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Verification of visibility forecasts from NWP model with satellite and surface observations

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सार – शीत ऋतु में भारत-गांगेय मैदानी क्षेत्र के अधिकांश भागों में कोहरे और दृश्यता का पूर्वानुमान करना महत्वपूर्ण होता जा रहा है क्योंकि घने कोहरे और कम दृश्यता की घटनाओं की अधिक बारम्बारता का सामाजिक-आर्थिक पक्ष पर प्रभाव पड़ता है। कोहरे का जीवनचक्र मुख्यतः विभिन्न मौसम विज्ञानिक कारकों से और वातावरण में कणिका द्रव्य की सूक्ष्म भौतिकी/रासायनिक विशेषताओं द्वारा नियंत्रित होता है। उच्च स्थानिक विभेदन वाले सांख्यिकीय मौसम पूर्वानुमान (एन डब्ल्यू पी) के वर्तमान मॉडल कुछ दिन पहले ही कोहरे के लिए अनुकूल परिस्थितियों का पूर्वानुमान समुचित सटीकता के साथ लगा सकते हैं। एन सी एम आर डब्ल्यू एफ ने नैदानिक फॉग स्कीम वाले यूनीफाइड मॉडल (एन सी यू एम) का उपयोग करके दृश्यता/कोहरे का पूर्वानुमान देना आरंभ कर दिया है। मॉडल में दृश्यता का आकलन कोहरे के कणों के कारण दृश्य परिधि में प्रकाश के विलुप्त होने के आधार पर किया जाता है। इस शोध पत्र में भारत-गांगेय मैदानी क्षेत्रों में एन सी यू एम से प्राप्त दिसम्बर, 2013 और जनवरी, 2014 के महीनों के दौरान दृश्यता/कोहरे के पूर्वानुमान को सतह और उपग्रह के प्रेक्षणों का उपयोग करके सत्यापित किया गया है। सत्यापन के लिए मौसम विज्ञानिक हवाई अड्डा रिपोर्ट (मेटार) से सतही दृश्यता प्रेक्षण और मध्यम विभेदन प्रतिबिम्ब स्पेक्ट्रोरेडियोमीटर (मॉडिस) का उपग्रह आधारित कोहरा उत्पाद का उपयोग किया गया है। भारत-गांगेय मैदानी क्षेत्रों के विभिन्न स्थानों में भारी और हल्की कोहरे की घटनाओं को बताने के लिए इस अध्ययन में दृश्यता की दो श्रेणियों पर आधारित कोहरे/कोहरे न होने की घटना बताने में एन सी यू एम लघु अवधि पूर्वानुमान ने अच्छा प्रदर्शन किया है।

ABSTRACT. Forecast of fog and visibility over most parts of Indo-Gangetic plains are becoming increasingly important in the winter season because of the high frequency of occurrence of dense fog and reduced visibility which has significant socio-economic impacts. The life cycle of fog is mainly controlled by different meteorological factors and the microphysical/chemical properties of the particulate matter in the atmosphere. The present day numerical weather prediction (NWP) models of high spatial resolution are able to forecast situations that are favorable for the occurrence of fog events with reasonable accuracy for few days in advance. NCMRWF has started producing visibility/fog forecasts using the Unified Model (NCUM), which has a diagnostic fog scheme. The visibility is computed in the model based on the extinction of light at visible ranges due to fog particles. The visibility/fog forecasts during the months of December, 2013 and January, 2014 obtained from NCUM over the Indo-Gangetic plains are verified using the surface as well as satellite observations in this study. Surface visibility observations from meteorological airport reports (METAR) and satellite based fog product from Moderate Resolution Imaging Spectroradiometer (MODIS) are used for the verification. NCUM short-range forecast shows good skill in indicating the occurrence of fog/no-fog events, based on two visibility categories defined in this study to represent the heavy and light fog events, over different locations over the Indo-Gangetic plains.

Key words – Fog, Visibility, MODIS, NWP models.

1. Introduction

Fog is an important meteorological phenomenon, which have significant socio-economic impacts. In India, during winter months the entire Indo-Gangetic plains of Northern India are affected by poor visibility conditions very frequently due to occurrence of fog. Formation of fog over any area depends on the typical meteorological, environmental and prevailing terrain characteristics of that area (Choudhary *et al*., 2007). Fog is a boundary layer phenomena and the most common type of fog, radiation fog occurs when the radiational cooling at night decreases the air temperature to its dew point temperature. Lack of turbulence, high moisture, light winds and clear sky are the favourable conditions for the formation of fog. The most conducive conditions for the formation of radiation fog is stable boundary layer. Studies related to fog formation on local scales such as airports in India suggest that fog mostly forms in association with western disturbance. Brij *et al*. (2003) analyzed the synoptic conditions during four fog seasons and concluded that fog may persist under certain synoptic condition which provides favorable conditions. Though fog formation takes place in the Indo-Gangetic plains on synoptic scale, its characteristics may change over regional to local scales depending upon the surface types, urban and non-urban regions, water bodies and wet surfaces. Despite the large scale favorable synoptic conditions, there are number of other causes which lead to fog formation. It has been observed that pollution plays a significant role on fog formation over India. Studies indicated that probability of fog formation continuously increased over Indo-Gangetic plains, is related to the increased numbers of thermal power plants in this region which contributes towards higher aerosol concentration (Prasad *et al*., 2006). Some aerosols acts as cloud condensation nuclei (CCN), thus the increase of aerosols in lower atmosphere causes the condensation of water vapor present in the atmosphere due to higher availability of condensation nuclei.

Visibility has reduced significantly over Indian subcontinent over last 30 years (Wang *et al*., 2009). During recent years, in winter season, low visibility conditions are frequently observed over Indo-Gangetic plains due to occurrence of large-scale intense fog conditions over most parts of the region. The city of Delhi lies in the western part of Indo-Gangetic plains, and is found to be one of the most polluted cities (Goyal and Sidhartha, 2003). A number of studies have been carried out to analyze the effect of air pollutants on the visibility of Delhi (Goyal and Sidhartha, 2003; Tiwari *et al*., 2011) also some studies (Tiwari *et al*., 2011; Mohan and Payra, 2009) focus on winter season when fog formation takes place. A few studies have been carried out to investigate the role of aerosols in reducing the visibility over Delhi (Singh and Dey, 2012). Fog formation in winter season in Delhi and nearby regions causes drastic reduction in visibility. In such cases, the air traffic not only gets affected at Delhi but also causes simultaneous closing of other nearby airports (Lucknow, Jaipur etc. due to large spatial extent of fog in the Indo-Gangetic plains. High aerosol concentration is found over Indo-Gangetic plains (Tiwari *et al*., 2011) which leads to frequent fog formation and reduction in visibility during winter season.

