrences of visibility at these different ranges per day in a month are available since 1964 and plotted in Figs. 4 (a-g). It may be noted that visibility corresponding to the first three poor ranges are nothing but corresponding approximated frequencies of dense to very dense fog, moderate to very dense fog and general fog categories respectively as defined in Sec. 3.2. It is interesting to note from Fig. 4(a) that number of hours of dense to very dense fog occurrence at IGI airport reducing visibility to 200m or less per day has shown significant increasing trend in the month of December, as it has increased from 0.2 hours in 1964-1968 to 0.8 hours in 1984-1988, to 2.1 hours in 1994-1998 and 1.5 hours in 1999-2003 with January having further higher increasing trends from 0.2 hours to 1.2 hours, to 1.4 hours and to 4.2 hours for the same period respectively. In other words, such intense fog occurrences have been increased by 7-10 times from mid 1960s till recent for December while their frequencies has been increased up to 20-times in January, an alarming raise one which will severely affects the aviation services including other transport services in intense winters at Delhi. Similarly, one can note trend of other two fog frequencies of visibility <400m and <800m respectively from Figs. 4(b&c), which have been increased from 0.3 and 0.4 hours in 1964-1968 to 1.6 and 5.7 hours in 1984-1988 and further to 2.8 and 8.5 hours in 1999-2003 respectively with January having further higher increasing trends in respective fog occurrences. Hence, both have increased by 9-times and 20-times for December and 20 - times and 30-times for January respectively. Few



Figs. 4(a-g). Trends of 5 yearly average hours of very poor and good visibility conditions for the month of December and January for the period 1964-2003



Figs. 5(a-h). Number of onset and dispersal of fog of various intensities & their cumulative % for the month of December & January

interesting features related to frequency of occurrences of further high visibility can be noted from Figs. 4(d-f). It shows number of hours at IGI airport visibility reduced to 1500 m or less, 3000m or less and 5000m or less respectively per day has also shown significant increasing trend in both the months as was in cases of occurrences of fog or lower visibilities. However, the increasing trend was nearly stagnated after 1994-1998 in Fig. 4(d), 1984-1988 in Fig. 4(e) and 1979-1983 in Fig 4(f). In case of December (January), the increase of the hours of respective visibility ranges per day from the beginning were .6 hours to 15.2 hours (.4 to14.4) from 1964-1968 to 1994-1998 in Fig. 4(d) while it was from 1.5 hours to 20.2 hours (1.2 to 20.5) from 1964-1968 to 1984-1988 in Fig. 4(e) and from 7.2 hours to 22.4 hours (7.0 to 23.1) from 1964-1968 to 1979-1983 in Fig. 4(f).

We have also plotted average number of hours per day with visibility reaching more than 5000m in Fig. 4(g) to understand how frequent a day IGI airport experiences good visibility conditions. Surprisingly, in totally contrast to sudden climatic jumps or unusual increasing trends in number of hours per day from 1964-1968 in all cases of different visibility up to 5000m as discussed before, average number of hours per day with visibility reaching more than 5000m was highest in the start of 1964-1968 with 16.8 (17.0) hours which slightly decreased to 14.7 (14.2) hours in 1969-1973 followed by very unusual decrease to 5.2 (5.8) hours, nearly a one third fall during 1974-1978. It again decreased to .9 (.7) hours during 1984-1988 in December (January) with a one fifth fall. Instead had stagnation in such high trends as observed in Figs. 4(d-f), the unusual decreasing trend continued till present period of 1999-2003 and thus finally making IGI airport, an unique airport in the world which have never been experienced good visibility conditions with visibility reaching more than 5000m in the last few years in December with average of only a chance of half an hour to have such good visibility in January. As a result of presence of such very unusual increasing trends in the occurrence of fog over IGI airport in the last 40-years, consequences have been felt in the aviation sector and thus, severely affecting both the airlines and common passengers in recent years due to increasing hours of suspending flight operations/diversion for many hours at the airport.

