An operational fog prediction system for Delhi using the 330 m Unified Model

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Funding information
NASA/HQ

We introduce the National Centre for Medium Range Weather Forecasting’s (NCMRWF) high-resolution (330 m) Unified Model implementation targeted at fog and visibility prediction over Delhi, the “Delhi Model” (DM). The requirement for running the DM in real time is that Delhi is highly vulnerable to fog-related issues and that low visibility conditions affect both airborne and ground transport during winter months. Enhanced orographic features at 330 m resolution, in conjunction with other surface boundary conditions used by the DM, have led to improvements in the simulation of spatio-temporal variability of visibility. During the winter season, the increased levels of pollution can have a significant impact on fog, or smog formation. Sensitivity experiments carried out using specified aerosol mass concentrations show that the visibility predicted by the DM is highly sensitive to the presence of aerosol. The impact of the urban heat island on visibility prediction is also investigated using recent high-resolution land use data from the Indian Space Research Organisation (ISRO) in the model.

KEYWORDS
fog, high-resolution model, pollution, visibility

1 INTRODUCTION
Fog is often not considered as an extreme weather event, but the low visibility associated with fog can create havoc in surface and air transport sectors, and affect many other socioeconomic factors, including public health. Delhi, the capital city of India, is one of the busiest places in the world and largely affected by poor visibility conditions during the winter period. Furthermore, enhanced pollution levels over Delhi may cause smog, which is a potential risk to human respiratory health through inhaled polluted substances. Improvement in low visibility predictions is crucial for taking necessary precautions so that the adverse effects can be minimized.

In general, skill of numerical models in predicting fog is relatively poor, since fog is a small-scale phenomenon and depends not only on the meteorological conditions (wind speed, humidity, temperature) but also on the surface and aerosol characteristics (Gultepe, Muller, & Boybeyi, 2006). Although a large number of observational studies regarding fog in Delhi based on ground-based instrumentation exist (e.g., Ghude et al., 2017; Mohan & Payra, 2009), modelling attempts in simulating fog formation processes are limited. Payra and Mohan (2014) present some three-dimensional (3D) simulations using the Weather Research and Forecasting (WRF) model, demonstrating that the model can produce reasonable forecasts at the mesoscale, but post-processing techniques can significantly improve the microscale skill. Visibility and fog predictions by the National Centre for Medium Range Weather Forecasting’s (NCMRWF) Unified Model (NCUM) global configuration were validated against satellite and ground-based visibility and fog measurements by Aditi, George, Gupta, Rajagopal, and Basu (2015). The study indicates the spatial extent of the low visibility areas (visibility < 1 km) associated with fog is simulated reasonably well, but not the magnitude of the visibility. It is expected that high-resolution models will
be able to reproduce the terrain features and associated turbulence characteristics more realistically than coarse resolution models. The Met Office London Model, covering a small area surrounding London at 330-m grid length (Boutle, Finnenkoetter, Lock, & Wells, 2016) is an ideal example of the efforts to improve fog forecasting by representing surface boundary conditions at fine resolution. This includes local orography, soil and vegetation, which can clearly influence better representation of fog formation, its distribution and dissipation. The classifications of different types of fog over India depending on the values of visibility observations are available in Aditi et al. (2015).

The aforementioned studies and importance of low visibility forecasts has motivated us to setup a model specifically for real-time fog and visibility prediction over the Delhi region at a high horizontal resolution, hereafter referred to as the “Delhi Model” (DM). The new generation high-performance computing infrastructure available at NCMRWF enabled us to run the DM at 330-m grid length. In the current study, we have evaluated the model performance and chosen some example fog case studies to discuss the sensitivity of results to aerosol concentrations and land use characteristics.

2 | MODEL DETAILS

A regional model configuration of the Unified Model (NCUM-R, Jayakumar et al., 2017) was used to setup the model over a domain covering the Delhi region at a horizontal grid length of 1.5 km. The initial and lateral boundary conditions are derived from the current operational 17-km grid length NCUM global model (Rakhi, Jayakumar, Sreevathsa, & Rajagopal, 2016). The details of the data assimilation employed in the parent global model (NCUM-GL) are given in George et al. (2016). Nested inside the NCUM-R, the DM covers a domain of 100 km × 100 km and is run for a forecast length of 36 hr based on 0000 UTC initial conditions. The NCUM-R model provides initial and boundary conditions to the DM at a downscaled resolution, and the boundary conditions are updated every 15 min. All atmospheric prognostic variables are provided by the parent model to the nested models through the lateral boundary conditions.