Fog and visibility prediction are a challenge to numerical weather prediction (NWP) models because the spatial and temporal scales of the event are highly variable and also of the complex processes associated with it. In addition, to fine horizontal resolution to represent the surface conditions (orography, soil, water and vegetation properties) which influence the fog formation, NWP models used for fog forecasting also require fine vertical resolution near the surface to resolve the processes in the near surface layers of atmosphere. NWP models are found to perform better when the fog and associated low visibility condition is widespread.

NCMRWF adapted Unified Model of Met Office, UK for numerical weather prediction of medium and extended range (NCMRWF Unified Model, NCUM). The present horizontal resolution of the model is approximately 25 km and has 70 vertical levels. The first level of the model is 20 meter above surface and top at 80 km. Visibility/Fog forecasts are generated using the NCUM, which has a diagnostic scheme for fog and visibility described in Section 2. The objective of the present study is to verify the visibility forecast from NCUM over different parts of Indo-Gangetic plains against surface and satellite observations. The data used in the present study for verification of visibility forecast is discussed in section 3. Section 4 is about the identification of fog spell and type based on METAR visibility observations available from different airports in the Indo-Gangetic plains during the period December, 2013 - March, 2014. Section 5 provides the verification of visibility forecast with satellite and METAR observations.

2. Diagnosis of visibility in NCUM

Visibility in NCUM, is a function of humidity and aerosol content. Clark *et al*. (2008) provides a detailed description of how visibility and aerosol content is related, which is being used in the NCUM fog scheme. Determination of atmospheric visibility mainly depends on two crucial factors; one is the relative humidity and second is the aerosol concentration (Koschmeider, 1924). A simple exponential scattering law is used to diagnose visibility in the model. For a given extinction coefficient β_{tot}, visibility is defined as

$$vis = -\frac{\ln \varepsilon}{\beta_{tot}} \tag{1}$$

where, ε is a fixed liminal contrast ((Koschmeider, 1924) assumed as 0.02 and β_{tot} is the total extinction coefficient of the atmosphere given as:

$$\beta_{tot} = \beta_{air} + \beta(RH, m) \tag{2}$$

The first term on R.H.S. of eqn. (2) (β_{air}) represents the extinction coefficient due to clean air and is taken equal to a visibility of 100 km to ensure that model will not produce unrealistic high visibility values. The second term represents the extinction coefficient due to aerosol particles which depends on relative humidity (RH) and dry aerosol mass mixing ratio (m).

TABLE 1

General visibility ranges and types of fog

Fog types	General visibility range (m)	General visibility range (m) used in present study
Shallow fog	1000-500	1000-200 (Light fog)
Moderate fog	500-300	
	350-200	
Dense fog	200-50	200-0 (Dense fog)
Very dense fog	<50	

Visibility is primarily determined by aerosol concentrations only when relative humidity is well below 100%. When relative humidity reaches close to or exceeds 100% aerosols particles rapidly take up water due to their hygroscopic nature (Kotchenruther *et al*., 1999) and become activated fog droplets. In the model, Clark *et al.* (2008) parameterized the hygroscopic growth of aerosol using simplified Kohler curve (Pruppacher and Klett, 1978), neglecting the effect of surface tension and with an activation parameter (B) of 0.5. The activation parameter B is further modified into 0.14 in the model based on the observations (Haywood *et al*., 2008).

In the model, β (RH, m) is expressed as

$$\beta(RH,\, m) = \pi Q\left(\frac{\overline{r^2}}{r_m^2}\right) N r_m^2 = \beta_0 N r_m^2 \tag{3}$$

where $\beta_o = \pi Q \eta \; and \; \eta = \overline{r^2} / r_m^2$, where Q is the extinction efficiency of aerosol particle, N is the aerosol number density, r is the radius of aerosol particles and r_m is the mean droplet radius given by

$$r_m = r_{md}\left[1 - \frac{B}{\ln(RH)}\right]^{1/3} \tag{4}$$

where r_{md} is the dry mean droplet radius.

