A study to improve night time fog detection in the Indo-Gangetic Basin using satellite data and to investigate the connection to aerosols

Rizwan Ahmed, Sagnik Dey* and Manju Mohan

Centre for Atmospheric Sciences, Indian Institute of Technology Delhi, Hauz Khas, India
Satellite Meteorology Division, India Meteorological Department, New Delhi, India

ABSTRACT: Fog is a socio-economically important weather hazard in the Indo-Gangetic Basin, Northern India, disrupting public life and incurring massive economic loss because of delays in road, rail and air traffic every winter (December–January). Accurate detection of the spatial extent of fog and forecasting of its persistence and dispersion are critical in minimizing this economic loss. In the present study, a satellite based bi-spectral brightness temperature difference (BTD) technique has been applied to detect night time fog over this region during the fog episodes of 2010–2011. The method, validated against ground-based observations from four urban centres (Amritsar, New Delhi, Lucknow and Varanasi), yields 83.9% accuracy in detecting fog for a total 393 satellite overpasses using the operational 2.5 °C BTD threshold. The accuracy further increases to 88.3% with a reduction in the BTD threshold to 1.5 °C. A minimum fog droplet number concentration of 3.23 cm⁻³ is required to degrade visibility below 1 km in the presence of aerosols at 95% RH in the Indo-Gangetic Basin. The results emphasize the need to improve treatment of aerosols in order to improve forecasting of fog occurrence in this region.

KEY WORDS fog; Indo-Gangetic Basin; satellite remote sensing; aerosols; relative humidity

Received 25 February 2014; Revised 15 May 2014; Accepted 22 May 2014

1. Introduction

The negative impact of fog on human life has long been recognized (e.g. Pisharoty and Desai, 1956). Fog in urban polluted areas could be strongly acidic or oxidized and may be regarded as an additional health hazard (Mohan and Nigam, 2003). However, its importance as a transportation hazard has increased during recent decades owing to an increase in air, road and marine traffic. Visibility is reduced below 1000 m during fog episodes (Tiwari et al., 2011), affecting public life. The economic loss due to disruption in normal traffic schedules and accidents can be comparable to many natural disasters (Gultepe et al., 2011). The Indo-Gangetic Basin (IGB) in northern India experiences frequent fog episodes every winter (December–January) resulting from suitable meteorological and environmental conditions (Choudhury et al., 2007). Of even more concern is the rapid increase in fog frequencies in the last two decades in New Delhi within the IGB (e.g. Jenamani, 2007). Presence of fog for more than 50% of the time during winter (Mohan and Payra, 2006) and an increase in fog frequency from 6.4 to 58% during the last four decades has also been reported in this region (Mohan and Payra, 2009). This alarming rise of fog events during the winter has been attributed to the rise in pollution levels and a gradual increasing trend in relative humidity (Syed et al., 2012). Greater aerosol particle concentration has been observed in New Delhi during foggy periods relative to non-foggy conditions (Mohan and Payra, 2009). As the meteorological conditions and aerosol concentrations vary spatially, detection of the spatial extent of fog is important, particularly for the aviation sector. This issue can only be addressed by using satellite images (Badarinath et al., 2009). For example, Moderate Resolution Imaging Spectroradiometer (MODIS) data were used by Gautam et al. (2007) to examine the spatial extent of fog over the IGB and the possible role of aerosol concentration on the formation of the fog/low clouds. However, robust satellite-based fog detection relies on the linear difference of brightness temperature (BTD) between two infrared window channels (e.g. Chaurasia et al., 2011). BTD > 0 °C indicates presence of fog where the BTD is calculated by subtracting the brightness temperature at a larger wavelength from the brightness temperature at a smaller wavelength. BTD < 0 °C indicates high clouds, whereas BTD = 0 °C indicates ‘clear-sky’ conditions (Eyre et al., 1984). The threshold value may vary from place to place and thus it is important to evaluate the applicability of the existing threshold values.

