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Prediction of dust storm events over northern parts of India using NCUM

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सार – प्री-मानसून सीज़न के दौरान भारत के उत्तर-पश्चिम भागों में धूल भरी आंधी आना आम बात है। इस अध्ययन का मुख्य उद्देश्य एक ऑपरेशनल न्यूमेरिकल वेदर प्रेडिक्शन मॉडल से डस्ट एरोसोल ऑप्टिकल डेप्थ (एओडी) पूर्वानुमान का उपयोग करके धूल की घटना के दौरान भारतीय क्षेत्र में धूल की गति का आकलन करना है। एक बिंदु स्थान पर धूल की घटनाओं की पहचान करने के लिए दृश्यता, हवा की गति के देखे गए मूल्यों का उपयोग किया जाता है। इसके अलावा, धूल की घटना के पहले, दौरान और बाद के दिनों के लिए उपग्रह अवलोकन का उपयोग धूल की घटना का पता लगाने के लिए किया जाता है। भारत के उत्तर पश्चिम भागों में धूल की घटनाओं के दौरान धूल एओडी के मूल्यों की भविष्यवाणी करने में परिचालन एनसीएमआरडब्ल्यूएफ एकीकृत मॉडल (एनसीयूएम) के प्रदर्शन का विश्लेषण किया जाता है। धूल AOD के अनुमानित मूल्यों की तुलना उपग्रह और एरोसोल ऑब्जर्वेशन नेटवर्क (एरोनेट) के ग्राउंड आधारित नेटवर्क से उपलब्ध टिप्पणियों से की जाती है।

25 मई, 2016 को जयपुर और लखनऊ में मनाई गई धूल की घटना को एनसीयूएम द्वारा तीसरे दिन के पूर्वानुमान तक अच्छी तरह से कैद किया गया है। जयपुर और कानपुर के बिंदु स्थानों पर अनुमानित धूल AOD की तुलना से पता चलता है कि NCUM धूल घटना के दौरान AOD के उच्च मूल्यों की भविष्यवाणी करने में सक्षम है।

ABSTRACT. Dust storms are common over north-west parts of India during the pre-monsoon season. The main objective of this study is to assess the movement of dust over Indian region during a dust event using the dust aerosol optical depth (AOD) forecast from an operational numerical weather prediction model. Observed values of visibility, wind speed are used to identify the dust events over a point location. In addition, satellite observations for the days prior to, during and after dust events are utilized to ascertain the dust event. The performance of operational NCMRWF Unified Model (NCUM) is analyzed in predicting the values of dust AOD during dust events over north west parts of India. Predicted values of dust AOD are compared with observations available from satellite and ground based network of Aerosol Observation Network (Aeronet).

The dust event of 25th May, 2016 observed at Jaipur and Lucknow is well captured by NCUM up to Day-3 forecast. The comparison of predicted dust AOD at point locations Jaipur and Kanpur reveals that NCUM is capable in predicting the high values of AODs during dust event.

Key words – Dust event, Dust AOD, NCUM, Aeronet, Visibility.

1. Introduction

Dust, one of the major types of troposhperic aerosols is a common aerosol type over deserts (Smirnov *et al.*, 2002; Masmoudi *et al.*, 2003) and is emitted by storms originating in arid and semi arid regions. Dust has been identified a major component of atmospheric aerosol by the Inter-Governmental Panel on Climate Change (IPCC) and the World Meteorological Organization (WMO). Dust particles scatter and absorb the solar radiation and also absorb and emit the outgoing long wave radiation, they can also affect the cloud properties by changing the number, concentration and size of cloud droplets, strongly affects visibility and also affects the ambient air quality and human health (Nastos *et al.*, 2011).

