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Forecasting fog over Delhi - An objective method

S. K. ROY BHOWMIK, A. M. SUD and CHARAN SINGH

India Meteorological Department, New Delhi-110 003, India

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सार – सूक्ष्म भौतिक मेसोस्केल और सिनॉप्टिक स्केल प्रक्रियाओं पर निर्भर रहने के कारण कोहरे का पूर्वानुमान करना एक कठिन समस्या है। इस शोध–पत्र में दिल्ली शहर की कोहरे की घटना के संबंध में दिल्ली के सिनॉप्टिक मूल्याँकन और गहन (सांउडिंग) विश्लेषण किए गए है और अन्ततः सांख्यकीय बहुविवेचनात्मक विश्लेषण को अपनाते हुए दिल्ली में कोहरे के पूर्वानुमान के लिए एक वस्तुपरक पद्धति विकसित की गई है। इस अध्ययन से यह पता चलता है कि : (*i*) परिसीमा स्तर में विशेषकर 925 है.पा. वाली प्रबल पुरवा हवाओं से बंगाल की खाड़ी में नमी की उपस्थिति और निचले स्तर में पश्चिम की ओर उत्तरी हवाओं से ठंडी वायु के अभिवहन, ऐसी दो सिनॉप्टिक स्केल विशेषताएँ है जो दिसंबर 1999 में दिल्ली में पड़े कोहरे की घटना से संबद्ध है। (*ii*) दिल्ली के गहन विशलेषण (1997–2000 के दिसंबर माह और जनवरी माह) से यह पता चलता है कि जब पवन की गति (1000 है.पा. पर) 5 नॉट्स से अधिक नहीं होती है, न्यूनतम तापमान 9° से. से कम होता है, औसांक अवदाब (1000 है.पा.) 6° से. से कम होता और ओसांक (1000 है.पा.) 6° से. से अधिक होता है तब दिल्ली में कोहरा बहुत अधिक होता है। कोहरे की अधिकांश घटनाएँ 1000 है.पा. और 700 है.पा. के बीच की पवन की पश्चगमन स्थितियों के साथ होती है। (*iii*) विभिन्न श्रेणियों में इन प्राचलों के थ्रेशहोल्ड मानों के साथ विकसित की गई वस्तु परक पद्धति काफी उपयुक्त पाई गई है।

ABSTRACT. The prediction of fog remains a difficult problem due to its dependence on micro-physical meso-scale and synoptic scale processes. In this paper synoptic evaluation and sounding analyses of Delhi are made in relation to the occurrence of fog over the city and finally an objective method is evolved for the prediction of fog over Delhi applying statistical multiple discriminating analysis. The study shows that : (*i*) Moisture incursion from the Bay of Bengal by the prevailing easterlies in the boundary layers particularly, at 925 hPa and lower levels cold air advection by the northerlies to the west are the two synoptic scale features associated with the fog episode over Delhi in December 1999, (*ii*) Sounding analyses of Delhi (December and January of 1997-2000) reveals that fog occurrence of Delhi are dominant when the wind speed (at 1000 hPa) does not exceed 5 knots, minimum temperature is less then 9° C, dew point depression (1000 hPa) is less then 6° C and dew point (1000 hPa) is greater than 6° C. Most of the fog occurrences are associated with the backing condition of wind between 1000 hPa and 700 hPa and (*iii*) The objective method developed with threshold values of these parameters at different ranges applying successive multiple discriminating analyses is found to be reasonably skillful.

Key words – Fog, Forecasting method, Multiple discriminating analysis, Skill score.

1. Introduction

During winter season (December and January) northern parts of India is very often effected by radiation fog. This generally starts from the month of October and continues till February. The frequency and intensity of fog is maximum in December and January. The impact and significance of fog ranges from disruption in aviation services, surface transportation and results to serious accidents caused in part by poor visibility. Inspite of considerable progress in the field of numerical weather prediction (NWP), current operational NWP models are incapable of simulating the fog process. This is because of dependency of fog on micro-physical and meso-scale processes that act with the boundary layer which is also influenced by the prevailing synoptic regime. The diagnosis and prediction of these interaction is not readily accomplished with the current operational model. As such till the time meso-scale numerical model can be used with a reasonable success there is an urgent need for developing a suitable objective method for forecasting fog. The present study is initiated with the aim of providing an objective aid for forecasting of occurrence of fog over Delhi.