3.4. *Onset and dispersal timings*

Figs. 5(a-h) show timings of onset frequencies, dispersal frequencies and their respective cumulative % of occurrences during these timings with respect to various fog intensities for the months of Dec and Jan. Comparison of various onset curves of Figs. 5(a&b) with Figs. 5(c&d) and dispersal curves of Fig. 5(e&f) with Fig. 5(g&h), shows onset timings of fog of various intensities of December are similar as January and also their dispersal timings. But the main difference between onset curves and dispersal curves are onsets for all types of fog follow very lengthy processes covering for very longer period of 1200 UTC till 2300 UTC and hence these curves are more parallel to *x*-axis except general fog for both months [Figs. 5(a-c)] while dispersal is for short period as various fog curves cover only shorter period for 0200 UTC till 0700 UTC. The longer duration it takes for their onsets mainly because of gradual fall of air temperatures from evening till early morning creating environmental conditions more favorable for fog formation of various intensities while the shorter duration it takes for their dispersals is due to sudden increasing of temperature as sun comes towards overhead and thus clearing all fog all in sudden due to steep rise of temperature at the airport. Considering individual cases for exact timings, Fig. 5(a) shows the most favorable timing of general fog onset is at 1500 UTC as the highest number of days of 98 days [Fig. 5(a)] which had fog onset during this time contributing alone 24% of the total onset of fog at IGI followed by at 1400 UTC and 1600 UTC when 67 and 52 onsets were taken place. Fig. 5(b) also shows the favorable timing of fog onset in December is during 1200 to 1800 UTC when around cumulative of 85% of fog onset had been taken place at IGI airport. Similarly, in case of January in Fig. 5(c), it shows the most favorable timing of fog onset is at 1600 UTC as it had highest number days of nearly 116 cases of onsets which contributing alone nearly 25% of onset [Fig. 5(d)] followed by at 1400 UTC and at 2300 UTC when 57 and 54 onsets were taken place. It has been also observed from Fig. 5(c) that most of the fog onset in January has been distributed for whole night between 1200 UTC - 2300 UTC rather than having a particular timing favorable for its onset. This is because January is most vulnerable for fog and some time fog reducing visibility below 1000m continues for few days without its complete withdrawal.

In case of dispersal timings of December, Fig. 5(e) shows the most favorable timing of general fog dispersal is at 0400 UTC (89 days, 26% of dispersal) [Fig. 5(f)]. Also, by 0500 UTC, 0600 UTC and 0700 UTC, in 82%, 93% and 98% of the general fog days respectively, fog has been dissipated at IGI airport [Fig. 5(f)]. One can also note from Fig. 5(f) that remaining 2% fog dissipates completely by 0900 UTC. Further, it may be noted that, during 0200-0600, more than 85% of the general fog have been dispersed. Hence the timing of the general fog dissipation in December is during 0200 to 0900 UTC with favorable period of fog dispersal during 0200-0600. In case of January in Fig. 5(g), it also shows the most favorable timing of general fog dispersal is at 0300 UTC (122 fog dispersal which alone contributed 30%