Northwestern part of Indian subcontinent is covered by Thar Desert, which is identified as one major dust source based on satellite observations and back trajectory analysis (Moorthy *et al.*, 2007). During pre-monsoon season (March-May), the frequency of dust storms is maximum over this region, when dust is transported by westerly and southwesterly winds from Thar desert (Kedia *et al*., 2011). The studies based on remote sensing data, conducted in past (Prospero *et al*., 2002; Washington *et al*., 2003) suggests high dust loading in the Gangetic basin during pre-monsoon season. A number of studies have been conducted over Indian region to study the optical properties of aerosols during a dust event. Gharai *et al*. (2013) studied dust storm event over Indian region using the multiple reflective and emissive channels of Moderate Resolution Imaging Sepctroradiometer (MODIS). The study conducted by Singh *et al*. (2008) summarized that high concentrations (> 200 µg m^{-3}) of particulate matter with diameter < 10 µm (PM10) are observed over north-west parts of India during dust events. A dust storm event over Hyderabad was studied by Badrinath *et al*. (2007, 2010) and aerosol optical depth (AOD) on dusty day was about 0.2 higher than that observed on non-dusty day. The dust storms cause air pollution and degradation in visibility over north-west parts of India. Thus, it is important to forecast the dust events over this region. An attempt has been made in the present study to identify the dust storm events over north west India and the output of a global numerical weather prediction (NWP) model is analyzed in predicting the dust storm event.

The main objective of the present study is to analyze the performance of NCMRWF Unified Model (NCUM) in forecasting the dust events over north west parts of India. The meteorological and satellite observations during the pre-monsoon season of 2016 are utilized to identify the dust events over the plains of north-west India. The dust AOD forecast obtained from NCMRWF Unified Model (NCUM) is used to forecast the dust event. The forecast of dust AOD is verified with AOD observations available from satellite (MODIS) and ground based observations at three stations during the selected dust event. The study is divided into different sections. Section 2 gives the description of NCUM along with the details of the prognostic dust scheme utilized in the model. The methodology and datasets are described in section 3. The results of the study are discussed in section 4 and conclusions of the study are summarized in section 5.

2. NCMRWF Unified Model (NCUM)

NCUM is the operational global model used for medium range forecast at NCMRWF. The horizontal resolution of the model used in the present study is approximately 17 km and the model has 70 vertical levels. The first level of model is at 20 m above surface and the model top is at 80 km. The dynamical core of the model uses semi-implicit, semi-Lagrangian formulation to solve the non-hydrostatic, fully compressible deep atmosphere equations of motion discretised on a regular latitude/longitude grid (Davies *et al*., 2005). The radiation scheme is the two-stream radiation code of Edwards and Slingo (1996) with 9 bands in longwave and 6 bands in short wave region. The atmospheric boundary layer is parameterized with turbulence closure scheme of Lock *et al*. (2000) which is further modified as described in Lock (2001) and Brown *et al*. (2008). The land surface and its interactions with the atmosphere are modeled using JULES (Joint UK Land Environment Simulator) surface model (Best *et al*., 2011; Clark *et al*., 2011). A mass flux scheme based on Gregory and Rowntree (1990) is used to represent convection and convective momentum transport. Large scale precipitation is represented using Wilson and Ballard (1999) and clouds are modeled using prognostic cloud fraction and prognostic condensate (PC2) scheme (Wilson *et al*., 2008a,b).

NCUM has a prognostic dust scheme described in Woodward (2011). Prognostic variables from NCUM are used to produce dust forecast. Dust scheme in NCUM comprises three sections: dust production, transport and deposition. Dust emission scheme is parameterized as a function of wind speed exceeding a threshold value, surface roughness minimum friction velocity (Marticorena and Bergametti, 1995) and soil moisture (Fecan *et al*., 1999).

The dust flux (G) is defined as:

$$G = 0.01H \times 10^{(13.4F_c - 6)}\left(\frac{M_{rel}}{M_{rel}^{tot}}\right) \quad (1)$$

where, F_c is the clay fraction, M_{rel} is the ratio of the mass of dust in a size division to total mass, M_{rel}^{tot} is the ratio of two dust bins mass to total mass and H is given as:

$$H = 2.61\rho(1-v)2U^{*3}\left(1+\frac{U_t^*}{U^*}\right)\left[1-\left(\frac{U_t^*}{U^*}\right)\right]\frac{M_{rel}}{g} \quad (2)$$

where, v is the vegetation fraction, ρ is the density of air, g is acceleration due to gravity, U^* is the surface layer friction velocity, U_t^* is threshold friction velocity given by :

$$U_t^* = \mathrm{A}\log_{10}\left(D_{rep}\right) + \mathrm{B}W + \mathrm{C} \quad (3)$$