2. Data and methodology

Some of the traditional methods available for objective forecasting of fog are: (a) Model output statistics (MOS), (b) Persistence (c) Synoptic and (d) Statistical. Model output statistics (MOS) guidance

TABLE 1(a)

Monthly frequency of fog over Delhi (1997-2002) with visibility < 800 meters

Year/month	1997	1998	1999	2000	2001	2002	Total
Nov	16	13	4	10	3	4	50
Dec	24	23	25	9	21	17	119
Jan	30	14	16	18	19	17	114
Feb	10	7	18	8	4	8	55
Average for the four months	20.0	14.3	15.8	11.3	11.8	11.5	

TABLE 1(b)

Monthly frequency of fog over Delhi (1997-2002) visibility < 1000 meters

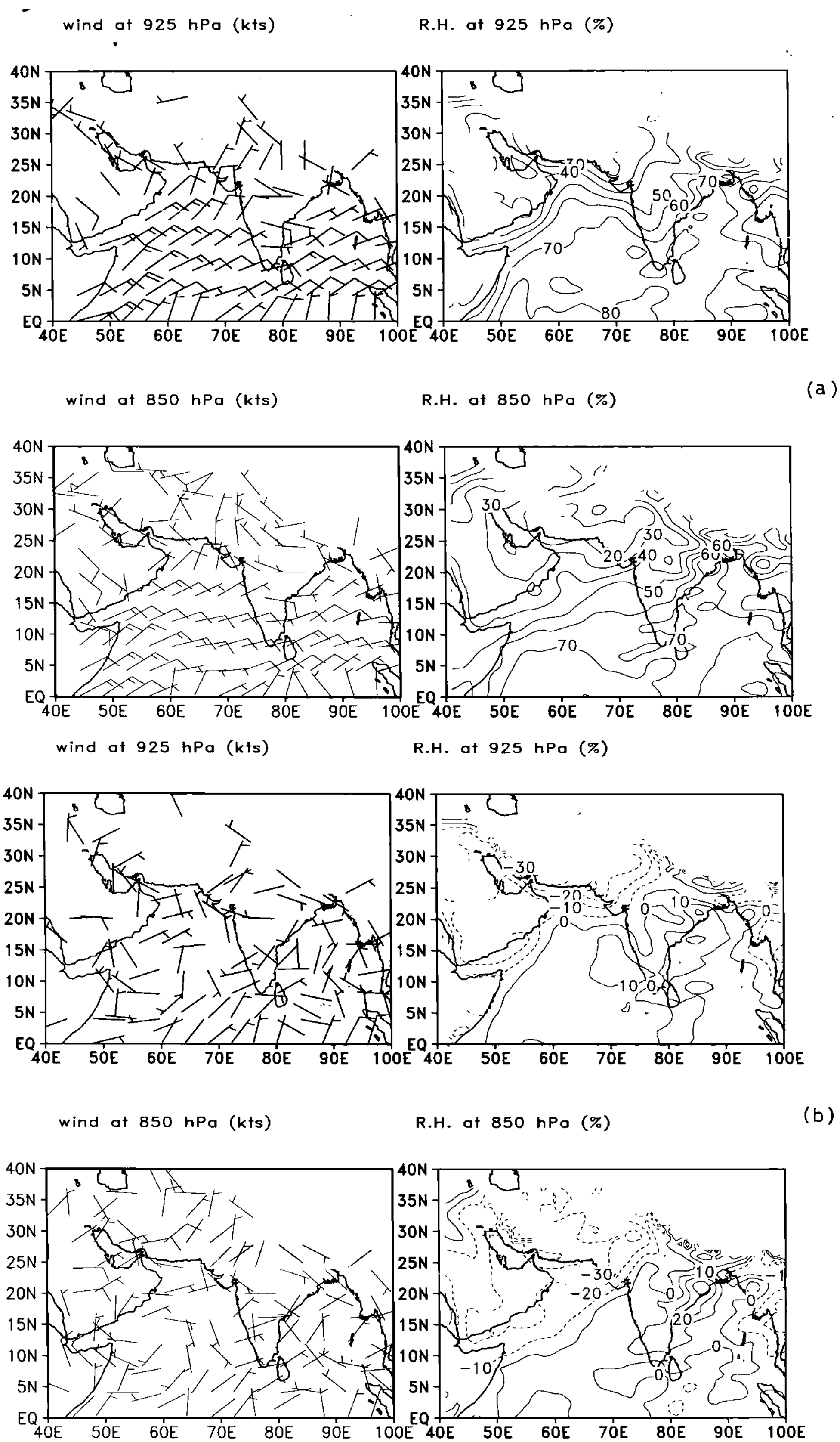
Year/month	1997	1998	1999	2000	2001	2002	Total
Nov	20	17	8	15	9	13	82
Dec	28	23	25	13	24	25	138
Jan	31	18	18	21	23	25	136
Feb	12	14	20	12	12	13	83
Average for the four months	25.3	18.0	17.8	15.3	17.0	19.0	