3. Data

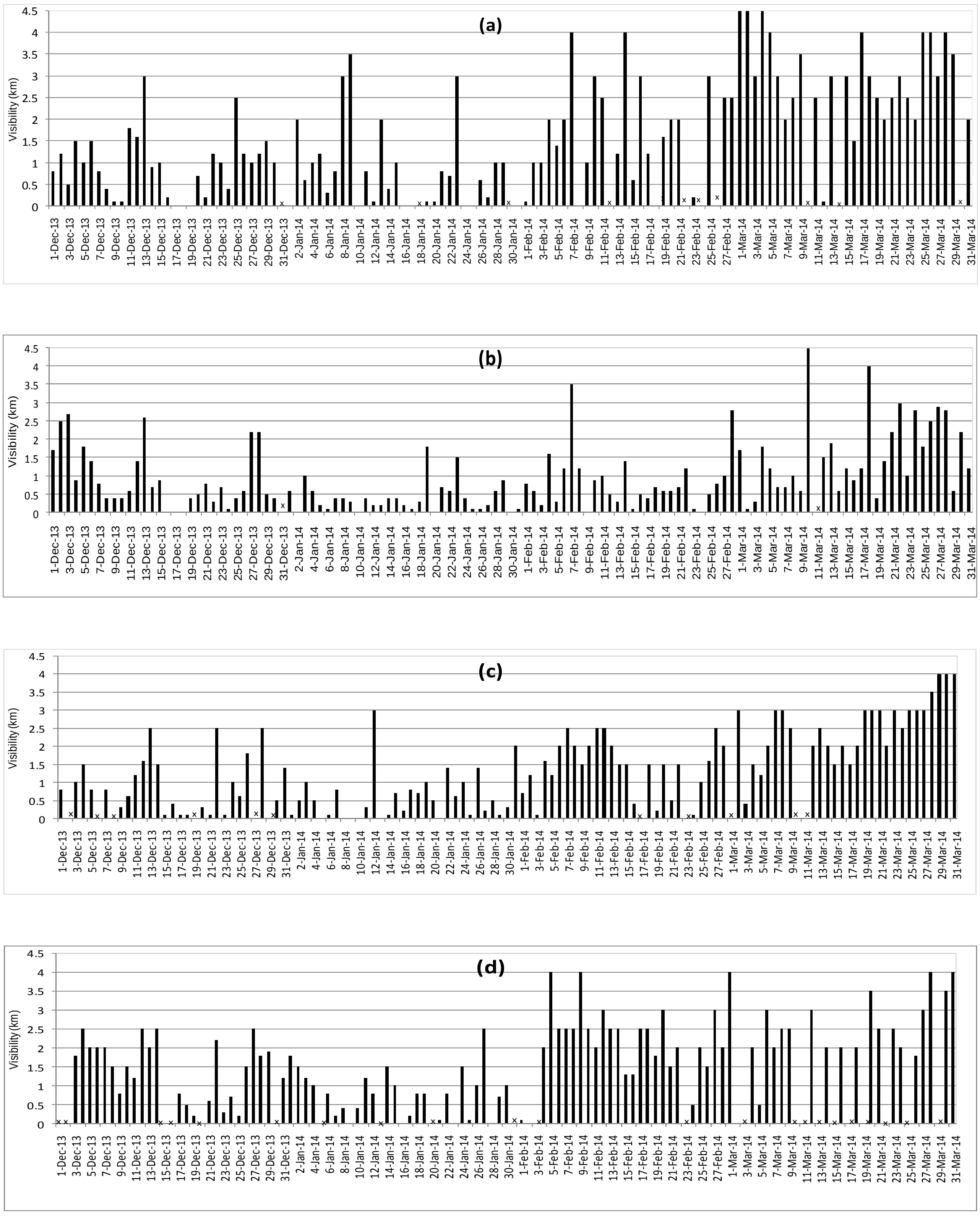
Visibility forecasts at an interval of three hours are generated daily for the entire forecast length of the NCUM every day (currently ten days). Visibility is calculated in meters at a single model level or level within surface layer (*e.g.*, 1.5 m). It is found that NCUM forecast values are generally one order higher compared to the observed values. Thus, in this study the model forecast values are divided by 10 and used in the forecast skill computations (however in figures, actual model forecast values are depicted). Visibility forecasts obtained from NCUM over Indo-Gangetic plains are verified against spatial extent of Moderate Resolution Imaging Spectroradiometer (MODIS) fog images (available at India Meteorological Department (IMD) website www.imd.gov.in). MODIS instrument, aboard the Terra and Aqua satellites, measures radiances in 29 spectral bands in 1 km, 5 bands in 500 m and 2 bands in 250 m resolution (King *et al*., 1992). MODIS fog detection scheme for representation of horizontal extent of fog is based on brightness temperature difference of radiances at 3.9 micron and 10.7 micron ($BT_{3.9}$ - $BT_{10.7}$) (Bendix *et al*., 2004).

Visibility forecasts at different airports locations in Indo-Gangetic plains are verified with Meteorological Airport Reports (METAR), which contains weather information from airport. METARS contains data for temperature, dew point temperature, wind speed and direction, precipitation, cloud cover and heights, visibility and barometric pressure. Half hourly METAR observations are available through Global Telecommunication System (GTS). Visibility in METARS is given in meters and is reported as prevailing visibility, which is the greatest distance that can be seen throughout at least half of the horizon circle. This is measured at different airports by eye estimation by observing different prefixed visibility landmarks and then superposing them on visibility polar diagram for estimating the final value (Jenamani and Tyagi, 2011) or through runway visibility measurement instruments in an interval of at least 30 minutes. Table 1, gives the classification of different types of fog depending on the values of visibility observations from METARS along with the criteria used in the present study to categorize the fog.

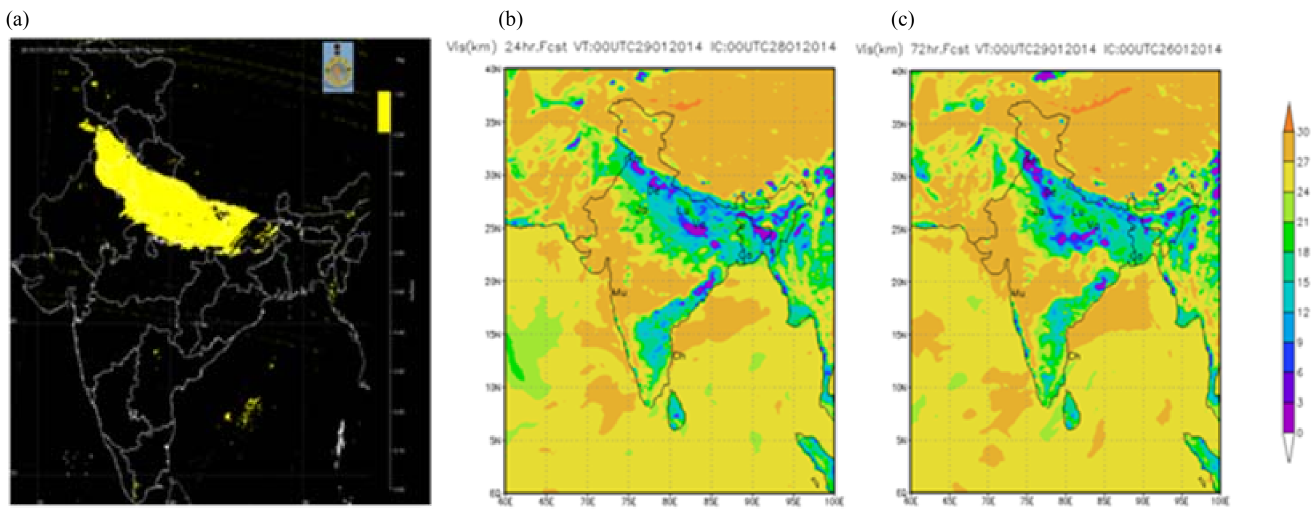
4. Identification of different fog spells over Indo-Gangetic Plains during winter season (December 2013 - March 2014)

To verify the visibility/fog forecast obtained from NCUM, the METAR observations available from different airports in the Indo-Gangetic plains are analyzed during the winter season (December 2013 - March 2014). The fog spells are identified based on the criteria given in Table 1, using METAR visibility observations. The METAR reports of four airports, Amristar, Delhi, Lucknow and Varanasi are used in the present study.