Where A, B and C are empirical constants and Drep is the representative particle diameter in a bin, W is the soil moisture at first layer of 10 cm of the soil. No dust is produced when the soil surface is frozen and on steep

TABLE 1

Intensity based classification of dust storm

Intensity of Dust Storm	Wind speed (m s^{-1})	Visibility (m)
Light	5.5-13.8	500-1000
Moderate	13.9-20.7	200-500
Severe	>20.0	<200

TABLE 2

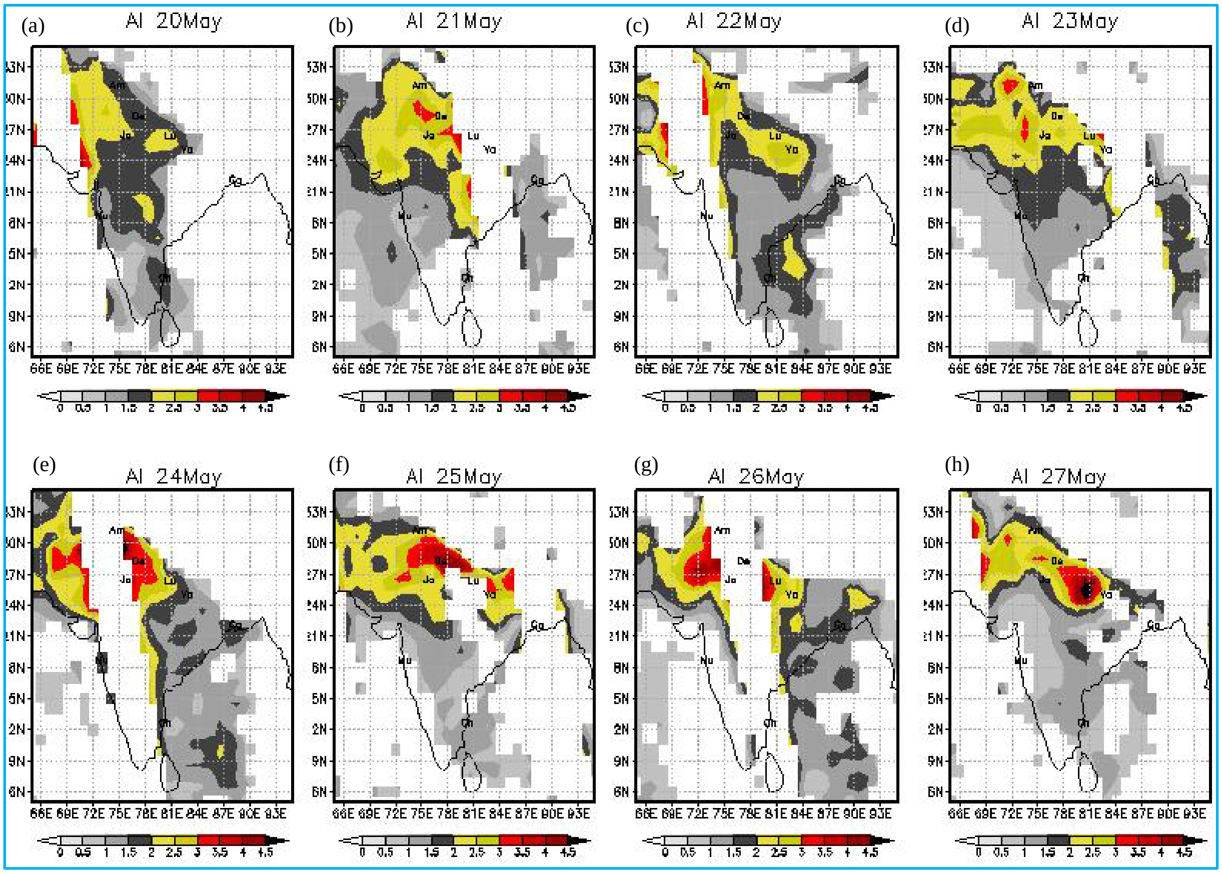
Days and hours with observed visibility less than 1 km during April-June 2016 at three stations