is a mean by which one may attempt to estimate or quantify meso-scale variation with reference to occurrence of fog. Unfortunately, the statistical guidance from the current operational NWP model has the basic inability to provide adequate information for reliable prediction of fog 6-24 hours in advance (Croft *et al.*, 1997). Persistence forecast has good chance of success but fails during the transition period of flow pattern. The basic idea of statistical technique development is to quantify the physical relation between the observed weather element of interest and other meteorological variables. For the purpose of selecting the appropriate statistical techniques to use, predictant weather elements are classified as continuous and categorical. Predictions of occurrence and non-occurrence of an weather event such as fog are categorical type. Multiple discriminant analysis (MDA) is used for categorical element. Very recently, in the development processes of forecasting visibility for a place Hindon near Delhi, Madan *et al.*, 2000 attempted for objective method applying different approaches such as auto regression, multiple regression, climatology and persistence. In the regression equation they used local meteorological elements such as surface wind, dry bulb and wet bulb temperature and cloud amount as predictors. But the comparison with the realised visibility showed that forecast had larger deviation and the forecast beyond six hours from the initial time are not satisfactory. The model developed by them following climatology persistence method is found to provide better visibility forecast. Mahapatra and Thulasi Das (1998) attempted to forecast fog over Bangalore Airport using different objective techniques such as persistence, synoptic, statistical (threshold value based on co-relation coefficients of predictors) and multiple discriminant analysis. For the comparison purpose they calculated accuracy of different methods. The comparison indicates that the multiple discriminant analysis method provides a better techniques both in terms of physical principles and statistics for the fog forecasting. In view of the fact discussed above the method adopted for formulation of the objective method in this study is the multiple discriminating analysis.

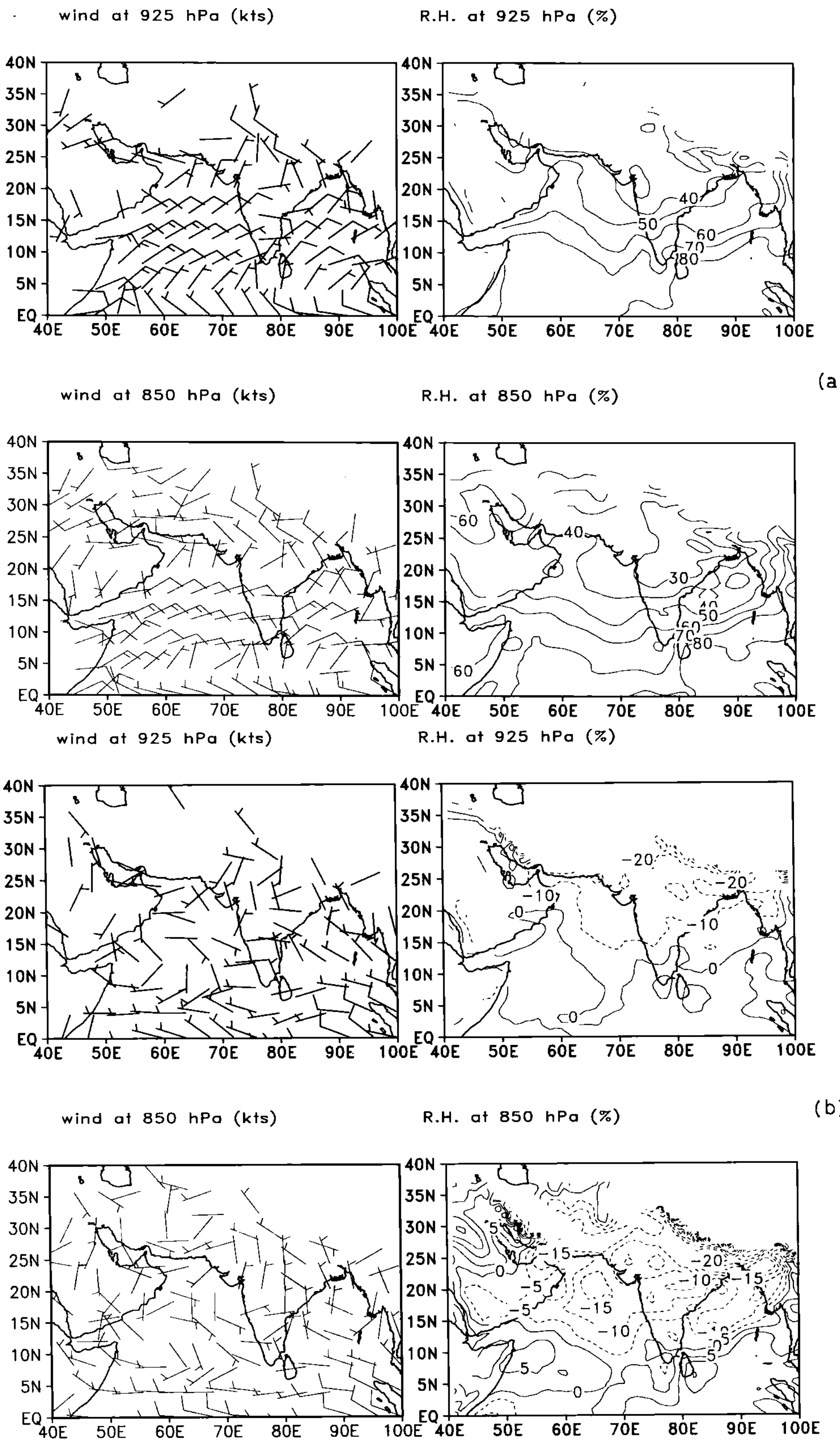
Impact of fog on city life is larger when the duration of the fog is longer. Using data for the year 1960-98 of IGI airport Delhi, Singh *et al*. (1999) documented that there is a clear cut peak around 1430 UTC when visibility deteriorates below 800 meters and visibility improves around 0300 UTC both for January and December.

