Simulation of Radiation Fog Events over Dhaka, Bangladesh Using WRF Model and Validation with METAR and Radiosonde Data

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ABSTRACT: Fog causes severe hazards in the fields of aviation, transportation, agriculture and public health over Dhaka, Bangladesh during the winter season every year. The characterization of fog occurrences, its onset, duration and dissipation time over Hazrat Shahjalal International Airport, Dhaka are the topics of interest in the present study. Attempts have therefore been made to investigate the climatological perspectives of fog over Dhaka, Bangladesh by conducting two selected dense fog events occurred during 24-25 December 2019 and 14-15 January 2020 using WRF-ARW model. The model performance is evaluated by analyzing different meteorological parameters namely visibility, relative humidity, temperature, and wind. The model outputs have been compared with METAR data from Dhaka Airport, Sounding data and INSAT 3D satellite images for validation purpose. Considering RMSE, the model underestimates of relative humidity. Model simulations are good for other meteorological parameters. Thermodynamic analysis reveals that calm wind persists at surface level during fog formation, southwesterly dry wind was over Dhaka and inversion layer is found to persist in the lower troposphere over Dhaka during the event dates. It is observed in the satellite images that fog/low-level cloud was present over Dhaka during the fog events.

Keywords: Fog, INSAT 3D, METAR, Visibility, WRF Model

INTRODUCTION

Dhaka, the capital city of Bangladesh, is facing frequent fog occurrences and hazards associated with low visibility during the winter season (December – February) every year. Fog causes severe hazards in the fields of aviation, transportation sector, agriculture, and public health. Fog is formed by radiation cooling of land surface after sunset by infrared thermal radiation in calm conditions with a clear sky. The cooling ground then cools adjacent air by conduction, causing the air temperature to fall and reach the dew point, forming fog (https://en.wikipedia). Fog will first form at or near the surface, thickening as the air continues to cool. The layer of fog will also deepen overnight as the air above the initial fog layer also cools. As this air cools, the fog will extend upward. Wind would disrupt the formation of radiation fog. Radiation fog is usually patchy, tends to stay in one place and goes away the next day under the sun's rays.

The fog phenomenon is associated with the comprehensive physical processes such as cloud microphysics, radiated transfer, horizontal and vertical diffusions in the planetary boundary layer (PBL) that are forced by the prevailing synoptic background as well as a mesoscale disturbance (Faruq et al., 2018). Combinations of these factors make fog forecasting over any region quite challenging.

Fog formation over different parts of Bangladesh is a common phenomenon in the winter season (December-February) every year. Most of the places observe dense fog during peak winter months of December and January. Both radiation and advection fog frequently occur over relatively flat areas like Bangladesh. Radiation fog also forms in the rear sector of a western disturbance while advection fog develops in the forward sector of the western disturbance (Dimir et al., 2015). The persistence and intensification of foggy conditions are also driven by the high concentration of pollutants and abundant moisture supply.

It is well known that Fog limits visibility and thus affects human activities that rely on good visibility condition. These activities are part of the core activities of modern societies, most notably aircraft operations, shipping (Fu et al., 2006), and road traffic (Bartok et al., 2012). As we talk about aviation, fog formation accidents compose 24% of all aviation accidents. The monetary impact of accidents, injuries, delays and unexpected costs from fog is about $720

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million annually (https://www.westcostweather.com /weather-for-pilots/fog). An understanding of fog climatology over the region of study will provide a foundation for future studies aiming to improve and make accurate predictions of fog and its impact on aviation applications.

The Advanced Weather Research and Forecasting (WRF – ARW) Model is a next-generation NWP Model used by researcher and forecasters all over the world. Monitoring the spatial and temporal extent of fog over large areas becomes difficult with ground-based observations alone. The efficiency of WRF model to predict the fog is studied by many researchers (Roman-Cascon et al. 2012.

Fog Hours have been identified on BMD criteria as those hours during which fog reduces visibility to less than 1000 m (Faruq et al., 2018). Two fog events namely 24-25 December 2019 and 14-15 January 2020 are selected for the present study. Details of fog events selected for this study is given in Table 1.

Table 1: Details of Fog Events Simulated in this Study

Event	Date	Total Fog			
		Visibility < 1000 m (light)		Visibility < 200 m (dense)	
		Onset-Dissipation	Total fog hours	Onset-Dissipation	Total fog hours
Event-1	24-25 December 2019	2000-0600	10	2000 - 0300	07
Event-2	14-15 January 2020	1900-0500	10	2100 - 0300	06

The objectives of this study are to simulate two dense radiation fog events using WRF-ARW model and validate with METAR and Radiosonde Data, and to compare simulated Temperature, Dew point Temperature, Wind speed, Relative Humidity with the observation during the fog situation.