Station	Day	Hour (IST)	Visibility (m)	Wind Speed (m s^{-1})	Intensity of Dust Storm
Jaipur	2 May, 2016	0900	500	8.2	Light
		1000	500	12.0	Light
		1100	500	11.0	Light
	10 May, 2016	0900	800	10.3	Light
		1000	500	14.4	Moderate
	12 May, 2016	1300	800	15.4	Light
	16 May, 2016	1100	600	20.6	Light
	25 May, 2016	1500	200	13.9	Moderate
Delhi	2 May, 2016	1300	800	5.1	Light
	16 May, 2016	1400	900	10.3	Light
	23 May, 2016	0900	600	6.2	Light
		1000	800	6.2	Light
Lucknow	25 May, 2016	1600	800	6.2	Light

slopes and coastal points, where wind speed may be anomalously high.

3. Methodology and datasets

The objective of the study is to identify the dust storm events over north west parts of India during the pre-monsoon season (March-May) of 2016. An event is identified as dust storm when dust raised by strong winds reduces horizontal visibility below 1 km. Dust storms can be classified as light, moderate and severe depending on the values of observed horizontal visibility and wind speed (Table 1 as per India Meteorological Department). The meteorological and satellite observations are utilized to identify the dust storm events over north-west India. The AOD forecasts from NCUM are available at



Figs. 1(a-h). Aerosol Index from OMI for 20 - 27 May, 2016