Fog is measured in terms of the minimum horizontal visibility associated with it. In this study a day is considered as fog-day for Delhi if the reported visibility at 0300 UTC at the Safdarjung airport is less than 1000 meters.

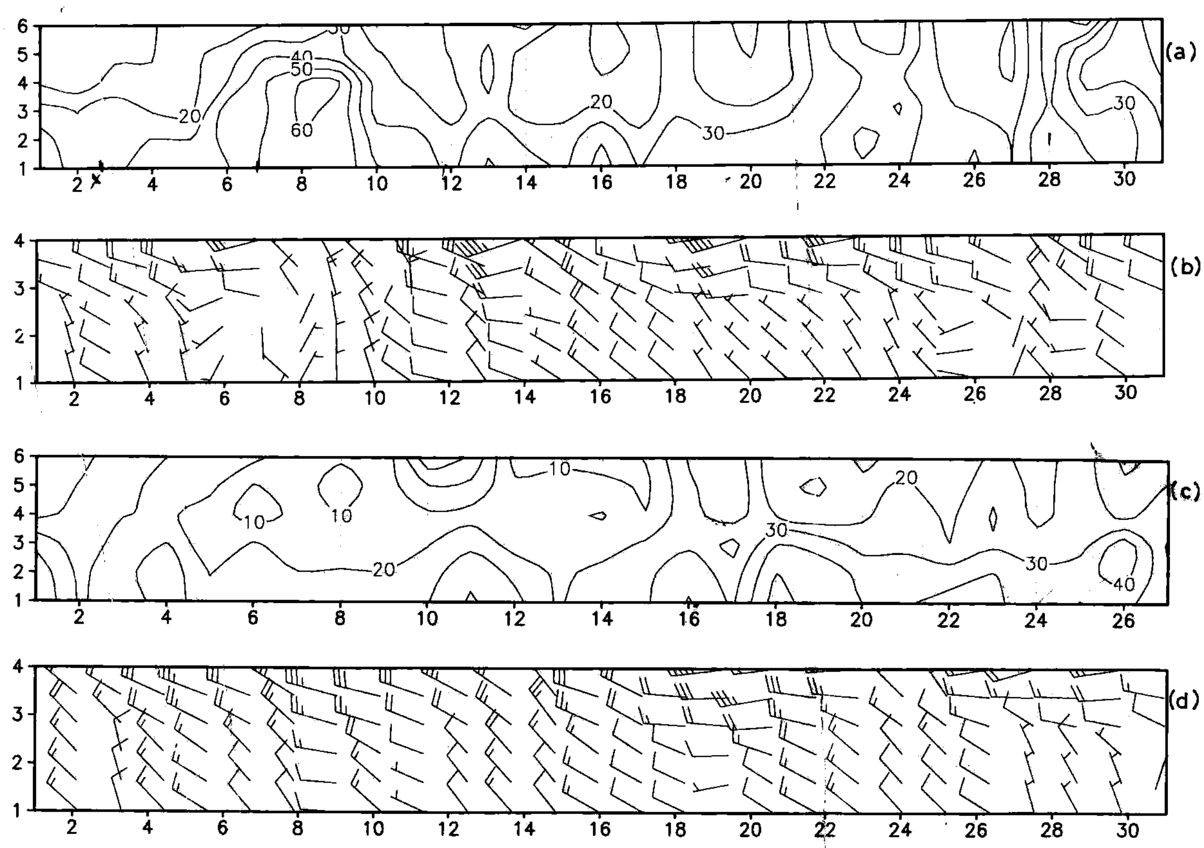
Monthly frequency of occurrence of fog (with visibility < 800 meters and < 1000 meters) over Delhi (Safdarjung airport) during November to February for the year 1997 to 2002 is presented in Tables 1(a&b).