At present, a 2.5 °C BTD threshold is employed by the India Meteorological Department (IMD) to detect night time fog using satellite data over the Indian subcontinent. Night time fog detection plays an important role in providing the forecast for fog spatial extent and dissipation for the following day. The current threshold was chosen based on the past studies (IMD catalogue, 2008). In the present study, the accuracy of this threshold value in detecting night time fog in the IGB has been examined by validating the method with ground-based measurements from four large urban centres. The feasibility of using night time BTD to make a fog forecast valid for next morning has been tested. Further, the influence of aerosols on the formation of fog droplet number concentration (N₈) and the resulting visibility degradation are quantified.

2. Methodology

In this work, two different sensors, MODIS and Advanced Very High Resolution Radiometer (AVHRR) are used to derive the
BTD imagery. The MODIS, on board NASA’s Earth Observing System’s Terra (since February 2000) and Aqua (since June 2002), satellite is a sensor with a broad swath (~2330 km), 36 bands ranging from 0.4 to 14.5 μm wavelengths and moderately high spatial resolution (250 m, 500 m and 1 km depending on the wavelength). Terra and Aqua cross the Indian region, including the IGB, between 60° UTC (i.e. 2130 local standard time, LST) and 2100 UTC (0230 LST). For deriving BTD images, two thermal infrared channels (with 11.0 and 3.9 μm) at 1 km resolution are used for MODIS imagery. AVHRR is the primary meteorological imaging instrument on board NOAA satellites and has six channels in the visible and IR regions. The overpass time of the AVHRR over the Indian region is from 1900 (0030 LST) to 2200 UTC (0330 LST). For fog detection and generation of BTD imagery, bands 3b (bandwidth range 3.55–3.93 μm) and 4 (bandwidth range 10.3–11.3 μm) are used. A total of 393 satellite images from Terra-MODIS, Aqua-MODIS and AVHRR were collected for the period December 2010 to January 2011 for analysis.

Thermal infrared images of MODIS at 3.9 and 11.0 μm wavelengths obtained over the Indian subcontinent on 1 January 2010 at 1655 UTC (2225 LST) are shown in Figures 1(a) and (b). The brightness temperatures of the pixels overlaying the ground-based monitoring site in Lucknow (the location is shown by a star) are 18 and 6.16 °C respectively. This leads to a BTD (BT11.0 − BT3.9) value of 5.98 °C, thereby indicating the presence of fog. The corresponding BTD values for the entire image were estimated and only the values >2.5 °C are shown in the BTD imagery (Figure 1(c)). The visibility measured from Lucknow at half-hourly intervals is also shown in Figure 1(c). Visibility was found to be <400 m during the period 0400 (2130 LST) to 0630 (1130 LST) UTC, thus confirming the presence of fog as also seen in the visible image of Kalpana I (Figure 1(d)).

New Delhi was chosen for the case study to examine the visibility degradation attributed to fog and aerosols. However, the method can be applied to anywhere, provided the aerosol composition is known. The microphysical database of fog from Koepe et al. (1997) was used in the Optical Properties of Aerosols and Clouds (OPAC, Hess et al., 1998) model to estimate the surface extinction co-efficient (bext). bext was then converted to visibility using Koschmieder equation (Koschmieder, 1924). The change in visibility for a wide range (0.01–1000 cm−1) of Np was examined. As visibility is also degraded due to aerosol extinction, aerosol composition described by Singh and Dey (2012) was considered to quantify the connection of visibility degradation to the combined effect of fog droplets and aerosols. During the winter, aerosols in New Delhi are comprised of insoluble and water-soluble particles and soot and dust particles (Singh and Dey, 2012). Using the seasonally representative aerosol scale heights estimated from CALIOP and reported in Singh and Dey (2012), the surface bext was estimated for aerosols at 80 and 95% RH for the prescribed composition during the fog-period. Visibility was then calculated for the combined effect of aerosols and fog droplets. Further, the relationship between aerosol number concentration (Np) and Nv was explored. Using the non-linear parametric relation between Nv and Np discussed in Singh and Dey (2012), the expected Nv was calculated for Np ranging from 0.01 to 1000 cm−3.