six different wavelengths 380, 440, 550, 670, 870 and 1020 nm (0.38, 0.44, 0.55, 0.67, 0.87 and 1.02 µm). The AOD forecast at 550 nm is used as the dust AOD forecast in the present study because the dust radiative effects are significant in visible wavelengths. The dust AOD forecast is verified with satellite and ground based observations during the selected dust storm event.

3.1. *Meteorological observations*

Visibility and wind speed observations available at three different locations in north west parts of India are analyzed to identify the dust events during March-May 2016. These observations are available from meteorological airport reports (METARS) of Jaipur, Delhi and Lucknow lying west to east in north India.

3.2. *Ozone Monitoring Instrument (OMI)*

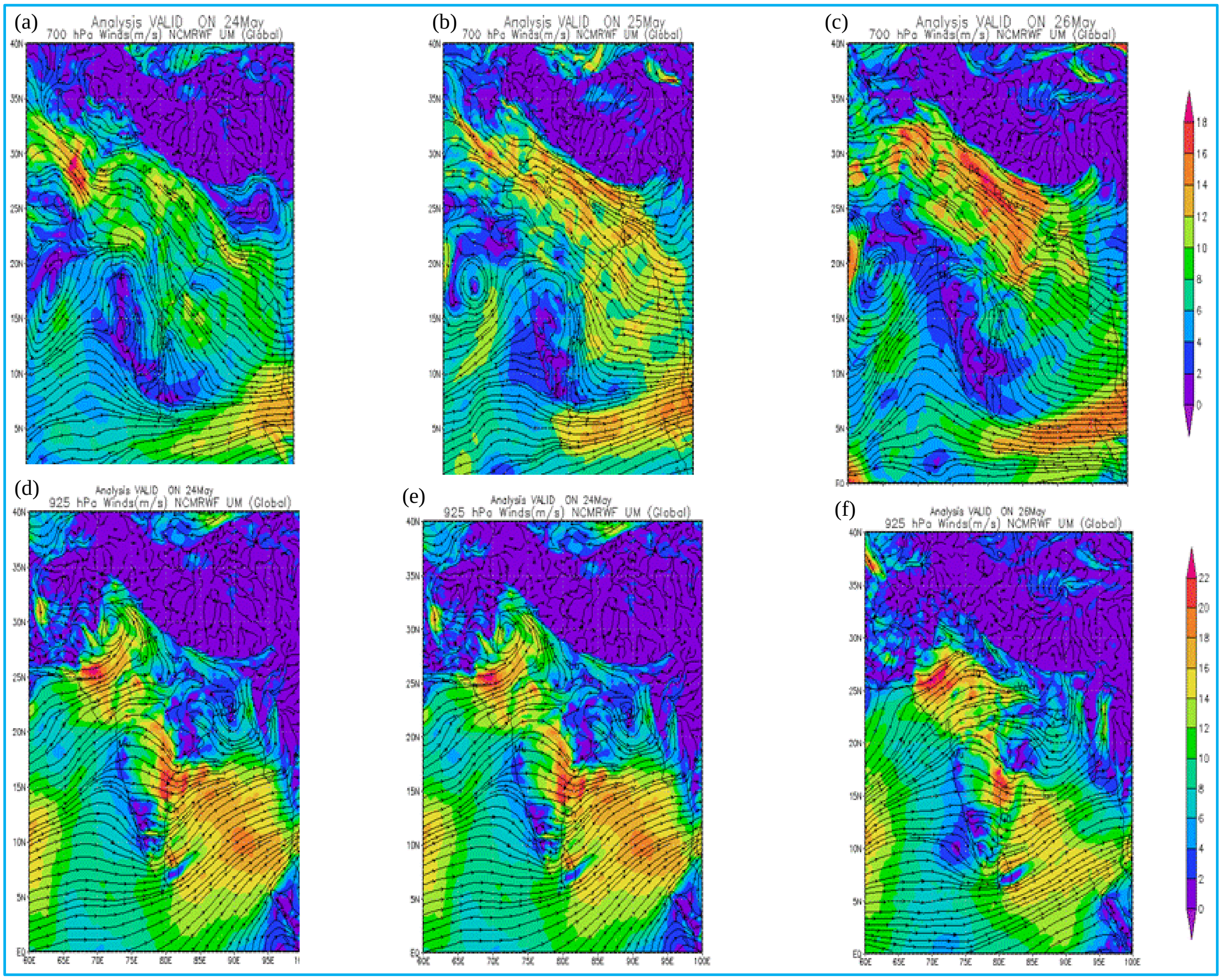
OMI on board Aura satellite was launched in July 2004 to record total ozone and other atmospheric parameters related to ozone chemistry and climate. The type of aerosol can also be detected by OMI. The aerosol index (AI) obtained from OMI data indicates different types of absorbing aerosols such as dust and soot. It is an index that detects the presence of ultra violet (UV) absorbing aerosols (dust, soot). It is defined as the difference between the observations and model calculations of absorbing and non-absorbing spectral radiance ratios.