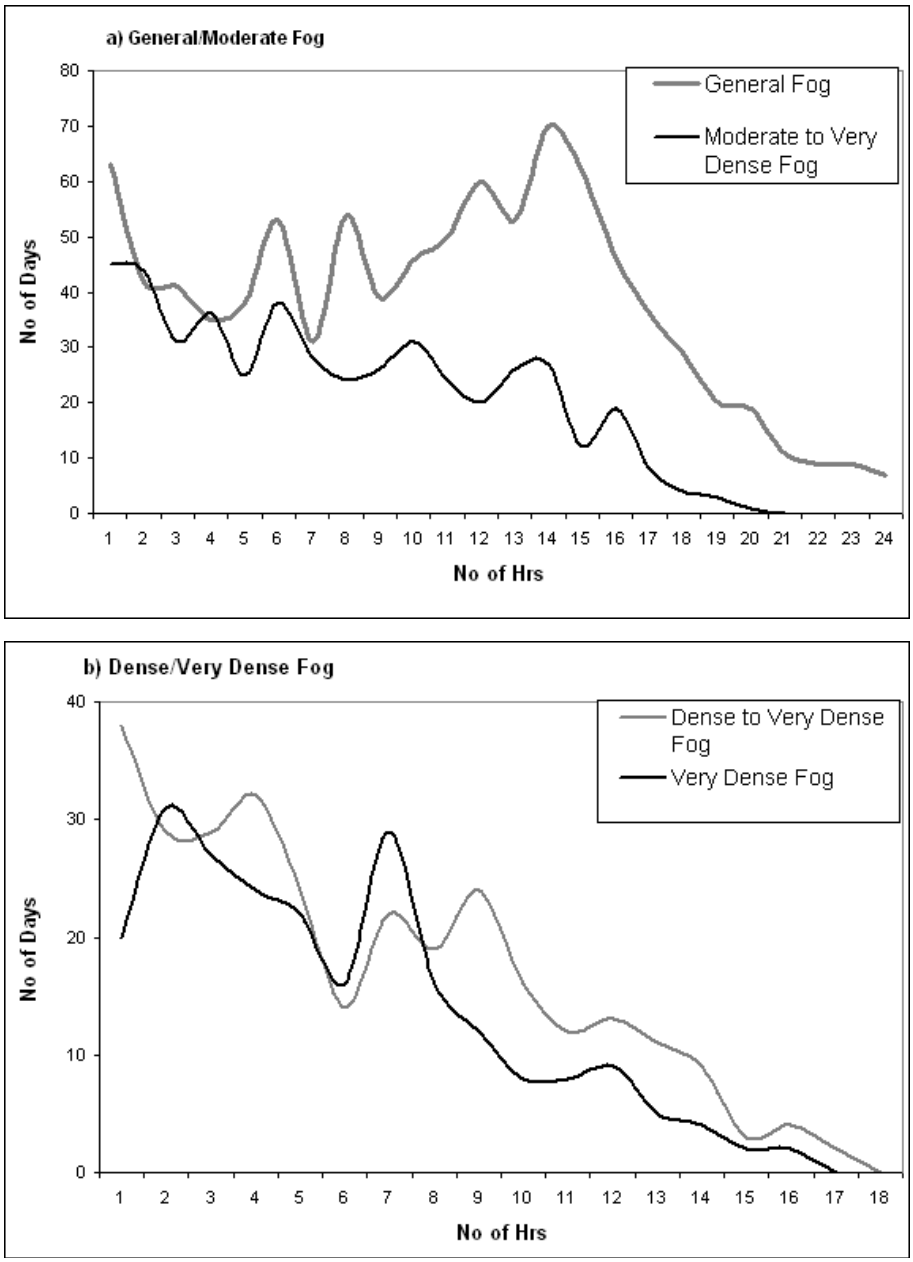
TABLE 4

Comparison of % of number of onsets and dispersals of fog of various intensities

	1200-1800 UTC			1900-2300 UTC		
	General	Moderate to Very Dense fog	Very Dense	General	Moderate to Very Dense fog	Very Dense
	% of Number of onsets of Fog of various intensities					
December	85%	59%	33%	15%	41%	67%
January	64%	42%	29%	36%	58%	71%
	% of Number of dispersals of Fog of various intensities					
	0200-0500 UTC			0600-0900 UTC		
December	82%	87%	98%	18%	13%	2% (Dispersed by 0600 UTC)
January	79%	90%	98%	21%	10% (Dispersed by 0700 UTC)	2% (Dispersed by 0600 UTC)