MODEL EXPERIMENTAL SET-UP

The Weather Research and Forecasting Model Version 4.0.3 (WRFv4.0.3) model has been used in this study. Advanced Research Weather Research Forecasting (WRF – ARW) model is a meso-scale model developed at the National Center for Atmospheric Research (NCAR) because of its superior performance in generating fine-scale atmospheric structures as well as its better forecast skill (Pattanayak and Mohanty, 2008). It is a limited-area, non-hydrostatic primitive equation model with multiple options for various parameterization schemes for different processes. WRF model is widely used in almost every meteorological application and produces mathematical simulation based on actual observational or idealized conditions (Mmm.ucar.edu, 2019).

The WRF-ARW model is run on a triple nested domain at 9 km, 3 km and 1 km horizontal resolution and the domain size is taken 62x85 km, 52x70 km and 40x58 km respectively (Figure 1). Out of the three domains, first domain (d01) covers full Bangladesh, along with portions of Kolkata, Bhutan, Agartala and Shilong. The second domain (d02) covers of Dhaka, Pabna, Tangail, Cumilla. Domain 3 which focuses on Dhaka is having a model resolution of 1 km. The vertical levels are increased to 50 eta level. Output history intervals are 180 minutes, 180 minutes and 60 minutes respectively with a time-step of 27 seconds.

Figure 1: Model Domains Used in this Study

The domain is centered over Bangladesh to represent the regional-scale circulations and to solve the complex flows of this region. The model is run using the Kain-Fritsch (new Eta) scheme for cumulus parameterization (Kain , 2004), Yonsei University (YSU) scheme for the boundary layer parameterization (Hong, et al., 2006), WSM 6 class graupel schemes for microphysics (Hong and Lim, 2006), and Rapid Radiative Transfer Model (RRTM) for longwave (Mlawer et al. 1997), and for short wave radiation scheme (Dudhia et al. 1989) for the selected case.

DATA USED AND METHODOLOGY

Data used

The Final (FNL) Global Data Assimilation System (GDAS) data of National Centre for Environmental Prediction (NCEP) with the 0.25°×0.25° horizontal and 6-h temporal resolution were used as the initial and lateral boundary condition. The United States Geological Survey (USGS) Global datasets with 30sec horizontal resolution were used to create terrain/topography and vegetation/land use field. METAR data at an interval of 30 minutes from Dhaka Hazrat Shahjalal International Airport (HSIA) located at 23.8434 N, 90.4029 E is used in this study. In addition, Synoptic 24hour fog data (visibility in m, onset-dissipation time, the meridional and zonal component of wind, temperature, dew point depression and relative humidity was collected from BMD (Bangladesh Meteorological Department). The atmospheric sounding data is used for thermodynamic analysis of the events from University of Wyoming (http://weather.uwyo.edu/upperair/sounding.html). Satellite imagery from Meteorological & Oceanographic Satellite Data Archival Centre (MOSDAC) (INSAT 3D image) has also been used to compare with the model output (https://www.mosdac.gov.in/gallery-products).

Methodology

The WRF-ARW model is used to carry out this study. Two events of radiation fog like 24-25 December 2019 and 14-15 January 2020 are selected for this study. The model is run for 24 hours using the initial condition at 1200 UTC of event day to next day 1200 UTC. The Grid Analysis and Display System (GrADS) and Read Interpolate Plot (RIP 4.7) are used for visualization of the graphics. INSAT 3D images from MOSDAC gallery are used for verification.

The climatology of the radiation fog is studied using BMD observed data of Dhaka station during November – February (winter season) from 2010 – 2019. Time series diagrams are plotted for visibility (km), relative humidity (%), air temperature (C), dew point temperature (C), dew point depression (C) and wind speed (m/s) using METAR data and studied. The analysis of model simulated air temperature, relative humidity, wind speed and dew point temperature etc., are studied. INSAT – 3D images of MOSDAC is used to validate the model outputs. Model simulated visibility is calculated using Kunkel (1984) formula using RIP4.7. The onset, duration and dissipation of dense fog events occurred on 24-25 December 2019 and 14-15 January 2020 of Dhaka are analyzed using the time series of visibility and compared. The thermodynamic characteristics of fog events occurred on 24-25 December 2019 and 14-15 January 2020 of Dhaka is also analyzed using skew-T diagram to validate the model output.

RESULTS AND DISCUSSIONS

Climatological perspective of Fog over Dhaka

Fog climatological information system is important for a better understanding of winter fog events in a daily and monthly time scale. Table 2 shows the monthly recorded fog events for November – February (winter months) from 2010 – 2019 for Dhaka (BMD observation).The highest number of fog event occurred in the month of December during (2014-15), and the highest number of fog event occurred in the month of January during (2015-16) time period.