Fig. 1 shows the observed visibility at 0000 UTC from December 2013 - March 2014 at all the four airports. Fig. 1(a) shows the observed visibility from METAR



Figs. 1(a-d). Observed visibility from surface observations (METAR) at 0000 UTC during December 2013 - March 2014 for (a) Amritsar (b) Delhi (c) Lucknow and (d) Varanasi (*x* denotes observations NOT available)



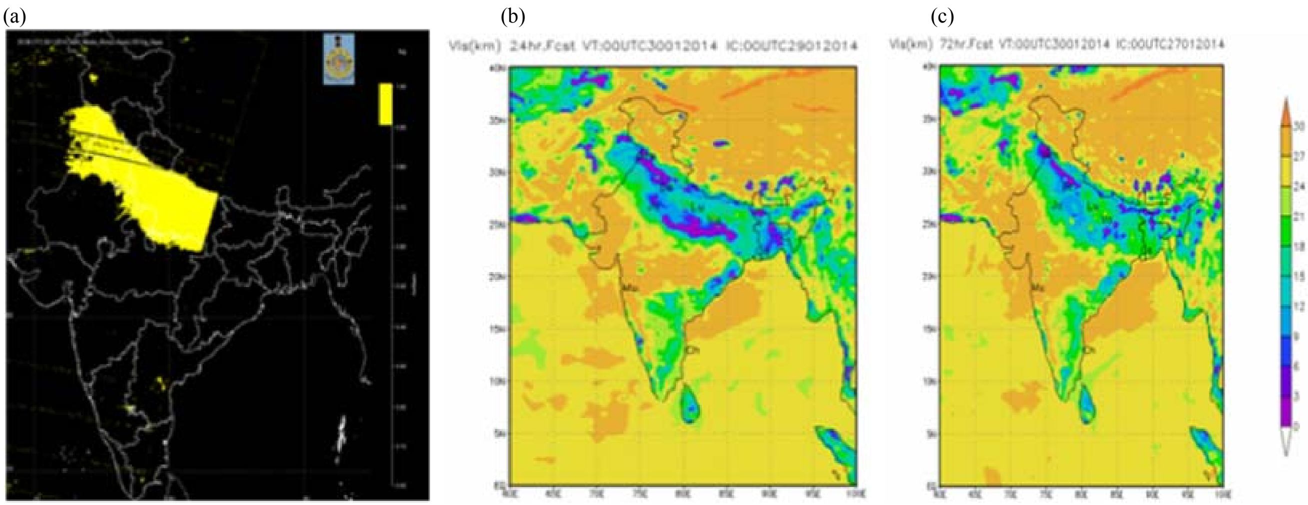
Figs. 2(a-c). Comparison of spatial extent of fog observed from (a) MODIS with (b) Day-1 and (c) Day-3 forecast of visibility (km) from NCUM valid for 29th January, 2014

observations at 0000 UTC from December 2013 to March 2014 at Amritsar. Visibility is found to be less than 1 km for eleven days, in which dense fog visibility of less than 200 m is observed only for three days and visibility values less than or equal to 1 km (light fog) for the remaining eight days during December 2013. Visibility is found to be greater than 1 km for remaining days indicating no fog. During January 2014, visibility is less than 200 m for eleven days which indicates the occurrence of dense fog. Moderate to shallow fog (light fog category-visibility less than 1 km) is observed for twelve days and no fog is reported for six days. Dense fog is observed only for two days and moderate fog is observed only for one day, fog was not observed for other days during February 2014. Similarly for March 2014, no fog was observed except for one day (12th March) when visibility was less than 200 m [Fig. 1(d)]. Thus, maximum number of days for which dense fog was observed over Amritsar was in January 2014.

Visibility observations over Delhi for the winter season at 0000 UTC are shown in Fig. 1(b). During December 2013, no fog was observed (visibility greater than 1 km) for nine days, fog was observed for twenty one days, in which dense fog was observed only for four days and for rest of the days light fog was observed. During January 2014, visibility observations over Delhi show moderate fog (visibility less than 600 m) for most of the days. Visibility is found to be less than or equal to 200 m for fourteen days in the month of January which indicates dense fog. For remaining days, visibility is found to be less than or equal to 1.0 km, which corresponds moderate to shallow fog. Only two non foggy days in Delhi are observed at 0000 UTC during January, which have visibility above 1 km. Fog is observed for most of the days (eighteen) over Delhi during February 2014, in which dense fog is observed for three days Dense fog is observed only for one day whereas light fog was observed for eight days during March 2014 over Delhi.

Fig. 1(c) shows the variation of observed visibility at 0000 UTC over Lucknow during December 2013 - March 2014. Over Lucknow, fog is observed for fourteen days in December 2013, with five days corresponding to dense fog and remaining corresponding to light fog. The observations at 0000 UTC for January 2014, indicate visibility less than or equal to 200 m for thirteen days which corresponds to dense fog. Fog was moderate to shallow for fourteen days with visibility greater than 200 m but less than or equal to 1.0 km. For four days visibility is found to be greater than 1.0 km at Lucknow at 0000 UTC. During February 2014, dense fog was observed only for three days whereas three days corresponds to light fog. Light fog is observed only for one day over Lucknow during March 2014 and no fog is observed for other days.

Over Varanasi the observed visibility at 0000 UTC during December 2013 - March 2014 is shown in Fig. 1(d). Fog is observed only for eight days over Varanasi in which dense fog is observed only for two days during December 2013. During January 2014, dense fog (visibility less than 200m) is observed for seven days. Moderate to shallow fog (visibility between 1.0 km



Figs. 3(a-c). Comparison of spatial extent of fog observed from (a) MODIS with (b) Day-1 and (c) Day-3 forecast of visibility (km) from NCUM valid for 30th January, 2014

and 200 m) is observed for ten days and fog was not observed (visibility higher than 1.0 km) for seven days in January 2014. During February 2014, only one day dense fog and one day light fog was observed. In March 2014, light fog is observed only for one day.