Figs. 1(a&b). Mean and anomaly fields of wind and relative humidity at 925 hPa and 850 hPa fog December 1999



Figs. 2(a&b). Same as in Figs.1(a&b) except for December 2000



Figs. 3(a-d). Vertical time section of (a) wind and (b) relative humidity during 1-30 December 1999; (c,d) same as (a,b) except for 1-27 December 2000. Pressure levels are 1000, 925, 850, 700 and 500 hPa. For the wind only first four levels are shown

The table shows that the highest frequency of occurrence of fog is during December and January. Where as for November and February the frequency is relatively less. In view of this the present study is restricted for the month of December and January only. Considerable interannual variability in the period November to March fog frequency is noted. The year 1997 recorded the highest incidence and the year 2000 recorded the lowest incidence. Also for December – January period to the year 1997 witnessed the highest (54) number of fog days and the year 2000 the lowest number of days (27). Interannual variability in fog events is apparently due to variability in synoptic scale processes in the lower atmosphere.

Singh *et al.* (1999) analyzed the climatology and trend of visibility of Delhi based on data for the period 1960 to 1998 of IGI airport. The study shows that duration of fog has increased considerably. The average duration of visibility less than 800 meters has increased from 0.3 hours/day during 1964 -1968 to 8.98 hours/day during 1994-98 both for the month of December and January.

As fog occurs with in the boundary layer, a forecaster must focus on the evolution of weather across the synoptic as well as meso-scales that lead to saturation of boundary layer with water vapour. In order to examine the influence of synoptic scale systems on the occurrence of fog, in the section 2 of this paper synoptic evaluation in respect of occurrence of fog is made. For the synoptic evaluation anomaly fields are computed using daily analysis field of India Meteorological Department operational NWP model and climatology data from National Center for Environment Prediction (NCEP), Washington. Again in order to identify the thermo dynamical environment in the boundary layer that is necessary for fog formation, in section 3, sounding data of New Delhi (Safdarjung), for the month of January and December during 1997-2000 are analyzed in relation to occurrence of fog. Finally in section 5 an objective method is formulated for prediction of occurrence of fog over Delhi applying successive statistical multiple discriminant analysis technique (Willson, 1988).

3. Synoptic evaluation of occurrence of fog

For the evaluation of synoptic scale features on the occurrence of fog, an intercomparison of monthly mean and anomaly flow pattern and relative humidity at boundary layers is made between two contrasting years with reference to occurrence of fog. With respect to occurrence of fog over Delhi in December, 1999 and 2000 are two contrasting years. During December 1999, Delhi was dominated by fog when it experienced intense fog of 24 days. Where as in December 2000 only 7 days fog was reported in Delhi. Figs. 1 (a&b) respectively present the mean and anomaly flow pattern and relative humidity at 925 and 850 hPa for December 1999. In December 1999, mean field at boundary layer (925 hPa and 850 hPa) shows location of subtropical high near Lat. 25.0° N/ Long. 55.0° E resulting weak (< 5 knots) northerly winds between Lat. 60.0° N/ Long. 75.0° E and Lat. 25.0° N to 35.0° N and advection of cold air at boundary layers over northern parts of country. At 925 hPa easterly winds are also seen over Gangetic West Bengal and adjoining areas. An anomaly cyclonic circulation lay over north India centred near Lat. 25.0° N and Long. 78.0° E which caused incursion of moisture over the region by the prevailing boundary layer easterlies from the Bay of Bengal. This is also reflected in the humidity field. The mean relative humidity, particularly at 925 hPa was clearly higher. Anomaly field shows positive anomaly (+ 10%) of relative humidity over the region extending from the north Bay of Bengal to westwards upto Long. 75.0° E between Lat. 25.0° N to 30.0° N. In December 2000 [Figs. 2 (a&b)] subtropical high at 850 hPa is seen near Lat. 20.0° N / Long. 55.0° E resulting northwesterly winds relatively stronger (5-10 knots) over the region. A considerable difference in the position of ridge at 850 hPa over northwest India and neighborhood is noticed between these two contrast years. In 2000 ridge located along Lat. 20.0° whereas in 1999 it was along Lat. 25.0°, 5.0° north of normal position, resulting weaker westerly component of winds over the northwest India. Anomaly fields were northwesterly at 850 hPa and southwest to southerly at 925 hPa between Lat. 30.0° N and 35.0° N. The humidity field was showing negative anomaly (–20%) over the country . Figs. 3(a-d) show the vertical time section of wind and relative humidity of December during 1999 and 2000 respectively based on model analysis field. The intercomparison reveals that in December 1999 lower levels humidity was higher and westerly component of winds were weaker resulting easterly anomaly compare to December of 2000.

Thus the comparison of synoptic fields of December between two contrasting years (1999 and 2000) reveals that fog episode of December 1999 was under the influence of boundary layer northerlies between Long. 60.0° E and 75.0° E over the northern parts of country and moisture incursion from the Bay of Bengal by the prevailing boundary layer easterly winds extending upto Long. 75.0° E.