Table 2: Number of Occurrence of Fog Days Recorded during Winter Months of the Year 2010-2019, Using Visibility Data for Dhaka Station *(Source: BMD observational Data)*

Year	November		December		January		February	
	Number of days	Fog occurred	Number of days	Fog occurred	Number of days	Fog occurred	Number of days	Fog occurred
2010-11	30	Nil	31	03	31	13	28	Nil
2011-12	30	Nil	31	11	31	05	29	Nil
2012-13	30	Nil	31	16	31	05	28	Nil
2013-14	30	Nil	31	08	31	14	28	02
2014-15	30	02	31	17	31	08	28	Nil
2015-16	30	03	31	08	31	14	29	07
2016-17	30	Nil	31	01	31	03	28	01
2017-18	30	Nil	31	07	31	09	28	05
2018-19	30	01	31	02	31	--	28	04

From Table 2, it can be observed that nearly 30% of total days have fog events over Dhaka during each winter season. It is not alarming, but aviation sector is highly affected due to dense fog event. From Table 3, it can be observed that more than 50% of total days have fog events at VGHS (METAR data) during each winter season. The maximum number of fog events mostly occurred in December – January months.

Synoptic and Meteorological Conditions

Before starting the analysis of WRF model output in simulating dense fog event, it is necessary to analyze the synoptic conditions prevailed before each fog event. Ideal conditions for the formation of fog are light winds, clear skies, and long nights. The months of December, January and February are most prone to foggy conditions. In winter, the synoptic and meteorological condition over Bangladesh was dominated by low wind speed and anti-cyclonic condition (Figure 2). The synoptic and meteorological condition leads to the onset of fog. From METAR data, the time series diagrams (Figure 4 and 5) were plotted for visibility (km), relative humidity (%), air temperature (C), dew point temperature (C), dew point depression (C) and wind speed (m/s).

From the satellite image from INSAT 3D, it is observed that low-level clouds/a spread of fog (from geophysical parameter sector) were present over Dhaka (Figure 3 (a)). Wind speeds of 2-7 knots bring more moist air in contact with the cool surface and cause the fog layer to thicken. Too strong wind prevents the formation of radiation fog due to mixing with drier air aloft. In a calm situation with a low dew point depression and moist soils, expect thick dew instead of radiation fog.

Event-1 (24-25 December 2019)

On 24-25 December 2019, dense fog (visibility reduced to 100m) persisted at VGHS, Dhaka for 7 hours between 2000 to 0300 UTC. The maximum and minimum temperatures were 21˚C and 13˚C (BMD observation) respectively. Mean sea level pressure was greater than 1016 hpa over the study area. (Figure 3(b)). From the cloud fraction forecast from MOSDAC gallery, it can be observed that the sky was clear during the onset time (Figure 3(c)). Rectangular marked area in Figure 4 covering the entire fog event. A sharp decrease in visibility, temperature, dew point depression, and wind speed are seen while fog onset takes place, and all the mentioned parameters remained low until the end of the fog event except wind speed (Figure 4). Wind speed varies from 0 m/s to 3 m/s during this event time. Relative humidity increased from 80% before onset to about 95% after fog initiation. Dew point depression dropped from 8 to 1˚C. Figure 4(a) indicates that fog started (visibility <1000 m) on 24 December 2019 at around 2000 UTC and continued up to 25 December 2019 till 0600 UTC and then dissipate. The maximum visibility on this time period was 2.5 km.

Figure 2: Synoptic Chart at Surface on 14 Jan 2020 00 UTC from BMD

Table 3: Number of Occurrence of Fog Days Using Visibility Data 2012-2020 at Dhaka Airport *(Source: http://rp5.co.uk/ Weather_archive_in_Dhaka_(airport),_METAR)*

Year	December		January		February	
	Number of days	Fog event occurred	Number of days	Fog event occurred	Number of days	Fog event occurred
2012-13	31	25	31	18	28	04
2013-14	31	12	31	19	28	07
2014-15	31	24	31	14	28	01
2015-16	31	11	31	19	29	07
2016-17	31	16	31	10	28	Nil
2017-18	31	18	31	25	28	08
2018-19	31	06	31	02	28	03
2019-20	31	09	31	16	29	01