dispersals, [Fig. 5(h)] followed by at 0400 UTC, 0500 UTC, 0600 UTC and 0700 UTC when 113, 64, 46 and 26 dispersals were taken place. Also by 0600 and 0700 UTC, nearly in 90% and 97% of the general fog days [Fig. 5(h)], fog has been dissipated at IGI airport. The dispersal continued till 0900 UTC by which time 100% fog have been dispersed at the airport. Further, it may be noted that, during 0300-0600 UTC, nearly 85% of the general fog have been dispersed [Fig. 5(h)]. Hence timing of the fog dissipation in January is during 0200 to 0900 UTC with favorable period of general fog dispersal during 0300 to 0600 UTC. In case of moderate fog to very dense fog [Figs. 5(a-d)], since their frequencies are more or less distributed uniformly with their cumulative % curves more or less raises uniformly till it touches 100%, there are no distinct most favorable timings for their onsets. But with their onset timing up to when 85% of the onsets of moderate to very dense fog have been taken place is very lengthy period of 1400-2200 UTC for both the months and hence can be called as their favorable timing. However, their dispersal in Figs. 5(e-f) and 5(g-h) shows existence of a well observed peaks with most favourable dispersal timing of at 0300 (42 dispersals) and 0400 UTC (67 dispersals) contributing 25% and 29% for December and January respectively. Also by 0600 UTC, 97% and 98% of their frequencies have been dissipated in December and January respectively. Hence, the time periods of 0200-0500 and 0200-0500 UTC are called as favorable time period of such fog dispersals as more than 85% of total moderate to very dense fog have been dispersed during such time [Figs. 5(f-h)]. In case of onset of very dense fog for both months in Figs. 5(c-d), like moderate fog, their frequencies are more or less distributed uniformly with variations of their frequencies. However, since more than 85% of the onset have been taken place during the period of 1400-2200 UTC in December [Fig. 5(b)] and during the period of 1600-2200 UTC [Figs. 5(d)] in January, *i.e.*, 2 hours after that of Dec., one can call them their favorable timings. In its absence of well defined onset timings, Fig. 5(e) shows the most favorable timing of dispersal for December as 0400 UTC with 24 days dispersal when 28% of dispersal took place and by 0500 UTC, 98% of dispersals completed [Fig. 5(f)]. Similarly, in case of January in Fig. 5 (g-h), the most favorable timing of very dense fog dispersal is at 0400 UTC like December, as it had very high number days of 48 (43% alone). The favorable timings of dispersals for both months are 0200-0500 and 0200-0400 UTC respectively as more than 85% of total fog have been dispersed during such timings [Figs. 5(f-h)].

In Table 4, onset/dispersal frequencies of fog of different intensities in % of frequencies for different cumulative timings were documented when most of them have been observed to have onsets or dispersals in the airport. By this, one can get information regarding how frequencies of onsets of higher intense fog show gradual increase with the time towards night and *vice-versa* for their dispersals towards noon. Among various onsets as computed in Table 4, it is interesting to note that most of the onsets (59%-85%) of general fog and moderate to very dense fog have been taken place at the airport during 1200-1800 UTC except the case of moderate to very dense fog of January while most of the onsets (67%-71%) of very dense fog were in the second half *i.e.*, late night from 1900 UTC till 2300 UTC. It also shows most of the cases of moderate to very dense fog onsets of January are also in the second half during the late night (58%). However in case of fog dispersals, Table 4 shows many similarities for both months. Most of the general fog (79%-82%), moderate to very dense fog (87%-90%) and very dense fog (98%) withdrew/dispersed between 0200-0500 UTC with marginal dispersals % happened thereafter. Table 4