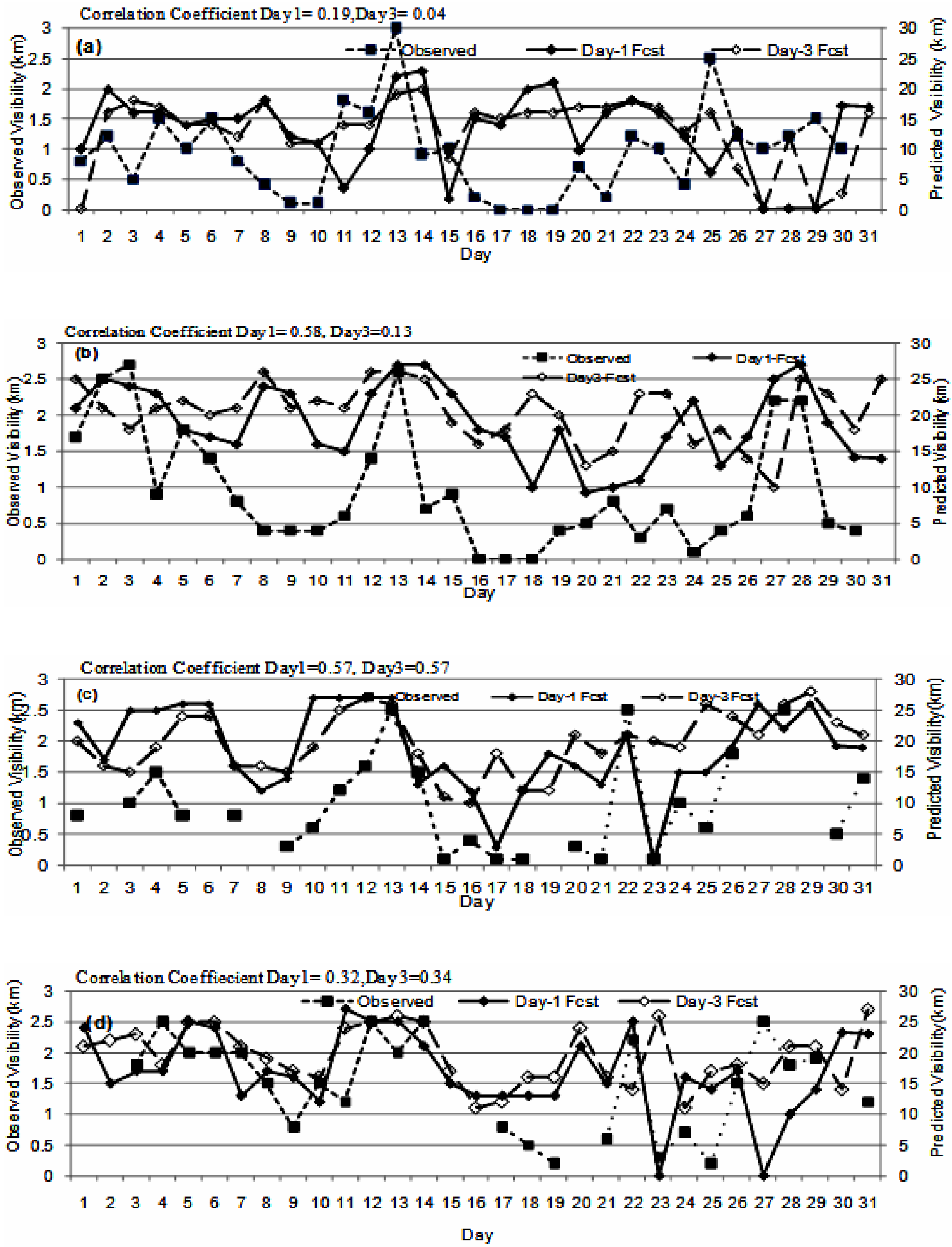
Based on the above analysis, it is clear that at all the four stations the maximum numbers of foggy days including both dense and light fog are observed during January 2014. During December 2013, few days of light fog were observed but dense fog events were rare. But during February and March 2014, occurrence of fog was very rare at all the four locations. Thus, the visibility/fog forecast obtained from NCUM during December 2013 and January 2014 at different stations is verified against observations.

To identify the common fog spell at all the airports further visibility observations from METAR reports of different stations are analyzed for the entire winter season. As discussed above very few foggy days were observed at all the stations during the whole winter season except January, the common fog spell at all the airports is found during January 2014. During 4 - 6, 6 - 13, 14 - 18, 20 - 26 and 29 - 31 of January 2014, long duration fog spells (visibility ranging from 200 m to 1.0 km) were observed over Delhi, and Lucknow, however over Amritsar the fog spells were experienced during 14 - 22 and 24 - 31 January. Due to non availability of observations over Varanasi for few days, it is difficult to identify the exact fog spells at this location. However, the observations indicate three fog spells from 4 - 10, 16 - 23 and 28 - 31 January at Varanasi. Thus, it can be concluded that Indo-Gangetic plains experienced severe fog spells a number of times during the month of January. For all the four stations the common fog spell identified from the analysis of METAR observations is during 29 - 31 January.