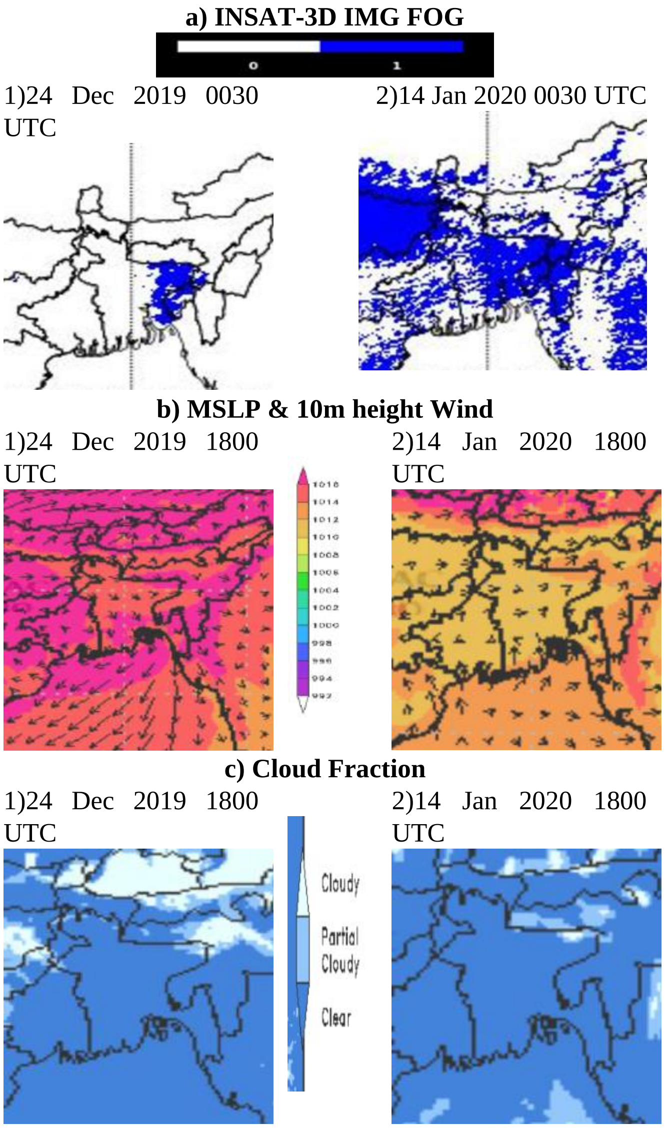

Figure 3: a) INSAT – 3D Images of FOG (0 = clear, 1 = fog), b) MSLP & 10m Height Wind and c) Cloud Fraction on 1) 25 December 2019 and 2) 15 January 2020

Source: https://www.mosdac.gov.in/gallery-products

Event-2 (14-15 January 2020)

On 14-15 January 2020, the dense fog persisted at VGHS, Dhaka for 6 hours between 2100 to 0300 UTC. The maximum and minimum temperatures were 24˚C and 12˚C (BMD observation) respectively. Relative humidity varied from 70% to 100% during this time. Mean sea level pressure was less than 1010 hpa over the study area (Figure 3(b)). From the cloud fraction forecast from MOSDAC gallery, it can be observed that the sky was clear during the onset time (Figure 3(c)). Rectangular marked area in Figure 4 covering the entire fog event. A sharp decrease in visibility, temperature, dew point depression, and wind speed are seen while fog onset takes place. Wind speed varies from 0 m/s to 3 m/s during this event time. Dew point depression dropped to 1˚C.

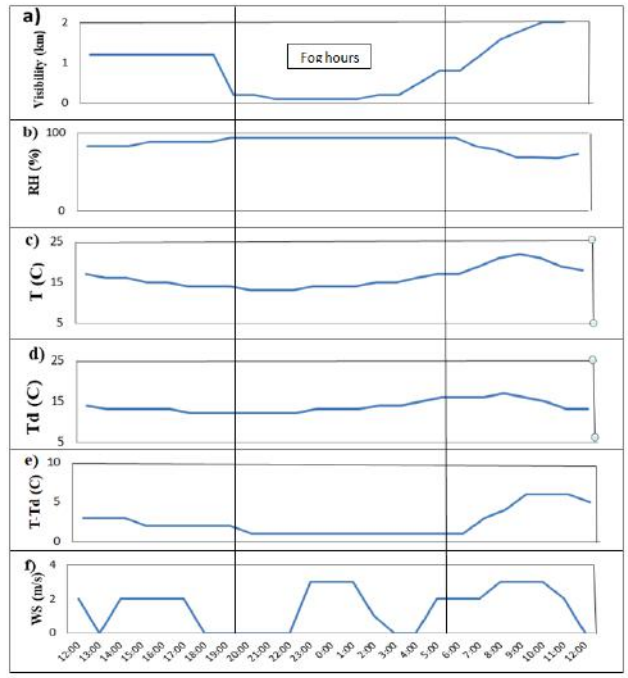

Figure 4: Time Series Plot of a)Visibility (km) b) Relative Humidity (%) at 2m c) Temperature (˚C) at 2m (˚C) d) Dew point Temperature at 2m (˚C) e) Dew point depression (˚C) at 2m and f) Wind speed (m/s) at 10m at event 1 (24-25 Dec 2019)

Figure 5 (a) indicates that fog started (visibility <1000 m) on 14 Jan 2020 at around 1900 UTC and continued up to 15 Jan 2020 till 0500 UTC and then dissipate. The maximum visibility on this studied time period was 2.5 km.

Analysis of Air Temperature, Relative Humidity, Wind Speed and Dew point Temperature

In this section, the model simulations of relative humidity, temperature, dew point temperature and wind speed are compared with the observations. It is for to examine the quality of simulations, including variations of fog-related parameters during each event. For validation, METAR data of Dhaka Airport (VGHS) (Lat 23.8434° N, Lon 90.4029° E) is used with model estimations. From Figure 6 (a), it is observed that the model accurately predicted the air temperature.