3. Results and discussion
Following the methodology discussed above, BTD images were generated for all of the 393 satellite observations. The accuracy of BTD = 2.5 °C was evaluated against ground-based observations at four stations in the IGB (Amritsar, New Delhi, Lucknow and Varanasi, located from west to east IGB, Table 1). The most accurate detection of fog can be achieved from ground-based visibility measurements. If visibility drops to below 1000 m, it indicates ‘fog’; whereas visibility in the range 1000–2000 m indicates ‘mist’. Visibility data at half-hourly intervals measured at these four sites have been collected from IMD and the true conditions at the surface during the satellite overpasses have been determined. The scatter plot between the visibility measured at the four ground-based sites and BTD obtained from the satellite images is shown in Figure 2. Overall, in 83.9% cases both ground-based observation and the coincident BTD imagery using a 2.5 °C threshold (dotted vertical line in Figure 2) indicate fog (i.e. visibility less than 1000 m). However, the accuracy level varies from place to place. For example, in New Delhi, the accuracy in detecting night time fog using this threshold is 67%, whereas the corresponding accuracy levels for Amritsar, Lucknow and Varanasi are 82, 92 and 94% respectively (Table 1). The overall accuracy of satellite-based fog detection further increases to 88.3% with a reduction in the BTD to 1.5 °C (dashed vertical line in Figure 2). Individually, accuracy level in New Delhi increases to 73.2%, whereas it increases to 86.4, 96.2 and 100%, respectively for Amritsar, Lucknow and Varanasi.

Two sets of outliers have been identified from Figure 2 that influence the accuracy level of satellite-based fog detection. One set corresponds to the conditions when ground-based measurements report ‘mist’ even if BTD values are >1.5 °C. At BTD = 2.5 °C only one case falls in this category. This increases to three cases (still only 0.7% of the samples), if the threshold is lowered to 1.5 °C. Judging by the large increase in accuracy level (from 83.9 to 88.3%) with respect to a small change (0.3–0.7%) in the outliers, BTD = 1.5 °C may be considered to be a more appropriate threshold for night time fog detection in the IGB. The second set of outliers is trickier to handle. These cases correspond to ‘fog’ based on ground-based observations, but BTD values are <1.5 °C. Further lowering of BTD will not help because of the large number of cases corresponding to ‘mist’ and ‘non-foggy days’ that will be misclassified as ‘fog’. Chaurasia et al. (2011) have examined the sensitivity of BTD in response to increasing fog droplet size and optical depth using a radiative transfer model. Based on their calculations, BTD becomes <1.5 °C for fog droplet size >9 μm and fog optical depth <3.5. The BTD shown in Figures 1 and 2 in Chaurasia et al. (2011) was calculated as BT11.0 − BT3.9, compared to calculations from the present study, BT11.0 − BT1.6. This further suggests that the second group of outliers corresponds to fog cases when either the fog droplet size exceeded 9 μm or fog optical depth dropped below 3.5, or both. As fog is a surface phenomenon, fog optical depth (which is defined as the column integrated value of bext due to fog) should be equivalent to the surface extinction co-efficient. Following the Koschmieder equation (Koschmieder, 1924), the extinction co-efficient of fog should be ≥3.912 km−1, because ‘fog’ is defined by visibility ≤1 km at ground-based sites. Hence, fog optical depth cannot be <3.912 and fog optical depth <3.5 can be ruled out as a possible explanation for the second outlier. This leaves the only possible physical explanation that the fog droplets grew >9 μm in size. Field measurements during various stages of dense fog formation and dissipation revealed the presence of small number of particles sized >10 μm over New Delhi (Mohan and Payra, 2006). Whether this statement is true for the entire IGB including the other stations cannot be confirmed due to lack of similar measurements of particle size distribution during the fog episodes. Furthermore,
A study to improve night time fog detection in the Indo-Gangetic Basin

2.2 °C

5.73 °C

7.93 °C

Figure 1. (a) MODIS infrared image at 3.9 μm obtained over the Indo-Gangetic Basin on 1 January 2011, (b) same image at 11 μm wavelength, (c) BT-D (BT_{11} − BT_{3.9}) image, (d) Kalpana-I visible imagery for 2 January 2011 at 0600 UTC showing fog extending from Punjab to Bihar in the Indo-Gangetic Basin and (e) visibility measured at ground in Lucknow (shown by star in (a)–(d) during the satellite overpass at 2225 LST. This figure is available in colour online at wileyonlinelibrary.com/journal/met