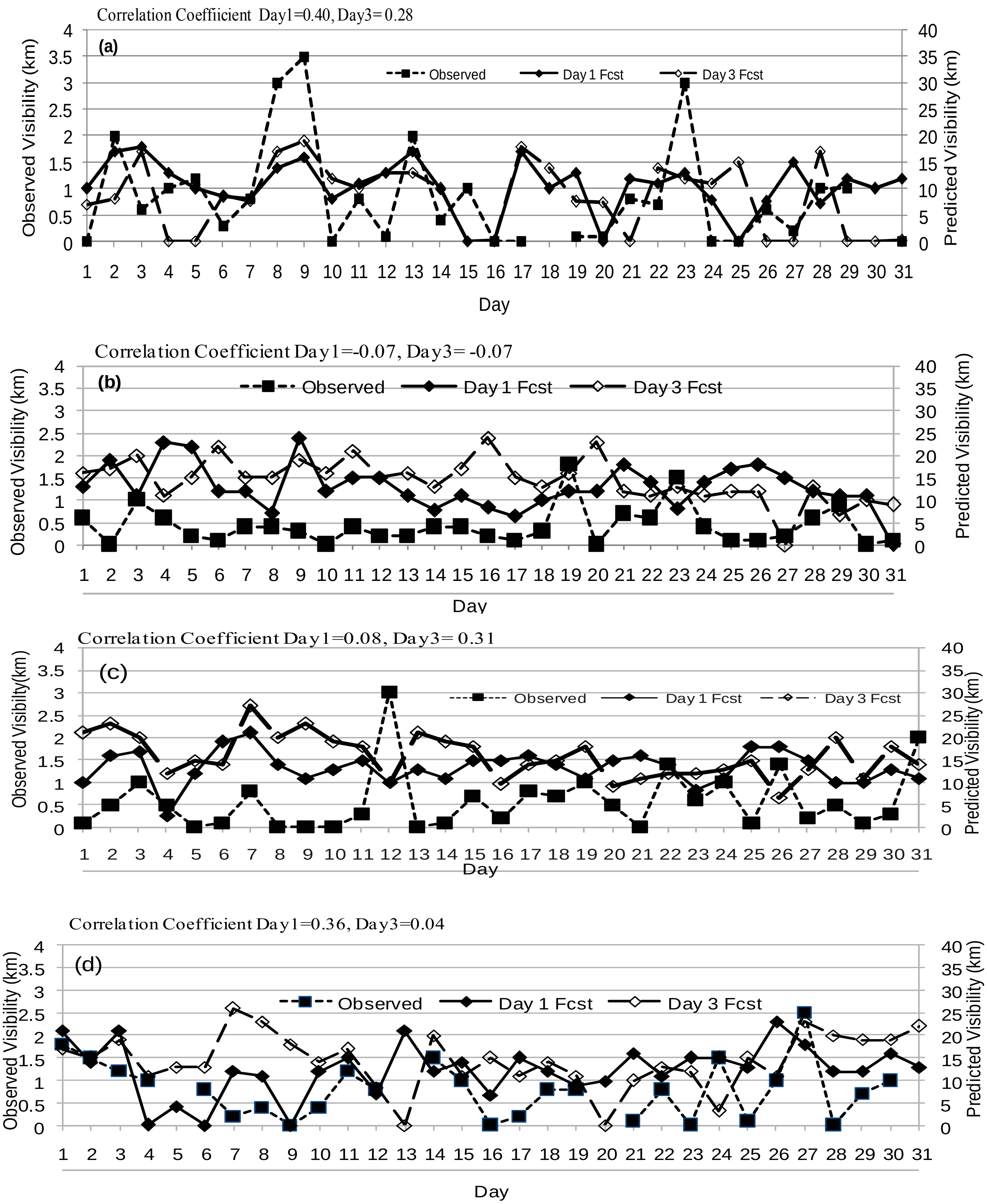
The spatial extent of the fog spells during this episode can be analyzed using the MODIS observation of fog and it was found that the Indo-Gangetic plains experienced fog spells coinciding with the METAR visibility observations. Fig. 2(a) and Fig. 3(a) show image of the MODIS night pass of 2200 UTC of 29th and 2300 UTC of 30th January respectively in which dense fog is detected over Indo-Gangetic plains including Amritsar, Delhi, Lucknow and Varanasi.

5. Verification of visibility forecast from NCUM with observations

The common fog spell experienced at all the four stations lying in the Indo-Gangetic plains is between 29 - 31 January. The spatial extent of fog for the selected fog spell can be analyzed using MODIS fog image. Visibility forecasts available from NCUM are compared with the observed fog images from MODIS. Figs. 2(a-c) shows the MODIS fog image for 2200 UTC of 29 January along with the Day-1 and Day-3 forecast valid for the same date. It is clear from the MODIS image that fog was observed over Indo-Gangetic plains from west to east including Amritsar, Delhi, Lucknow and Varanasi. Day-1 forecast from NCUM valid for 29th January [Fig. 2(b)] also shows low visibility over Indo-Gangetic plains. Model predicted



Figs. 4(a-d). Comparison of Day-1 and Day-3 forecast of visibility from NCUM with METAR observations at (a) Amritsar, (b) Delhi, (c) Lucknow and (d) Varanasi during December, 2013



Figs. 5(a-d). Comparison of Day-1 and Day-3 forecast of visibility from NCUM with METAR observations at (a) Amritsar, (b) Delhi, (c) Lucknow and (d) Varanasi during January, 2014 visibility is minimum at Amritsar, Delhi and Varanasi, however over Lucknow predicted visibility is found to be relatively higher. Day-3 forecast of visibility [Fig. 2(c)] is small over Indo-Gangetic plains including all the four stations. Thus, the model is able to capture the spatial extent of the fog event in this case.

Comparison of spatial extent of fog using MODIS fog image for 30th January with Day-1 and Day-3 forecast of visibility obtained from NCUM is shown in Figs. 3 (a-c). Predicted visibility is in minimum range for all the four stations in Day-1 forecast [Fig. 3(b)]. Day-3 forecast [Fig. 3(c)] of visibility also shows the low visibility over entire Indo-Gangetic plains. Visibility is more in Day-3 forecast at Varanasi as compared to Day-1 forecast. Both Day-1 and Day-3 forecasts show drop in visibility over the areas where the fog is indicated in the MODIS spectral differential fog product. Thus, NCUM is able to capture the spatial extent of fog up to three days in advance in some cases.

Day-1 and Day-3 forecasts of visibility from NCUM are compared with METAR observations at all the four stations during December 2013 and January 2014. Figs. 4(a-d) shows the comparison of Day-1 and Day-3 forecasts of visibility obtained from NCUM with observed visibility from METAR reports at 0000 UTC at all the four stations during December 2013. It can be seen that at all the four stations the trend in visibility is captured well in both Day-1 and Day-3 forecast however the values of predicted visibilities are found to be much higher as compared to the observations. NCUM is able to capture the drop in visibility as observed both in Day-1 and Day-3 forecast. For all the stations visibility is found to be decreasing from 7 - 9 December. It is clear from Fig. 4(a) that over Amritsar NCUM is able to predict the drop in visibility from 8 - 9 December in both Day-1 and Day-3 forecasts but from 7 - 8 December both Day-1 and Day-3 predicts increase in visibility. However, over Delhi both Day-1 and Day-3 forecasts shows decrease in visibility from 7 - 8 December [Fig. 4(b)] in agreement with the observations. Similarly over Lucknow, Day-1 forecast show drop in visibility from 7 - 8 December but then increase in visibility from 8 - 9 December however, Day-3 forecasts show decrease in visibility from 7 - 9 December [Fig. 4(c)]. Similar situation is found over Varanasi, with Day-1 forecast predicting increase in visibility from 7 - 8 December and then drop in visibility from 8 - 9 December. Day-3 forecast predict the drop in visibility from 7 - 9 December [Fig. 4(d)].