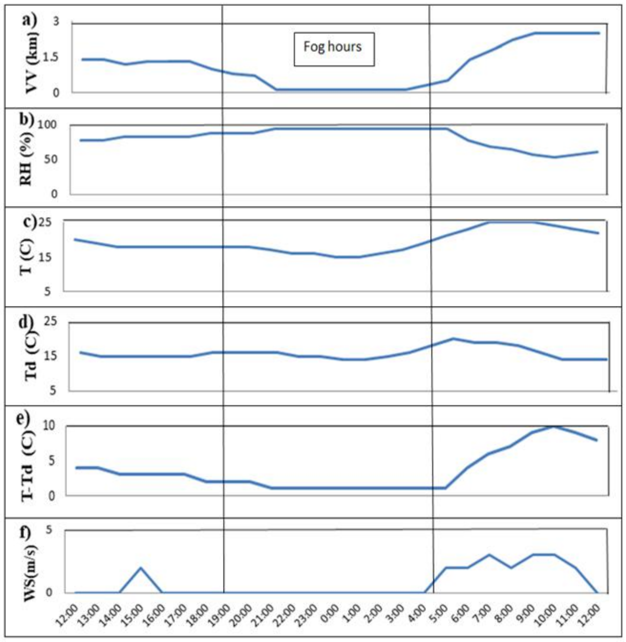

Figure 5: Time Series Plot of a)Visibility (km) b) Relative Humidity (%) at 2m c) Temperature (˚C) at 2m (˚C) d) Dew point Temperature at 2m (˚C) e) Dew point depression (˚C) at 2m and f) Wind speed (m/s) at 10m for event 2 (14-15 Jan 2020)

The RMSE were 2.674 and 1.323 for event 1 and event 2 respectively (Table 4). During dense fog hours, the relative humidity reached a maximum for both cases. But the model couldn't predict relative humidity reasonably (Figure 6 (b)). Model underestimated the real state. The genesis of fog usually takes place during low wind conditions. Considering the RMSE, error in prediction of wind speed is less in comparison. Zero wind conditions were not detected by the model (Figure 6 (c)). The model gave underestimated prediction of dew point temperature (Figure 6 (d)).

Table 4: Root Mean Square Error (RMSE)

Date	RH (%)	Td (˚C)	T (˚C)	WS (m/s)
24-25 December 2019	27.471	5.738	2.674	1.207
14-15 January 2020	**18.469**	4.406	**1.323**	1.174

Analysis of Model predicted Visibility

Model simulated visibility was analyzed in this section. Visibility was calculated using Kunkel (1984) formula using RIP4.7. Model underestimated visibility. For event 1, the observed onset time was 2000 UTC while the model predicted onset time was 2100 UTC. Fog dissipates (visibility > 1000m) at 0600 UTC. Model wrongly predicted the dissipation time (Figure 7). Shifting of the spatial extent of visibility is seen from the figure. Figure 8 shows model simulated visibility on 14-15 January 2020 (event 2) for 1800 UTC, 2100 UTC, 0000 UTC and 0300 UTC. The model gave a better estimation of visibility for event 2.

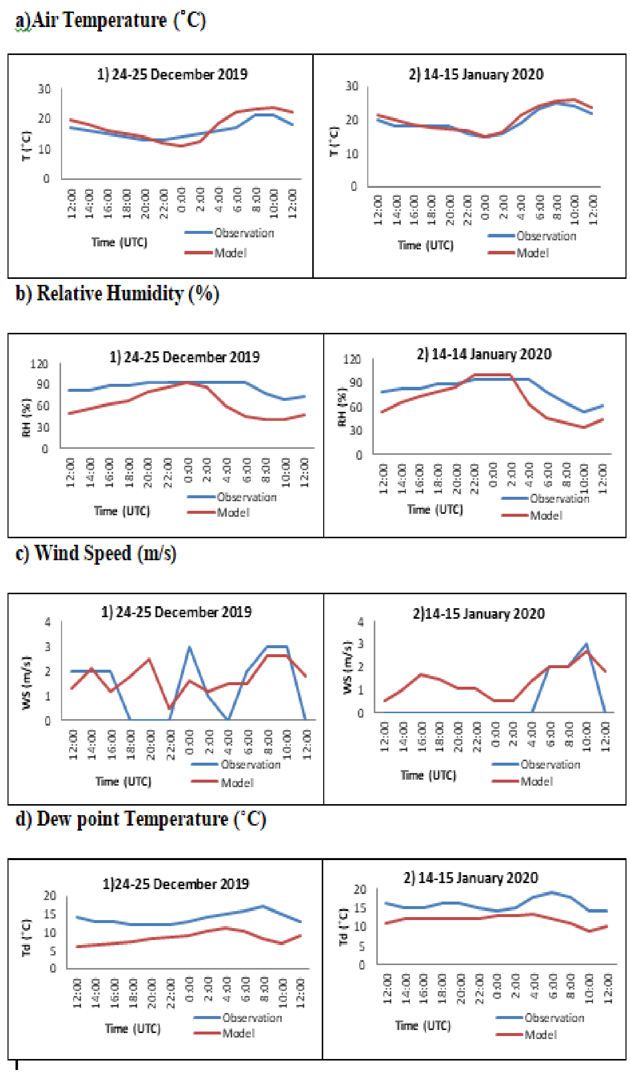

Figure 6: Comparison of a) Temperature (˚C) at 2m, b) Relative Humidity (%) at 2m, c) Wind Speed (m/s) at 10m d)Dew Point Temperature (˚C) at 2m Predicted by Model

with Observation at Dhaka Airport (VGHS) on 1) 24-25 December 2019 and 2) 14-15 January 2020.