4. Sounding analysis

The fog occurrence strongly depends upon radiation flux and their cooling mechanism that lead to saturation of boundary layer. This moisture and sensible heat flux may also be get modified through advection and boundary layer modification processes. Croft *et al*. (1997) reported that dense radiation fog is associated with weak backing between 1000 hPa & 700 hPa (cold air advection) or neutral wind pattern over southern region of USA. Due to earth's radiation cooling, on calm and clear night in winter, the temperature of the air close to ground falls rapidly. If this process is continued for a long period the condensation of water vapour in the air takes place. Again very light surface wind provides mixing of the surface layer through some what deeper layer so that fog becomes generally dense and more widespread. Thus fog formation depends on two factors namely cooling factor and moistening factor. Because of these consideration following parameters reported at 0000/0300 UTC on the same day are examined to include as check list in relation to occurrence of fog over Delhi.

(a) *Cooling factors*

(*i*) Minimum temperature of the day

(*ii*) Wind direction at 1000 hPa

(*iii*) Backing or veering between 1000 hPa and 700 hPa

(b) *Moisture factors*

(*i*) Dew point at 1000 hPa

(*ii*) Dew point depression at 1000 hPa

(*iii*) Wind speed at 1000 hPa.

The frequencies of these parameters corresponding to occurrence and non-occurrence of fog over Delhi during the month of December and January for the period 1997-99 are presented in the frequency Tables 2-7.

It is obvious that the frequency of occurrence of fog increases with the decrease of wind speed, dew point

TABLE 2

Relationship of wind speed to the frequency of occurrence of fog over Delhi (Data : Dec-Jan 1997-2000)

Wind speed (knot)	Frequency of occurrence of fog	Frequency of non-occurrence of fog	Total occasion
Calm	24 (92%)	02	26
1-2	23(82%)	05	28
3-5	57(67%)	27	84
6-10	14(58%)	10	24
>10	12(50%)	12	24
Total	130(69%)	56	186

TABLE 3

Relationship of Dew point depression (*T-Td*) to the frequency of occurrence of fog over Delhi (Data : Dec-Jan 1997-2000)

Dew point depression (*T-Td*) °C	Frequency of occurrence of fog	Frequency of non-occurrence of fog	Total occasion
0	11(92%)	01	12
1-2	49(83%)	10	59
3-4	47(68%)	22	69
5-6	20(65%)	11	31
> 6	03(20%)	12	15
Total	130(69%)	56	186

TABLE 4

Relationship of minimum temperature to the frequency of occurrence of fog over Delhi (Data : Dec-Jan 1997-2000)

Minimum temperature (°C)	Frequency of occurrence of fog	Frequency of non-occurrence of fog	Total occasion
≤ 5	38 (84%)	07	45
6-7	50(76%)	15	65
8-9	28(73%)	10	38
10-11	12(32%)	15	27
>11	2(18%)	09	11
Total	130(69%)	56	186

TABLE 5

Relationship of Dew point temperature (*Td*) to the frequency of occurrence of fog over Delhi (Data : Dec-Jan 1997-2000)

Dew Point temperature (*Td*) °C	Frequency of occurrence of fog	Frequency of non-occurrence of fog	Total occasion
≤ 2	8 (34%)	15	23
3-4	13(54%)	11	24
5-6	30(75%)	10	40
7-8	42(77%)	12	54
> 8	37(82%)	08	45
Total	130(70%)	56	186

TABLE 6

Relationship of wind turning to the frequency of occurrence of fog over Delhi (Data : Dec-Jan 1997-2000)

Conditions	Frequency of occurrence of fog	Frequency of non-occurrence of fog	Total occasion
Backing	88 (80%)	21	109
Neutral	20(62%)	12	32
Veering	22(49%)	23	45
Total	130(69%)	56	186

TABLE 7

Relationship of wind direction to the frequency of occurrence of fog over Delhi (Data : Dec-Jan 1997-2000)

Wind Direction (degree)	Frequency of occurrence of fog	Frequency of non-occurrence of fog	Total occasion
Calm	24 (92%)	02	26
31-90	30(73%)	11	41
331-30	27(62%)	16	43
271-330	37(62%)	16	43
211-270	07(78%)	02	09
151-210	06(60 %)	04	10
91-150	09(64%)	05	14
Total	130(70%)	56	186