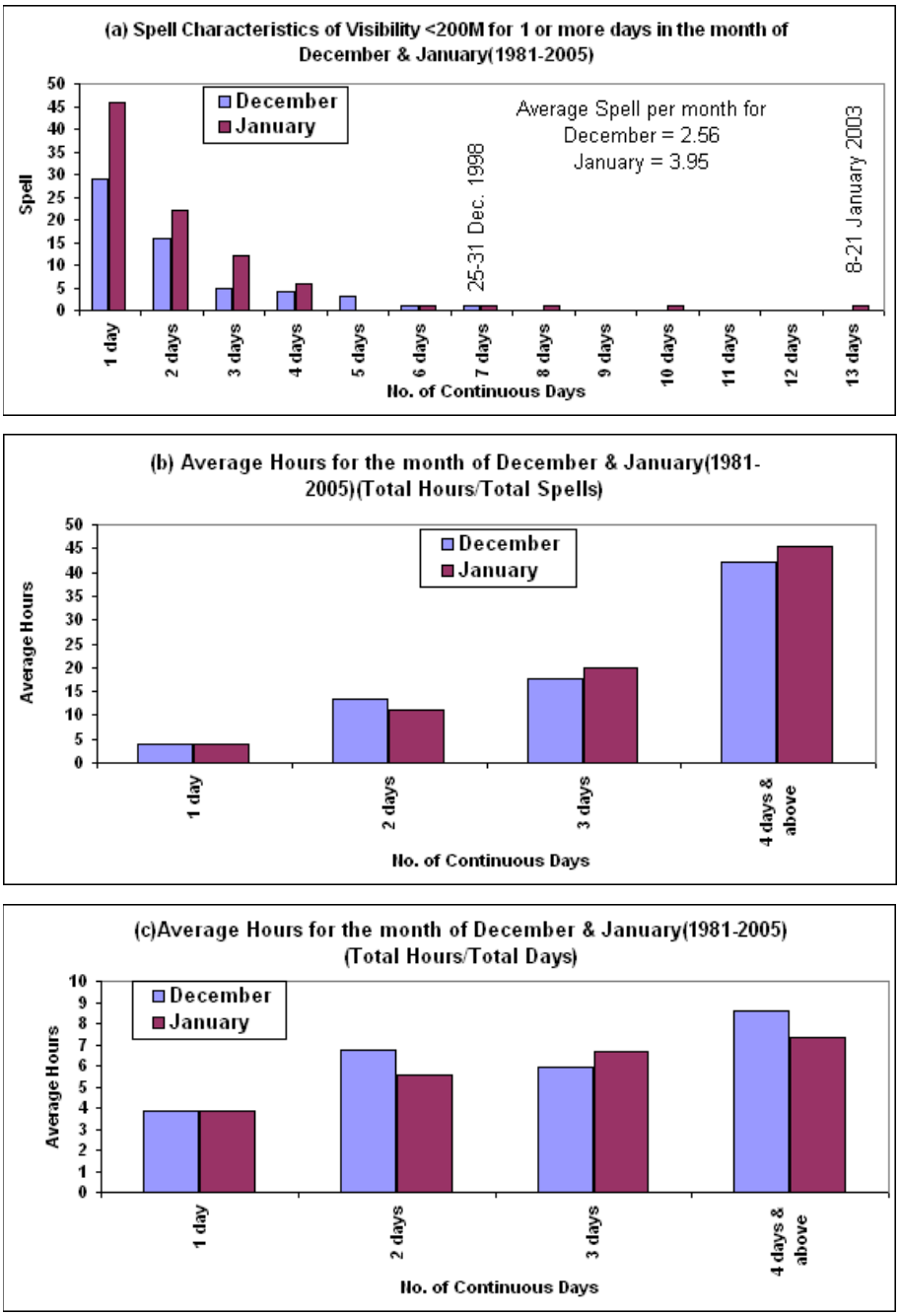


Figs. 6(a&b). Consecutive hours of fog of various intensities last *vis-à-vis* number of days

can be used as guidance at the airport while issuing forecasts for timing of deterioration/improvement of visibility for onsets/dispersals for various types of fog in both months.

3.5. *Climatological occurrences of consecutive hours of fog of different intensities*

Climatological total numbers of days of occurrences of fog of various intensities *vis-à-vis* consecutive hours of occurrences of 1 hour, 2 hours, etc. have been computed if it occurred continuously for respective hours on those days without changing in visibility range conditions corresponding to that fog. These types of information can be used by forecaster to have an idea about likely hood of a particular fog remaining for prolonged timings without improving or deteriorating in the respective range. Fig. 6(a) shows number of general fog days observed in whole data period of Dec - Jan (1981-2005) *vis-à-vis* number of consecutive hours they prevailed. It shows existence of highest number days (70) having such fog which prevailed uninterruptedly for 15 hours once it has