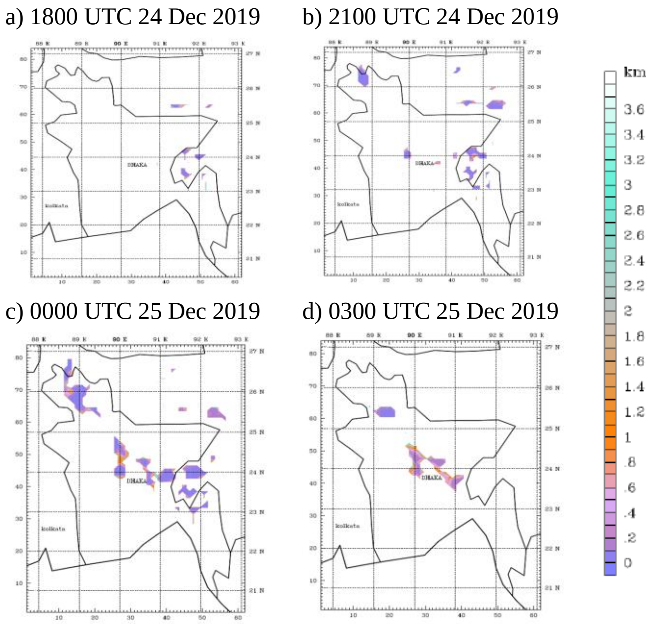

Figure 7: Model Simulated Visibility in km on 24-25 December 2019 (d01) for a) 1800 UTC, b) 2100 UTC, c) 0000 UTC and d) 0300 UTC (forecast starting from 24 December 2019 1200 UTC) Visualized by RIP.

Comparison of onset, duration, and Dissipation of fog event

To compare the onset, duration and dissipation time of fog events occurred on 24-25 December 2019 and 14-15 January 2020, a table is prepared (Table 5).

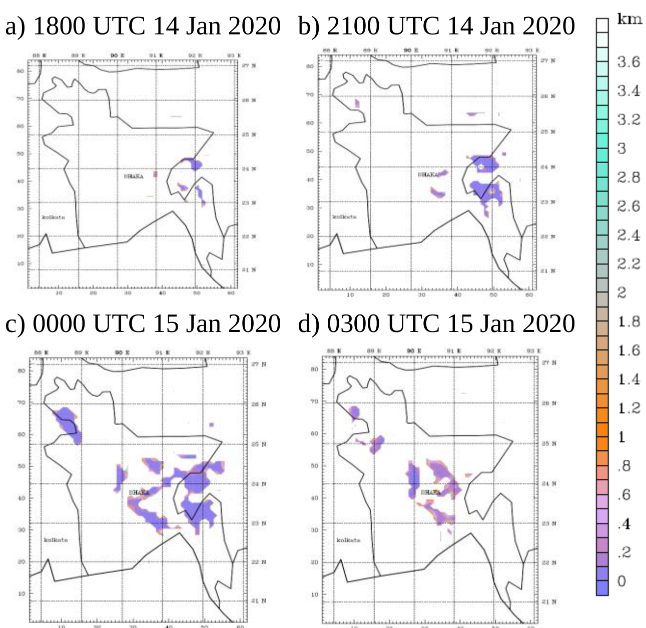

Figure 8: Model Simulated Visibility in km (d01) on 14-15 January 2020 for a) 1800 UTC, b) 2100 UTC, c) 0000 UTC and d) 0300 UTC (visualized by RIP).

Table 5: Comparison of Onset, Duration and Dissipation Time of Fog Events with Observation.

Date	Time of Onset (UTC)		Duration (hour)		Dissipation (UTC)	
	Observed	Simulated	Observed	Simulated	Observed	Simulated
24-25 December 2019	2000	2100	10	5	0600	0300
14-15 January 2020	1900	2100	10	6	0500	0300

Thermodynamic Analysis of Fog

Thermodynamic analysis is very important for understanding of fog formation. In this section skew-T diagram is analyzed to validate the model output (Figure 9). Information about some observational parameter and related sounding indices (Showalter index, Lifted index) are included in Table 6 and 7. Upper air sounding (RS) data from Wyoming University website are used to make this table. Previous weather condition is important for fog formation. From the Table 6, it can be seen that the inversion layer became deeper on the event date than the previous date. Inversion layer is a layer in the atmosphere in which temperature increases with altitude. Inversions act to prevent mixing in the lower regions of the troposphere, so condensation nuclei become trapped quite easily and contribute to the formation of fog.