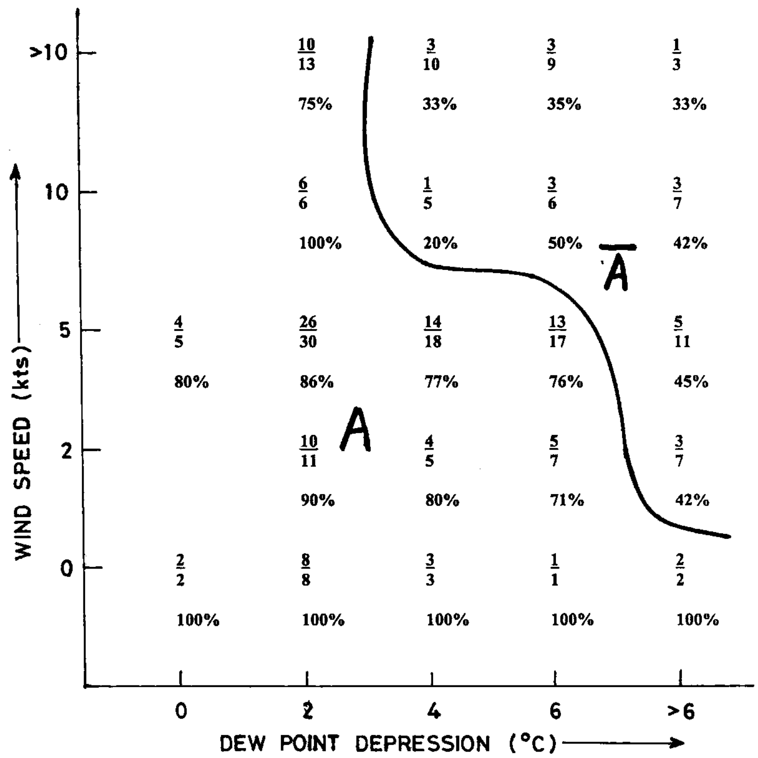


Fig. 4. Wind speed and dew point depression are graphically connected with occurrence of fog. The fraction denotes number of occurrence to the total number of cases in the range

depression, minimum temperature and with the increase of dew point. These variables indicate fairly strong relationship with the occurrence of fog. Fog occurrences are dominant when the wind speed does not exceed 5 knots, minimum temperature is less than 9° C, dew point depression is less than 6° C and dew point is more than 6° C. It is also interesting to note that fog occurrences are mostly associated with the backing condition (cold air advection) between 1000 hPa and 700 hPa.

5. Formulation of objective method

The multiple discrimination analyses method (Willson,1988) involves relating the predictor variables graphically to the cases of predictant (occurrence of fog). Mahapatra and Thulasi Das (1998) applied this technique to combine graphically two parameters dry bulb temperature and dew point depression with the occurrence of fog over Bangalore airport. While Croft *et al.*, (1997) utilized wind speed and dew point depression for the South Region in USA. In the present study the following four variables showing strong relationship with occurrence of fog are finally selected:

(a) Dew point depression at 1000 hPa reported at 0000 UTC.

(b) Wind speed at 1000 hPa reported at 0000 UTC.

(c) Minimum temperature of the day reported at 0000 /0300 UTC.

(d) Dew point at 1000 hPa reported at 0000 UTC.

These variable are combined graphically and related jointly to the frequency of occurrence of fog on the same day applying successive multiple discrimination analysis method. In the first step (a) dew point depression and (b) wind speed are combined graphically in relation to the occurrence of fog. Fig. 4 is prepared by considering wind speed and dew point depression as co-ordinates. The fraction denotes the number of occurrence to the total number cases in the range. The diagram is divided into areas A and $\overline{A}$ by fitting subjectively a curve so that cases of occurrence are prominent in area A and most non-occurrence in $\overline{A}$. Now the process is repeated

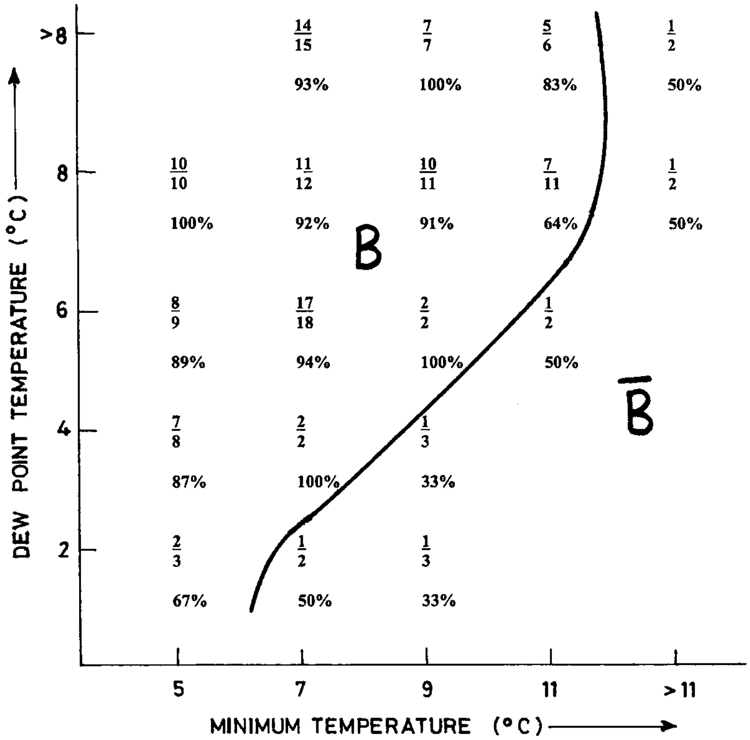


Fig. 5. Same as Fig.4 with reference to minimum temperature and dew point

with the cases fall in area A and Fig. 5 is prepared by considering (c) minimum temperature and (d) dew point as co-ordinates. The Fig. 5 is divided into areas B and $\overline{B}$ so that most of the occurrence fall in B.