Figs. 5(a-d) shows the comparison of Day-1 and Day-3 forecasts of visibility obtained from NCUM with observed visibility from METAR reports at 0000 UTC during January 2014 for all the four stations. It can be seen that NCUM is able to indicate the drop in visibility during various fog spells experienced over different stations, although the magnitude of model visibility values are much higher compared to the observations. However, in most of the cases, NCUM is not able to predict sudden increase or decrease in visibility as observed in the METAR observations. The comparison of Day-1 forecast of visibility from the model with the observations over Amritsar [Fig. 5(a)] indicates that model is able to predict the drop in visibility during fog events 5 - 6, 9 - 10, 13 - 14 and 23 - 24 January as observed in the METAR observations. Similarly, over Delhi, NCUM shows the drop in visibility in one day advance during the intense fog spells 4 - 6, 9 - 11 and 29 - 31 January [Fig. 5(b)]. NCUM is able to capture the drop in visibility as observed in METAR observations over both Lucknow [Fig. 5(c)] and Varanasi [Fig. 5(d)] reasonably well. Thus, in good number of fog cases during January, NCUM is able to indicate the drop in visibility at different places in Indo-Gangetic plains. However, model is not able to forecast the reduction in visibility in some cases. For instance, over Delhi [Fig. 5(b)], the observations indicate a drop in visibility from 24 - 26 whereas model predicted an increase in the visibility in Day-1 forecast and decrease in its Day-3 forecast. Also, in some cases, NCUM over-predicted the reduction in visibility.

To understand the relation between the location specific observed and predicted values of visibility more clearly, correlation coefficients are computed for Day-1 and Day-3 forecast of visibility with METAR observation at all the four stations for the month of December 2013 and January 2014 [correlation coefficient values are given in Figs. 4(a-d). and Figs. 5(a-d)]. During December 2013, highest correlation between the forecast and observation is found at Delhi and Lucknow for Day-1 forecast whereas lowest is seen over Amritsar. For Day-3 forecast, highest correlation is found over Lucknow and lowest over Amritsar. However, Delhi and Lucknow shows a very poor correlation between the observed and forecast values in January. But over Amritsar, the January values are better than that in the December month.

To verify the forecast skill of fog from the NCUM, the Day-1 and Day-3 visibility forecasts during December 2013 and January 2014 are converted to dichotomous (Yes/No) forecast. A dichotomous forecast says "yes, an event will happen", or "no, the event will not happen" by specifying a threshold to separate "yes" and "no" events. The fog is classified into two categories in this study, the dense fog and light fog and yes/no forecast of both the categories are verified. The light fog is combined class of moderate and shallow fog whereas dense fog represents dense and very dense fog (Table 1). The four

TABLE 2

Forecast skill for Day-1 and Day-3 forecast of visibility (divided by 10.0) from NCUM during December 2013 using Dichotomous (Yes/No) forecast with visibility threshold as 1 km

Statistics	Amritsar		Delhi		Lucknow		Varanasi	
	Day-1	Day-3	Day-1	Day-3	Day-1	Day-3	Day-1	Day-3
Hits	06	04	04	00	03	01	01	00
Misses	11	16	18	21	15	15	07	08
Correct negatives	08	09	08	08	07	09	15	17
False alarms	05	01	00	01	00	00	02	00
Total	30		30		25		25	
Forecast skills								
Accuracy	0.46	0.43	0.40	0.26	0.40	0.40	0.64	0.68
Bias	0.64	0.25	0.18	0.05	0.16	0.06	0.37	0.00
Threat score	0.27	0.19	0.18	0.00	0.16	0.06	0.10	0.00
False alarm ratio	0.45	0.2	0.00	1.00	0.00	0.00	0.66	0.00

combinations of forecasts (yes or no) and observations (yes or no) called the joint distribution, are:

- Hit - event forecast to occur and did occur
- Miss - event forecast not to occur, but did occur
- False Alarm - event forecast to occur, but did not occur
- Correct Negative - event forecast not to occur, and did not occur

Based on the different combinations of joint distribution a number of categorical statistical measures are computed based on WMO 2008, to describe the particular aspects of forecast performance. Categorical statistics which are computed in the present study from the yes/no contingency table for both categories (dense fog and light fog) are:

Accuracy (Fraction Correct) **:** It gives what fraction of the forecast are correct overall and is defined as:

Accuracy = (Hits + Correct Negatives) / Total

The perfect score is 1 and it ranges from 0 to 1.0.

Bias Score (frequency bias) **:** It is a measure of ratio of the frequency of forecast events to the frequency of observed events. It ranges from 0 to infinity with perfect score of 1.0.

Bias = (Hits + False Alarms) / (Hits + Misses)

Threat Score **:** Gives a measure of the fraction of observed and/or forecast events that are correctly predicted, *i.e.*, how well the forecast "yes" events corresponds to observed "yes" events.

Threat Score = Hits / (Hits + Misses + False Alarms)

It has a perfect score of 1.0 with range from 0 to 1.0 and 0 indicates no skill.

False Alarm Ratio **:** Gives the measure of what fraction of predicted "yes" events actually did not occur.

False Alarm Ratio = False Alarms / (Hits + False Alarms)

For all the four stations, the Yes/No forecast is computed with two classes (dense fog and light fog). The light fog represents visibility between 200-1000 m and the dense fog corresponds to visibility less than 200 m. The number of hits, misses, false alarm and correct negative for all the four stations are listed in Table 2 based on 24 hr forecast (Day-1 forecast) and 72 hr forecast (Day-3

TABLE 3

Forecast skill for Day-1 and Day-3 forecast of visibility divided by 10.0) from NCUM during December 2013 using Dichotomous (Yes/No) forecast with visibility threshold as 200 m

Statistics	Amritsar		Delhi		Lucknow		Varanasi	
	Day-1	Day-3	Day-1	Day-3	Day-1	Day-3	Day-1	Day-3
Hits	00	00	00	00	02	00	01	00
Misses	07	06	04	04	02	05	02	02
Correct negatives	20	21	26	26	21	20	21	23
False alarms	03	03	00	00	00	00	01	00
Total	30		30		25		25	
Forecast skills								
Accuracy	0.66	0.70	0.86	0.86	0.92	0.80	0.88	0.92
Bias	0.92	0.00	0.00	0.00	0.50	0.00	0.66	0.00
Threat score	00	0.00	0.00	0.00	0.50	0.00	0.25	0.00
False alarm ratio	1.0	1.0	0.00	0.00	0.00	0.00	0.5	0.00

TABLE 4

Forecast skill for Day-1 and Day-3 forecast of visibility (divided by 10.0) from NCUM during January 2014 using Dichotomous (Yes/No) forecast with visibility threshold as 1 km