© 2014 Royal Meteorological Society


aerosol indirect effect theory suggests that in polluted conditions, a large number of aerosols restrict the growth of the cloud droplets leading to an enhanced lifetime (e.g. Albrecht, 1989) thereby implying the presence of a large number of small sized particles. As the microphysical processes of fog droplets can be considered similar to low level clouds and aerosols were found to influence profoundly the occurrence of fogs in the IGB (Gautam et al., 2007), it can be concluded that aerosol concentration might have been low during the outlier cases allowing the fog droplets to grow large in size. Other factors such as aerosol composition and liquid water content may also influence the fog droplet size distribution and this issue needs future attention using collocated measurements.

Having demonstrated the success of the BTD technique in detecting night time fog over the IGB, the empirical relationship between the BTD during a night time overpass with the visibility
The accuracy of fog dissipation forecast in this region. Dispersion in this region. Further investigation is required to concentration may be a key parameter in influencing the fog concentration. This implies that variations in aerosol number (as aerosol number distribution influences fog droplet number (as shown in Table 1) based on the previous night’s BTD. A previous study by Singh and Dey (2012) has shown that reduction in aerosol number concentrations (mostly water-soluble and soot particles) leads to an improvement in visibility because of less attenuation of visible light by aerosols and fog droplets (as aerosol number distribution influences fog droplet number concentration). This implies that variations in aerosol concentration may be a key parameter in influencing the fog dispersion in this region. Further investigation is required to quantify the aerosol–fog connection that may help in improving accuracy of fog dissipation forecast in this region.

Visibility degrades exponentially with an increase in \(N_F\) (Figure 4) and becomes insensitive to further increases in \(N_F\) for \(N_F > 12\, \text{cm}^{-3}\). Visibility drops below 2 km (haze condition) for \(N_F = 2.73\, \text{cm}^{-3}\) and below 1 km (fog) for \(N_F = 5.35\, \text{cm}^{-3}\). \(N_F = 4320\, \text{cm}^{-3}\) is required to form 2.73 cm\(^{-3}\) fog droplets, whereas \(N_a = 1.17 \times 10^6\, \text{cm}^{-3}\) is required to form 5.35 cm\(^{-3}\) fog droplets. In New Delhi, mean winter \(N_a\) was found to be 1.61 \times 10^6\, \text{cm}^{-3} (Singh and Dey, 2012), which implies that the condition is always favourable for haze. Presence of aerosols also attenuates the visible light and further degrades the visibility. For example, at 80% RH, visibility degrades below 1 km for \(N_F = 4.17\, \text{cm}^{-3}\) instead of \(N_F = 5.35\, \text{cm}^{-3}\) because of the additional contribution of aerosol extinction. A large fraction of water-soluble particles in New Delhi during the fog season results in hygroscopic growth of the particles. This leads to even larger \(b_{ext}\) of aerosols at higher RH. At 95% RH, \(N_F = 3.23\, \text{cm}^{-3}\) is sufficient to degrade visibility below 1 km.

This analysis provides a quantitative estimate of the influence of aerosol composition and value for fog droplet number concentration and the resulting visibility degradation. These results have important implications in terms of resolving this issue. As shown in Singh and Dey (2012), visibility (or surface \(b_{ext}\)) is most sensitive to water-soluble and soot particles. Using previously published results and new calculations shown in this study, it can be concluded that a reduction of 20% each of water-soluble and soot particles will lead to an improvement of ~21% in visibility. This is because reduction in \(N_a\) will decrease \(b_{ext}\) of aerosols and thus visibility will be enhanced. Also, less \(N_F\) will lead to formation of fewer fog droplets (less \(N_F\)) improving the visibility. The results indicate clearly that treatment of realistic aerosol number concentration and composition at high space-time resolution are required to improve the forecasting of fog onset and dispersion using the model.