Figs. 7(a-c). Frequency of various fog spells based on consecutive days they last and their average hours /spell/day

set in over the airport and lowest number of days (7) having highest consecutive hours of 24 *i.e.*, for whole day. Similarly, in case of moderate to very dense fog days which reduced the visibility below 500 m plotted in Fig. 6(a), it is interesting to note an existence of highest number of days (45) having such fog which prevailed at the beginning itself *i.e.*, it prevailed only a single hour followed by a decreasing in their number of days thereafter to 0 with almost no days having moderate fog to continue uninterruptedly more than 21 hours once set in over the airport during the data period. In case of dense to very dense fog days plotted in Fig. 6(b), it shows similar variation with occurrences of highest number days of 38 prevailed only a single hour followed by a nearly decreasing in their number of days to 14 having consecutive hours as 6 hours followed by an increase to

24 having consecutive hours as 9 hours of occurrences. Thereafter, number of occurrences having further higher number of consecutive hours of fog has been of decreasing trend and reaches to 0 with almost no days having moderate fog to continue uninterruptedly more than 17 hours once set in over the airport during the data period. For very dense fog occurrences plotted in Fig. 6(b) which affects the aviation sector very much, the variation number of days against consecutive hours shows occurrences of two peak values of occurrences of 31 days and 29 days with consecutive hours of occurrences as 2 and 7 hours respectively followed by a systematic decreasing in frequencies of their number of days thereafter to 0 with almost no days in the airport data record having very dense fog to continue uninterruptedly more than 17 hours once set in over the airport during the data period.

3.6. *Climatological characteristics of consecutive days a fog spell lasts*

Like we discussed in Sec. 3.5 on consecutive hours, it will be very much useful for fog forecasting at IGI for use in aviation if one finds climatic information related to continuation of a fog spell especially dense to very dense fog ($v < 200$m) to next few days with average duration of each days *i.e*., spell characteristics based on present hourly data. We have computed such information's for both months from daily data but plotted only for dense fog or higher cases for use in aviation in Figs. 7(a-c) which shows occurrence frequencies of various spells for both months that last consecutive days of 1, 2, 3 etc. in Fig. 7(a) along with variation of average hours of dense fog observed per spell and per day corresponding to various spells in Figs. 7(b&c). Analysis shows presence of total number of dense fog spells for the whole period of 1981-2005 irrespective of number of days these were continued consecutively which affected aviation severely over IGI as 59 and 91 with average of 2.56 and 3.95 each year for December and January respectively. Fig. 7(a) shows existence of highest number spells as 29 and 46 of 1-day type followed by 16 and 22 spells of 2-days type and then linear decreasing up to spell of 4 and 6 spells of 4 days type for December and January respectively. The longest spell was prevailed for December (January) was during 25-31 December of 1998 (7-21 January 2003) which has lasted consecutively for 7 days (and 13 days). Fig. 7(b) shows linearly increasing hours per spell with increase of their number of consecutive days they covered. Similarly, Fig. 7(c) also shows even increase in the average number of hours of fog per day present in the respective spells with increase of their number of consecutive days for both months with highest average hours of fog per day of 8.59 (7.37) hours for all spell having 4-days and above. Hence the study shows longer is the spell, the fog will remain over IGI for higher hours per day to day up to which the spell continues.

4. Conclusion

Intensity based fog climatological information system developed in the present study addresses many vital issues raised by the users at IGI airport from years and if used properly will help in minimizing its impact drastically on both flight operations and passenger's sufferings in each fog season. Some of them in brief are:

(*i*) IGI normally experiences 23, 10, 4 and 5 (24, 13, 7 and 8) days and 233, 41, 10 and 24 hours (221, 40, 14 and 36) of general, moderate, dense and very dense fog respectively in December (January). Hence less intense fogs are more in the former month while higher intense fogs are more in the latter month. It also shows more in the intensity of fog, lesser is the number of fog days and their total hours with presence of very high variance and trends relative to their corresponding means. The variances are so high that even the standard deviations in case higher intense fog conditions during both months are higher than mean for some cases.