According to listed value of Showalter index and Lifted index, atmosphere was very stable during 23-26 Dec 2019 and 13-16 Jan 2020. Freezing level represents the altitude in which the temperature is at 0˚C in a free atmosphere. Wind direction at 925 hpa level was north-northwesterly. From 13 January 2020 to 16 January 2020, sounding data was missing for Dhaka station. In this case, data of Agartala station is used in this study.

Table 6: Observational Parameter and Sounding Indices at Dhaka Station using RS Data

Date	Time	Wind speed at 500 hpa knot	Wind direction at 925 hpa in deg	Inversion layer (thickness) hpa	Freezing level hpa	Showalter index	Lifted index
23-12-19	00 Z	54	345	905-1000	580	12.36	12.46
	12 Z	44	315	925-1000	620	11.49	9.46
24-12-19	00 Z	63	315		595	15.91	12.42
	12 Z	71	295	700-1000	580	20.90	12.06
25-12-19	00 Z	63	340	850-1000	620	16.62	15.01
	12 Z	55	315	900-1000	650	14.90	10.85
26-12-19	00 Z	61	325	925-1000	650	9.46	13.83
	12 Z	59	45	915-955	655	5.26	8.20

Source: http://weather.uwyo.edu/upperair/sounding.html

Table 7: Observational Parameter and Sounding Indices at Agartala Station Using RS Data

Date	Time	Wind speed at 500 hpa knot	Wind direction at 925 hpa in deg	Inversion layer (thickness) hpa	Freezing level hpa	Showalter index	Lifted index
13-01-20	00 Z	35	70	760-875	525	23.15	14.62
14-01-20	00 Z	56	0	800-950	555	15.00	12.12
15-01-20	00 Z	70	350	825-925	560	13.68	13.74
16-01-20	00 Z	59	320	895-1000	520	13.99	15.24

(Source: http://weather.uwyo.edu/upperair/sounding.html).