Statistics	Amritsar		Delhi		Lucknow		Varanasi	
	Day-1	Day-3	Day-1	Day-3	Day-1	Day-3	Day-1	Day-3
Hits	12	03	11	08	08	04	07	05
Misses	11	08	18	21	19	23	14	15
Correct negatives	04	12	01	02	01	02	06	06
False alarms	02	06	01	00	03	02	00	01
Total	29		31		31		27	
Forecast skills								
Accuracy	0.55	0.65	0.38	0.32	0.35	0.19	0.48	0.40
Bias	0.60	0.74	0.41	0.28	0.33	0.22	0.33	0.30
Threat score	0.48	0.60	0.36	0.28	0.28	0.13	0.33	0.24
False alarm ratio	0.14	0.20	0.08	0.0	0.11	0.33	0.0	0.16

forecast) during December 2013 with visibility threshold of 1 km. At all the stations the number of misses is found to be more as compared to hits in both Day-1 and Day-3 forecasts. At Amritsar and Delhi misses are found to be more for Day-3 forecast. The accuracy by which model is able to predict the moderate to shallow fog in Day-1 forecast is found to be 46% at Amritsar, 40% at Delhi, 40% at Lucknow and 64% at Varanasi. Almost same accuracy is observed for all the stations in Day-3 forecast except Delhi where it is found to be 26%. The numbers of correct negatives indicate that model is able to predict the non fog events reasonably well.

TABLE 5

Forecast skill for Day-1 and Day-3 forecast of visibility (divided by 10.0) from NCUM during January 2014 using Dichotomous (Yes/No) forecast with visibility threshold as 200 m

Statistics	Amritsar		Delhi		Lucknow		Varanasi	
	Day-1	Day-3	Day-1	Day-3	Day-1	Day-3	Day-1	Day-3
Hits	03	03	01	01	00	00	01	00
Misses	08	08	13	13	13	13	08	08
Correct negatives	17	12	17	17	18	18	16	19
False alarms	01	06	00	00	00	00	02	00
Total	29		31		31		27	
Forecast skills								
Accuracy	0.68	0.51	0.58	0.58	0.58	0.58	0.62	0.70
Bias	0.36	0.81	0.07	0.07	0.0	0.0	0.33	0.0
Threat score	0.25	0.17	0.07	0.07	0.0	0.0	0.09	0.0
False alarm ratio	0.25	0.66	0.0	0.0	0.0	0.0	0.66	0.0

To verify the model performance further, Yes/No forecast is used with visibility threshold of 200 m. Table 3 gives the joint distribution along with forecast skill scores for all the four stations for both Day-1 and Day-3 forecasts during December 2013. Over Amritsar and Delhi no hits are found in both Day-1 and Day-3 forecasts however, over Lucknow and Varanasi the number of hits are found to be 2 and 1 respectively in Day-1 forecast and no hits are found in Day-3 forecasts. The number of misses is also found to be small for all the stations in both Day-1 and Day-3 forecasts and the maximum number of correct negatives are found at all the stations in both Day-1 and Day-3 forecasts. The accuracy is found to be more than 60% at all the stations in both Day-1 and Day-3 forecasts.

Table 4 lists the number of hits, misses, false alarm and correct negative for all the four stations based on Day-1 forecast and Day-3 forecast during January 2014 for visibility threshold of 1km. It is clear that for Day-1 forecast with visibility threshold of 1 km maximum numbers of hits are found for Amritsar and Delhi, whereas for Lucknow and Varanasi numbers of misses are found to be greater than the number of hits. The statistics indicate that model is able to predict the moderate to shallow fog in one day in advance with accuracy of 55% at Amritsar, 38% accuracy at Delhi, 35% at Lucknow and 48% at Varanasi. Other scores also indicate that performance of model is found to be reasonably good over all the stations in predicting the moderate to shallow fog in one day advance For Day-3 forecast with visibility threshold of 1 km the number of hits are found to be less as compared to Day-1 forecast at all the stations. The statistics indicate that model is able to predict the moderate to shallow fog in three day advance with accuracy of 65% at Amritsar, 32% at Delhi, 19% at Lucknow and 40% at Varanasi. The reasonably high values of threat score indicates that the model has some skill in forecasting the moderate to shallow fog.

Table 5 gives the joint distribution along with forecast skill scores for all the four stations for both Day-1 and Day-3 forecasts with visibility threshold of 200 m during January 2014. The numbers of hits are found to be very less for all the four stations as compared to the misses in both Day-1 and Day-3 forecasts. However, for all the stations the number of correct negatives (*i.e.*, neither the fog was observed nor predicted) are found to be higher as compared to missed events. This indicates that the model presently has very little skill in forecasting dense fog events. However, the high correct negatives indicate that non-occurrence of events is satisfactorily produced by the model. Because of this (correct negatives), the accuracy for all the four stations is found to be more than 50 % in both Day-1 and Day-3 forecasts and more compared to the light fog events.

6. Conclusions

Visibility/fog forecast by NCUM over the Indo-Gangetic plains during December 2013 and January 2014 is verified using surface and satellite observations. The study is mainly focused on the Day-1 and Day-3 forecast of fog and visibility by the model. The model visibility forecast corresponds to two different visibility ranges, representing the dense and light fog, which is verified against visibility observations. The comparison of visibility forecast from model with MODIS fog product reveals that NCUM is able to indicate the spatial extent of the occurrence of fog three days in advance over most part of Indo-Gangetic plain. The surface visibility observations from METAR at four different locations over the Indo-Gangetic plain are also used for verification. It is found that NCUM 24 hour forecast shows good skill in indicating the occurrence of fog/no-fog events based on both visibility categories defined in this study over most of the locations selected for this study. The study is carried out for only one season. However, extensive verification study using a larger dataset can only provide the skill of the model forecast. Present study indicates that the skill of the model forecast as shown by threat score is more for the occurrence of light fog. However, in some cases the observed trend in visibility is not captured well by the model and the predicted visibility values are higher compared to the observations. The visibility forecast by the model is mainly dependent on the forecast accuracy of the near surface meteorological conditions. An improvement in the near surface weather forecast through high resolution models with realistic representation of surface processes may improve the fog forecast also. Currently the model uses climatological aerosol distributions. The visibility forecast can be further improved by realistic representation of aerosols and appropriate growth factors in the high resolution model.

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