(*ii*) Extreme years having highest and lowest number of days or hours for fog of all intensities have also been documented for both months to understand how worst respective fog can be for IGI from aviation aspects. Such values are so threatening that the most dense fog can remain as high as 20 days as in 2003 with a total of 127 hours *i.e*., when airport was closed with more than 6-hours of average per day in that month for 20 days. In case of extreme occurrences on a particular date, it shows very dense fog remaining uninterruptedly for 15 and 17 hours respectively for respective months disrupting the air traffic in most part of the day.

(*iii*) Linear trend analysis of number of days and total number of hours for both months since 1981 and 1960s shows presence of linearly significant increasing trend in all types of fog in days and hours of occurrences. It show the intense fog occurrences (reducing visibility 200 m or less) over IGI airport have been increased by 7-10 times from mid 1960s till recent for December while their frequencies has been increased up to 20-times in January. Similarly, it further shows number of hours of fog reducing visibility to 400 m or less and 800 m or less per day, 1500 m or less, 3000 m or less and 5000 m or less have been increased up to 3-30 times from 1960 till as was concluded in cases of occurrences of fog or lower visibilities. In contrast, study of trends of number of hours per day with visibility reaching more than 5000 m over the IGI at airport shows it was highest in the start of 1964-1968 with 16.8 (17.0) hours which significantly decreased

to 0.9 (0.7) hours *i.e*., to a one fifth hours during 1984-1988 in December (January). Instead of stagnation in such high trends, the unusual decreasing trend continued till present period of 1999-2003 and thus finally making IGI airport, an unique airport in the world which have never been experienced good visibility conditions with visibility reaching more than 5000 m in the last few years in December with average of only a chance of half an hour to have such good visibility in January. Hence all of these different types of trend analysis confirm that the fog occurrences over the airport have been increasing significantly with increasing intensity.

(*iv*) The favourable onset time periods of general fog, moderate to very dense fog and very dense fog in the day for December (January) are 1200-1800, 1400-2200, 1400-2200 (whole period of 1200 -2300, 1400-2200, 1600-2200) UTC respectively by when more than 85% of the total onsets have been completed with most favourable timings of onsets as 1500, 1600, 2100 (1600, 1600, 2100) UTC when nearly 25%, 14%, 17% (25%, 13%, 17%) onsets take place. Their respective favorable dispersal time periods are 0200-0600, 0200-0500, 0300-0500 (0300-0600, 0200-0500, 0200-0400) UTC by when fog of more than 85% of the total fog days have been dissipated with most favourable timings of dispersals as 0400, 0300, 0400 (0300, 0400, 0400) UTC when nearly 26%, 25%, 28% (30%, 25%, 43%) of dispersals take place. It is interesting to note that most of the onsets of less intense fog of first two types were in the first half of the night *i.e*., 1200 till 1800 UTC while most of the reaming types are in second half *i.e*., late night from 1900 UTC till 2300 UTC except the case of moderate to very dense fog of January. Most of the onsets of later fog are also in the second half during the late night. However in case of fog dispersals timing, a common timing of 0300-0500 UTC could be identified during when most of the fog of respective intensities (70-75%, 70-72% and 80-83%) have been withdrawn/dispersed during both months.

(*v*) Comparison among onsets and dispersals timings for both months also show that onset period is very lengthy for all cases of fog covering the evening till early morning of next day from 1200 UTC till 2300 UTC (11 hours) while dispersals period is very short at morning starting from 0200 UTC which mostly ends by 0700 (5 hours). This important climatological information can be used as guidance at the airport while issuing forecasts for timing of deterioration/improvement of visibility due to onsets/dispersals of various types of fog in both months.

(*vi*) Analysis of consecutive hours *vis-à-vis* number of occurrences for the whole period of data shows existence of highest number days of 70 days of general fog, prevailed uninterruptedly up to very long of 15 hours once it has set in over the airport, followed by a highest of 31 days of very dense fog occurrences merely continuing up to only 2 hours with 45 and 38 days of occurrences of fog of other medium intensities up to only one hour. Similarly, climatological characteristics of fog spells having various consecutive days of intense fog occurrences were brought out in the present study for use in forecasting of dense fog spells continuity to next day with average hours it will remain per day till spell ends once it occurs.

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