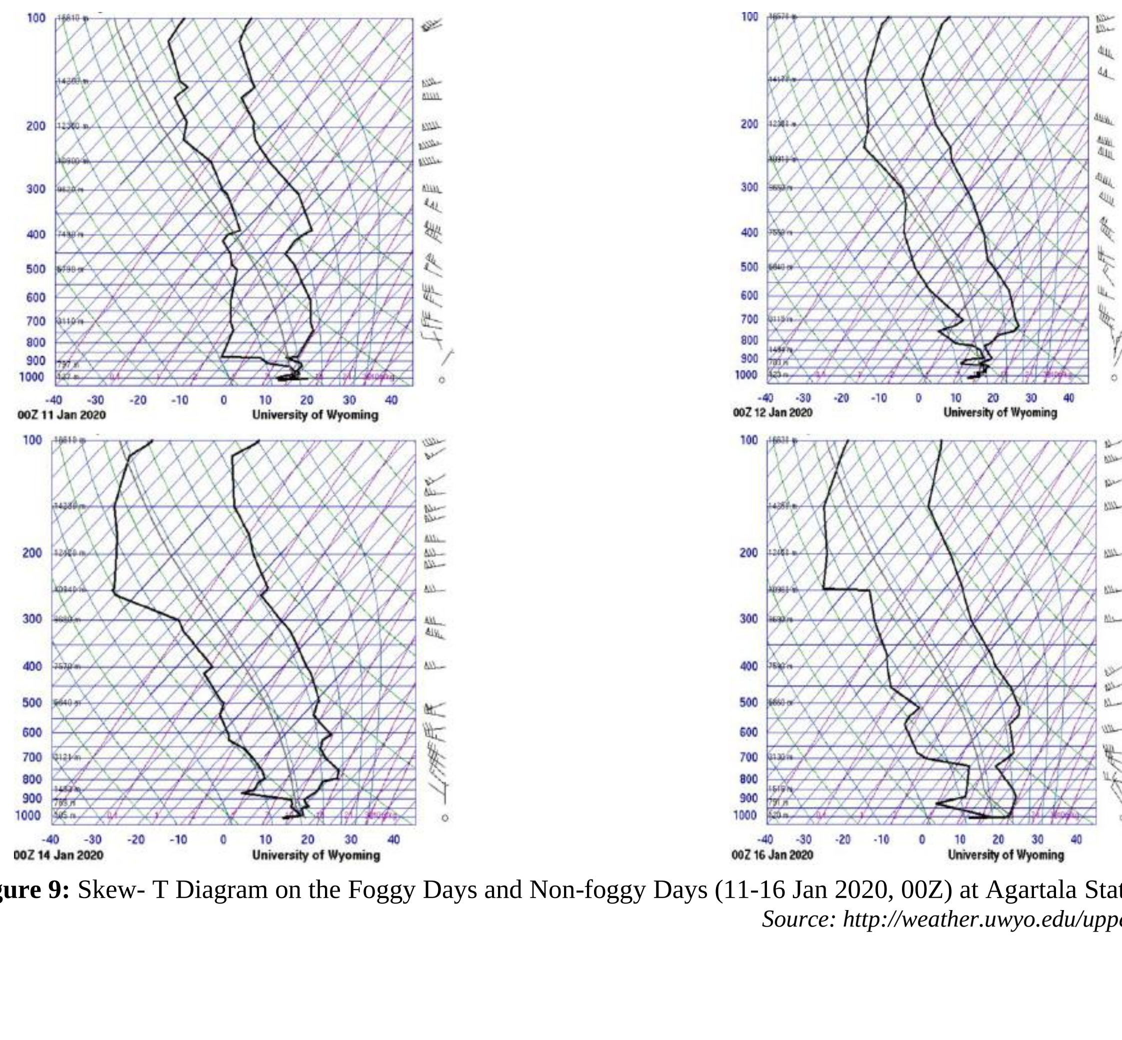

Figure 9: Skew- T Diagram on the Foggy Days and Non-foggy Days (11-16 Jan 2020, 00Z) at Agartala Station

Source: http://weather.uwyo.edu/upperair/sounding.html

CONCLUSION

The combination of WSM6 microphysics schemes with QNSE PBL, coupled with Noah-MP Land Surface Model (M6P4L4) was able to detect two events studied though the predicted onset time was not accurate. This may be because visibility was manually picked up from the nearest grid of Dhaka in the model domain. Duration of dense fog (visibility < 200 m) of the two events was accurately predicted by the model. In that case, more sensitivity test has to be conducted for several dense fog events and different model resolution to achieve a reasonable result. The model underestimates the observed value of relative humidity. Model simulations are good for other meteorological parameters. Thermodynamic analysis tells that calm wind persisted at surface level during fog formation, southwesterly dry wind was over Dhaka and inversion layer was persisted in the lower troposphere over Dhaka during the event dates. It is observed in the satellite images that fog/low-level cloud was present over Dhaka during the fog events.

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REFERENCES

Bartok, J., Bott, A. and Gera, M. (2012). Fog Prediction for Road Traffic Safety in a Coastal Desert Region. *Boundary-Layer Meteorol,* 145: 485–506.

Dimir, A. P. Niyogi, D. Barros, A. P. Ridley, J. Mohaty, U. C. Yasunari, T. and Sikka, D. R. (2015). Western disturbances: a review. *Reviews of Geophysics,* 53(2): 225-246.

Dudhia, J. (1989). Numerical study of convection observed during the Winter Monsoon Experiment using a mesoscale two dimensional model, *J. Atmos. Sci.* 46: 3077–3107.

En.wikipedia.org (2019). Weather Research and Forecasting Model. [online] Available at: https:// en. wikipedia.org/ wiki/ Weather_Research_and_Forecasting_Model [Accessed 23 Jul. 2019].

Faruq, M.O., Ahmed, S., Hasan, S.M.Q., Mallik, M. A. K., Akhter, M.A.E., Alam, M.S., Hossain, M.A. and Haque, S. M. M. (2018). Feasibility of Fog Forecasting over Bangladesh using WRF Model and a Comparison with ECMWF model products. https:// independent. academia.edu/ Md Omar2.

Fu, G., Jingtian, G., Shang-Ping Xie, Yihong, D., Meigen, Z., (2006). Analysis and high-resolution modeling of a dense sea fog event over the Yellow Sea/. *Atmospheric Research*, 81(4):293-303.

.Hong, Y. S. and Lim, J. (2006). The WRF Single-Moment 6-Class Microphysics Scheme (WSM6), *J. Korean Meteor. Soc.*, 42: 129-151.

Hong, Y.S., Noh, J. Y. and Dudhia, J. (2006). A new vertical diffusion package with an explicit treatment of entrainment process, *Mon. Wea. Rev.* 134: 2318–2341.

Kain, J.S. (2004). The Kain–Fritsch Convective Parameterization: An Update, *J. Appl. Meteor.*, 43: 170–181.

Mlawer, E. J., Taubman, S. J., Brown, P. D., Iacono, M. J. and Clough, S. A. (1997). Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the long wave, *J. Geophys. Res.*102D: 16663–16682.

Mmm.ucar.edu. (2019). Weather Research and Forecasting Model | MMM: Mesoscale & Microscale Meteorology Laboratory. [online] Available at: https://www.mmm.ucar.edu/weather-research-and-forecasting-model [Accessed 23 Jul. 2019].

Pattanayak, S. and Mohanty, U. (2008). A comparative study on performance of MM5 and WRF models in simulation of tropical cyclones over Indian seas. *Current Science*, 95(7): 923-936. Retrieved May 27, 2021, from http://www.jstor.org/stable/24103192.

Román-Cascón, C., Yagüe, C., Sastre, M., Maqueda, G., Salamanca, F., and Viana, S. (2012). Observations and WRF simulations of fog events at the Spanish Northern Plateau, *Adv. Sci. Res.*, 8, 11–18, https:// doi. org/10.5194/ asr-8-11-2012.