The model uses the ENDGame dynamical core (Wood et al., 2014) and a full suite of parameterized physical processes, such as mixed-phase microphysics (based on Wilson & Ballard, 1999), cloud (Smith, 1990), radiation (based on Edwards & Slingo, 1996) and land-surface scheme (Best et al., 2011). Critical relative humidity (RH) for the DM is higher than NCUM-R (Table S1 in Appendix S1, Supporting information) following the approach used in the London Model (Boutle et al., 2016), to simulate less sub-grid cloud cover variability in higher resolution models with respect to the coarse resolution model. The sub-grid turbulence scheme used here is the blended scheme (Boutle, Eyre, & Lock, 2014), which dynamically combines the one-dimensional (1D) boundary-layer scheme of Lock, Brown, Bush, Martin, and Smith (2000) with a 3D Smagorinsky scheme using a mixing factor of 0.5. The model time step of the DM is 12 s, and it uses 80 vertical levels with model top at 38.5 km, and 14 model levels below 1 km. The DM and NCUM-R setups are compared in Table S1 in Appendix S1.

Surface boundary conditions for the model are provided through ancillary files. Orography is derived from the NASA Shuttle Radar Topographic Mission (SRTM) 90 m digital elevation map. Since fog is highly conditioned by the surface turbulence, finer resolution of the terrain and local landscape features around Delhi has a major role in representing its evolution/dissipation accurately in the model. Figure 1 shows a map of the orography for the two nested models along with that of NCUM-GL. Boxes represent the nested domains. The orography of the Aravalli hills south and southeast of Delhi airport is captured well in the DM.

Unnikrishnan et al. (2016) recently showed the advantage of Indian Space Research Organisation (ISRO) land use/land cover (Lu/Lc) instead of the International Geosphere and Biosphere Programme (IGBP) Lu/Lc for the
short-range forecast of precipitation and surface temperature from the NCUM. The ISRO Lu/Lc has a resolution of 30 m and is derived for a more recent period compared to that of IGBP. Therefore, ISRO Lu/Lc is used in the DM, providing information on land cover types such as urban, forest and shrub land. A fixed aerosol mixing ratio value is used, and the importance of this is discussed in Section 4.

3 | VISIBILITY PARAMETERIZATION

Visibility in the model (in meter) is calculated from the extinction coefficient using a modified Koschmieder relationship (Koschmieder, 1924):

\[
\text{Visibility} = -\frac{\ln(e)}{\beta_{\text{ext}}}
\]

where \( e \) is the liminal contrast and \( \beta_{\text{ext}} \) is the extinction coefficient. A more realistic liminal contrast value of 0.05 is used instead of Koschmieder’s value of 0.02, as suggested by Blackwell (1946). The visibility parameterization used in the DM follows Clark et al. (2008). The total extinction coefficient is the sum of extinction coefficients of clean air and aerosol or fog particles. The extinction coefficient due to aerosol or fog particles, which depends on relative humidity, RH (%), and aerosol mass mixing ratio, \( m (\mu g/kg) \), is given as:

\[
\beta_{\text{RH},m} = \int\alpha Q(r)r^2 (\text{RH},r_d)N(r_d)dr_d
\]

where \( Q \) is the extinction efficiency and \( r \) is the droplet radius (m). Aerosol particles are characterized by a number density, \( N (m^{-3}) \), and their dry radius, \( r_d \). Both of these terms depend on the ratio of \( m \) to the standard mass mixing ratio (\( m_0 \)) using the following equations:

\[
N = N_0 \left( \frac{m}{m_0} \right)^{(1-3p)}
\]

\[
r_d = r_0 \left( \frac{m}{m_0} \right)^p
\]

where \( r_0 \) is the radius of a “standard” aerosol particle (0.11e^{-3}m), \( p \) is the power used to represent the variation in aerosol particle size with mixing ratio and \( N_0 \) is the standard number density of the aerosol which is taken as 200.0e^{-3}m^{-3} from Haywood et al. (2008).

The standard mass mixing ratio (\( m_0 \)) is given by:

\[
m_0 = \frac{4}{3} N_0 \pi r_0^3 \left( \frac{\rho}{\rho_a} \right)
\]

where \( \rho \) is the density of the aerosol taken to be 1700 kg m^{-3}, roughly that of ammonium sulphate, \((NH_4)_2SO_4\), and \( \rho_a \) is the density of air. \((NH_4)_2SO_4\) is the dominant aerosol type in the fog water sampled in Delhi as part of winter fog experiment (Ghude et al., 2017).