To use this method in practical forecasting, start is made with the parameter (a) and (b) in Fig. 4. If then point falls in $\overline{A}$ no fog is the forecast. If the point falls in A, then proceed to Fig. 5 with parameter (c) and (d). If the point falls in B occurrence of fog is the final forecast output.

6. Performance and limitation of the model

The successes of this technique depends on the skill of the accurate estimates of the predictors. India Meteorological Department issues daily local forecast valid for next 24 hours for the city at around 0700 UTC based on 0000 UTC and 0300 UTC observations and updates the forecast at around 1500 UTC based on 1200 UTC observations. Though technique is developed for prediction of occurrence of fog 24 hours in advance, the forecast can be updated during the subsequent observation hours depending on the trend of the predictors and utilizing synoptic knowledge.

In order to take care of trend of predictors, while using predictors of previous day, Mahapatra and Thulasi Das (1998) applied the composite method where in addition to the threshold values of predictors, threshold values of change in the predictors are also utilised in the discrimination analysis. But they noted that the method is most suitable for issue of forecasts at 1800 UTC for the occurrence of fog next day morning with the lead time of 6 hours only. One may use the following method of estimating predictors. A predictors (P) is estimated as :

$$Pe = Po + \Delta P, \qquad \text{if } \Delta P > 0$$

$$= Po - \Delta P, \qquad \text{if } \Delta P < 0$$

Where, Pe is the estimated value of P for the next day at 0000 UTC. Po is the observed value of P at 0000 UTC at the time when forecast is issued and ΔP is the 24 hours change of P at the observation time. It is expected that ΔP derived from NWP model output may provide better results. Here we test the performance of model with the developed dataset using persistence method of estimating predictors. It is in other words, we used 0000 UTC observations (predictors) to forecast occurrence of fog on the next day morning. For the purpose of evaluating the skill of the method, we compute categorical statistics (Stanski *et al.*, 1989) such as bias and threat skill scores. A bias score (B) and threat score (T) are defined as :

$$B = (F+H)/(M+H)$$

$$T = H/(F+M+H)$$

Where,

F = Number of false alarm (occurrence of fog forecast but is not realised)

M = Number of missing (non-occurrence of fog forecast but fog occurred)

H = Number of hits (forecast occurrence as well as non occurrence of fog is realised)

Bias score (B) and threat score (T) becomes 1 in case of F=M=0. When a bias score is less than unity the model indicates under-forecast, otherwise over-forecast.

The skill score obtained from the development data set are as follows :

H	F	M	B	T
146	12	28	0.86	0.78

The result shows scores are reasonably good but forecast is slightly under predicted.

The skill scores obtained from the independent dataset of December 2000 and January 2001 are shown below :

H	F	M	B	T
55	5	2	1.05	0.88

In this case forecast is slightly over predicted but reasonably good skill score is noticed.

The skill score computed for the months of December 2001 and January 2002 are also given below:

H	F	M	B	T
44	13	5	1.16	0.72

7. Summary and concluding remarks

In this paper occurrence of fog over Delhi has been examined in terms of synoptic evaluation using model analysis field and sounding analysis of Delhi. Finally an objective technique is developed using the sounding data applying graphical discriminating analysis for prediction of occurrence of fog over Delhi.

Synoptic evaluation based on the intercomparison of lower level flow pattern and relative humidity of December between the two contrasting years of 1999 and 2000 reveals that domination of fog during December 1999 was due to increased moisture over the region under the influence of prevailing easterlies in the boundary layers from the Bay of Bengal and advection of cold air by the northerlies to the west of Delhi.

Sounding analysis of Delhi reveals that fog occurrence of Delhi are dominant when the wind speed at 1000 hPa does not exceed 5 knots, minimum temperature is less than 9° C, dew point depression (1000 hPa) is less than 6° C and dew point (1000 hPa) is greater than 6° C. It is also very interesting to note that most of the fog occurrences are associated with the backing condition of wind between 1000 hPa and 700 hPa.

The objective method developed based on sounding data of Delhi with these threshold values at different ranges is found reasonably skillful. However, success of this technique depends on the skill of accurate estimation of the predictors. Though the technique is developed for prediction of occurrence of fog for 24 hours in advance, the forecast can be updated during subsequent observation hours depending on the trend of the predictors, utilising synoptic knowledge and numerical guidance from NWP models.

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