Table 1. Details of satellite based fog detection days and validation against ground observations for New Delhi, Amritsar, Lucknow and Varanasi during the winter of 2010–2011. MODIS and NOAA images are taken between 1900 and 0230 LST. The numbers (in % and within parentheses) are the level of accuracy for each case.

<table>
<thead>
<tr>
<th>City</th>
<th>MODIS (Terra + Aqua) observations</th>
<th>NOAA observations</th>
<th>Total observations</th>
<th>Perfect matching with BTD ≥ 2.5°C</th>
<th>Perfect matching with BTD ≥ 1.5°C</th>
<th>Persistence of fog till 0630 LST for night time BTD ≥ −1°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>New Delhi</td>
<td>60 (28.6°N, 77.2°E)</td>
<td>37</td>
<td>97</td>
<td>65 (67.0%)</td>
<td>71 (73.2%)</td>
<td>83 (85.6%)</td>
</tr>
<tr>
<td>Amritsar</td>
<td>60 (31.6°N, 74.9°E)</td>
<td>36</td>
<td>103</td>
<td>79 (82.3%)</td>
<td>83 (86.4%)</td>
<td>46 (47.9%)</td>
</tr>
<tr>
<td>Lucknow</td>
<td>62 (26.9°N, 80.9°E)</td>
<td>41</td>
<td>111</td>
<td>95 (92.2%)</td>
<td>96 (93.2%)</td>
<td>76 (73.8%)</td>
</tr>
<tr>
<td>Varanasi</td>
<td>59 (25.3°N, 82.9°E)</td>
<td>38</td>
<td>97</td>
<td>91 (93.8%)</td>
<td>97 (100%)</td>
<td>76 (78.4%)</td>
</tr>
</tbody>
</table>

© 2014 Royal Meteorological Society

Figure 2. Scatter plot between visibility (in m) measured at ground at four cities in the IGB coinciding with the satellite overpasses and BTD (in °C) from the corresponding satellite images during winter of 2010–2011. ‘Fog’ is detected for visibility <1000 m, whereas ‘mist’ is detected for visibility ranging between 1000 and 2000 m. The IMD BTD threshold is 2.5°C, whereas the new proposed threshold is 1.5°C.

Figure 3. Scatter plot between BTD (in °C) for the night time overpasses and visibility (in m) measured at ground at 0630 LST next day.
A study to improve night time fog detection in the Indo-Gangetic Basin

4. Conclusions

In this work, a satellite-based technique was presented for identification of night time fog and an improvement was suggested of the existing threshold being used over the Indo-Gangetic Basin (IGB). The interpretations are made based on the analysis of a total of 393 satellite observations during the winter of 2010–2011. The influence of aerosol number concentration for a representative aerosol composition of fog droplet number concentration and resulting visibility degradation is quantified. The quantities are specific to New Delhi and on a broader scale, the IGB; however the method can be applied to any region. Thus, the method and results have global application and implications. The major conclusions of the present study are as follows.

1. 1.5°C appears to be more appropriate brightness temperature difference (BTD) threshold for night time fog detection over the IGB relative to a 2.5°C BTD (presently applied at the India Meteorological Department), as the accuracy increases from 83.9 to 88.3%;
2. night time fog detection using a 1.5°C BTD threshold from the satellite images becomes difficult if fog droplets grow >9 μm;
3. a BTD >−1°C during the night time has a 70% chance of the fog persisting until next morning at 0630 LST;
4. at least 5.35 cm\(^{-3}\) fog droplet number concentration is required to degrade the visibility below 1 km in New Delhi, which reduces to 3.23 cm\(^{-3}\) in presence of aerosols at 95% RH;

The study should be expanded to the entire IGB with a larger sample size. More importantly, it points to the fact that treatment of aerosols may be the key in improving the forecast of fog formation and dissipation in this region.

Acknowledgements

The corresponding author acknowledges research grant from DST under contract Fast-Track scheme (SR/FTP/ES-191/2010) through a research project operational at IIT New Delhi (ITD/IRD/RP02509). The authors are also grateful to the Satellite Division of India Meteorological Department, for providing the MODIS, NOAA and Kalpana data used here. The authors thank the reviewers for their comments to improve the original version of the manuscript.

References


© 2014 Royal Meteorological Society