The activation radius used in the Clark et al. (2008) parameterization is given by:

\[
r_{\text{act}} = \sqrt{\frac{3br_d^3}{A}}
\]

where \( A=1.2e^{-9} \), is a constant involving the surface energy of water and \( b \) is the activation parameter which controls the aerosol composition. \( b \) is an approximation of the hygroscopicity parameter (\( \kappa \)) which represents the effect of chemical composition on cloud condensation nuclei activity. For the DM, we have chosen the value of 0.53 based on the study by Petters and Kreidenweis (2007). This is significantly larger than the value used for UK applications \((b = 0.14; \text{Clark et al., 2008})\), and may help to effectively simulate the pollution haze found over Delhi during the winter periods.

4 | SENSITIVITY OF DM VISIBILITY TO AEROSOL MASS CONCENTRATION

We have chosen a fog case on 12 December 2015 reported over Delhi for conducting sensitivity experiments and validation of visibility prediction skill of the DM in comparison with NCUM-R. This was the first fog case reported in winter 2015–2016 (Indian Meteorological Department [IMD] weather reports). Widespread fog was observed over Delhi and nearby regions with visibility around 50 m. A dense fog set in around 0630 IST (UTC + 0530) and dissipation started by 0830 IST. Short-range model predictions made from 0530 IST, 11 December 2015 were examined (Figure 2). A greater spatial extent and persistence of low visibility values is shown by the DM compared to NCUM-R, in agreement with IMD observations of the event. Large spatial variability of fog is also shown in the DM, which is generally found to be a key benefit of these very high-resolution models (Boutle et al., 2016).

Although the spatial and temporal extent of the fog was reasonably well forecast, the precise visibility values are typically overestimated. The default value of the aerosol mass mixing ratio (\( m \)) of 10 \( \mu g/kg \) is representative of clean, maritime air, typical in the UK, and so we investigate changes to this to be more representative of the polluted, continental air in Delhi. Observational studies by Srivastava, Dey, and Tripathi (2012) showed that the annual aerosol concentration value over major cities of the Indo-Gangetic plain is generally around 200 \( \mu g/kg \). Figure 3 shows the temporal variability of the visibility from model experiments increasing “\( m \)” from 10 to 50 \( \mu g/kg \), 100 and up to 200 \( \mu g/kg \), along with METAR observations at Indira Gandhi International Airport, Delhi. Analysis shows that the visibility range in the night time is dropping with the enhanced \( m \) values, in better agreement with to the observations. During the morning hours, in conjunction with the high RH, zero visibility is simulated in all the experiments. In addition to that we can see the delayed rise in visibility.
with the increase of \( m \) value in the morning. This demonstrates how low visibility forecasts are highly sensitive to both high aerosol concentrations and high relative humidities, which is in agreement with the observational work by Mohan and Swagata (2009). We used the enhanced aerosol mass mixing ratio of 200 \( \mu \)g/kg for both NCUM-R and DM to generate the visibility product in real time for the winter period of 2016–2017.

5 | VISIBILITY PREDICTION BY THE DM AND ITS VERIFICATION

The prevailing meteorological conditions during the fog case on 30 November 2016 from both NCUM-R and DM forecasts as well as METAR observations at Indira Gandhi International Airport, Delhi, are depicted in Figure 4. While the surface RH and near surface temperature (1.5 m) are in general agreement, subtle differences can be seen between these model forecasts, such as the ability of the DM to produce high RH values, in better agreement with the observations. Both the models are able to capture the trend in observed visibility values, and the DM forecast is able to give visibility ~0.5 km lower than the NCUM-R during the morning hours. Correlation coefficient values from DM (NCUM-R) forecast against observation for the diurnal variation of visibility, temperature and RH for the aforementioned fog case is calculated as 0.671 (0.592), 0.923 (0.931), 0.627 (0.584), respectively. The DM is not able to predict the lower observed visibility values, despite having a good simulation of RH. This is likely to be due to a lack of interactive aerosol in the model, which (in reality) will be trapped below the inversion during the night, leading to further enhanced aerosol concentrations and lower visibilities. In addition, fog in the model is dissipating faster.
than seen in the observations, resulting in higher visibility too early in the morning. Again, this is likely to be linked to the ventilation of aerosol from the near surface as the inversion weakens after sunrise (Gera, Gupta, Mohanan, & Gera, 2013), a process which is absent from the model.

Figure 4 (right column panels) shows the visibility predicted by NCUM-R and the DM throughout January 2017. Note that NCUM-R use the same visibility parameterization as the DM, as discussed in Section 3. The model is able to predict the major dense fog events covering 2–4-day periods during 1–3, 16–20 and 27–30 January, with relatively few false alarms. Similar to the 30 November case study, the DM generally outperforms NCUM-R, giving lower visibilities which are often linked to higher RH values. This is a direct result of the higher resolution, improved orography and land use data in this model, leading to enhanced simulations of the local meteorology, e.g., valley cooling. This is in general agreement with results presented in Boutle et al. (2016), which show that the enhanced resolution model performs statistically better.

6 | URBAN HEAT ISLAND EFFECT ON VISIBILITY FORECAST

The urban heat island impact of the Delhi megacity is highly correlated to the Lu/Lc categories (Mohan et al., 2013). Figure 5a and b show the urban canopy fraction from both IGBP and ISRO. A large increase of urbanization within Delhi and its suburbs is clearly visible in the ISRO Lu/Lc. Sensitivity of visibility predictions to Lu/Lc data from IGBP and ISRO is shown in Figure 5c and d. A break in the fog is found, with higher visibility regions overlapping with the presence of urban land-use. A more extensive break in the fog is simulated when ISRO Lu/Lc is used, compared to the IGBP. Images from MODIS-Terra (Figure 5e) over Delhi very clearly show “holes” in the fog during the period of our study, due to no fog (or thinner fog) over the city due to the urban heat island effect. The spatial distribution and size of the holes using ISRO Lu/Lc over the DM domain is more consistent with this satellite observation than IGBP run. The reduction of fog over the urban canopy is due to changes in the surface temperature and the humidity gradient, i.e., the urban heat island (Figure S1 in Appendix S1). Another noticeable feature is the formation of fog patches for a short while over the urban heat island zone, occasionally observed in the model predictions, even after the fog has largely dissipated. The surface conditions are well-simulated in the experiments using the DM, in accordance with previous studies which show that the model can effectively simulate the effect of urban areas on atmospheric conditions (Azevedo,
Chapman, & Muller, 2016). The land surface model represents urban areas using a bulk parameterization. The relative simplicity of the scheme reduces computational requirements when compared to more complex (multilayer) models, while retaining the ability to reproduce the urban effects reasonably well (Azevedo et al., 2016; Tomlinson et al., 2013).

7 SUMMARY AND DISCUSSIONS

Potential use of a high-resolution nested model specifically setup for real-time fog prediction over Delhi for the winter period has been discussed. Surface boundary features of the model at 330-m grid length help the DM to simulate the surface turbulence more realistically than coarser resolution models. Similar to results presented in Boutle et al. (2016), the enhanced resolution leads to general improvements in fog forecasting for the DM (relative to the NCUM-R), particularly in representing the variability of fog. With the enhanced aerosol concentration, the DM shows lower visibilities during foggy periods, generally in better agreement with the Delhi airport visibility observations. The influence of the urban heat island on the visibility predictions over the city using ISRO Lu/Lc is quite evident, and much improved, in comparison with the use of IGBP Lu/Lc.

Real-time forecast products from the DM and nested parent model (NCUM-R) for the winter period were made available on the website http://www.ncmrwf.gov.in/product_main_ind.php. In addition to the forecast products, verification of the previous day visibility predictions with METAR observations over Delhi is provided. Future model developments will replace the fixed aerosol distribution with inventory values for aerosol emissions, based on the Delhi Fog Field Campaign conducted at Delhi airport during the winter.
of 2016–2017 (Ghude et al., 2017) and a simple prognostic model of aerosol evolution. This should significantly help with the representation of aerosol trapping near the surface during the night, further reducing the visibility. We have also successfully incorporated the ISRO Cartosat digital elevation map (source resolution of 30 m) into the DM, and sensitivity of visibility predictions to this will be reported in the future.

ACKNOWLEDGEMENTS

Thanks to the National Remote Sensing Center, ISRO, India for the Lu/Lc data. For Figure 5(e), We acknowledge the use of data products or imagery from the Land, Atmosphere Near real-time Capability for EOS (LANCE) system operated by the NASA/GSFC/Earth Science Data and Information System (ESDIS) with funding provided by NASA/HQ.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

How to cite this article: Jayakumar A, Rajagopal EN, Boutle IA, et al. An operational fog prediction system for Delhi using the 330 m Unified Model. *Atmos. Sci. Lett*. 2018;19:e796. https://doi.org/10.1002/asl.796