$$AI = 100\left[\log_{10}\left(I_{360}/I_{331}\right)_{\text{measured}} - \log_{10}\left(I_{360}/I_{331}\right)_{\text{calculated}}\right] \quad (4)$$

where, I_{360} and I_{331} are spectral radiances at 360 and 331 nm respectively. Positive values of *AI* indicate absorbing particles such as dust and soot whereas negative values of *AI* indicate presence of non absorbing aerosols and clouds.Level-3 OMI AI data is taken from the website of Giovnni-https://giovanni.sci.gsfc.nasa.gov/giovanni/.

3.3. *MODIS AOD Observations*

Moderate Resolution Imaging Spectroradiometer (MODIS) onboard NASA's polar orbiting Terra and Aqua



Figs. 2(a-f). Analysis windstream from NCUM at 700 hPa (a), (b), (c) and at 925 hPa (d), (e), (f)

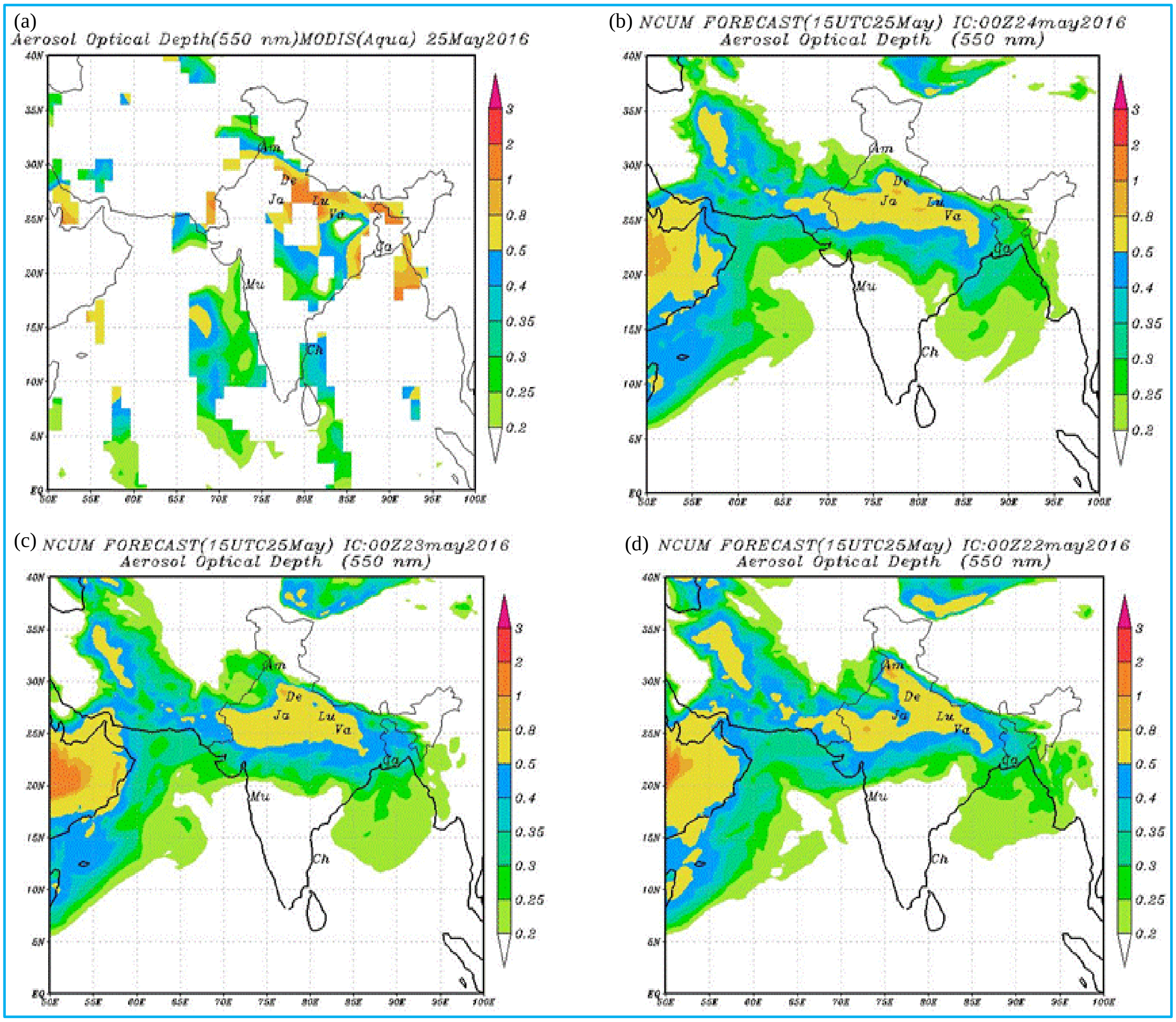
satellite provides daily global data of different aerosol products in 36 spectral bands ranging from visible to thermal infra red (0.41-14.38 µm). The present study utilizes AODs at 550 nm from MODIS Aqua Level 3 products available on Giovanni website (http://giovanni.gsfc.nasa.gov). These products are available on a spatial resolution of 1° × 1° on daily and monthly basis, globally.

4. Results and discussions

4.1. *Dust events over north west India during pre-monsoon season 2016*

The analysis of visibility observations available from METARS of Jaipur, Delhi and Lucknow reveals that the value of visibility is reported less than 1 km at all the stations for six days. The observed wind speed values for these selected days are analyzed to ascertain the intensity of dust storm at the selected locations. Table 2 gives the observed values of visibility, wind speed and type of dust storm identified at these locations. It is clear that none of the station reported visibility less than 200 m and wind speed greater than 20 ms^{-1} for the six selected days and thus based on Table 1, no severe dust storm is reported at any of the stations. Dust storm of light intensity is observed over Delhi and Lucknow, whereas over Jaipur, dust storm of moderate intensity is observed for two days and light intensity dust storm is observed for other days.

The analysis of meteorological conditions suggest occurrence of moderate to light intensity dust storms for few days over different stations during the pre-monsoon season of 2016. A dust storm of moderate intensity occurred over Jaipur on 25th May 2016, whereas Delhi and Lucknow experienced light dust storm on 23rd and 25th



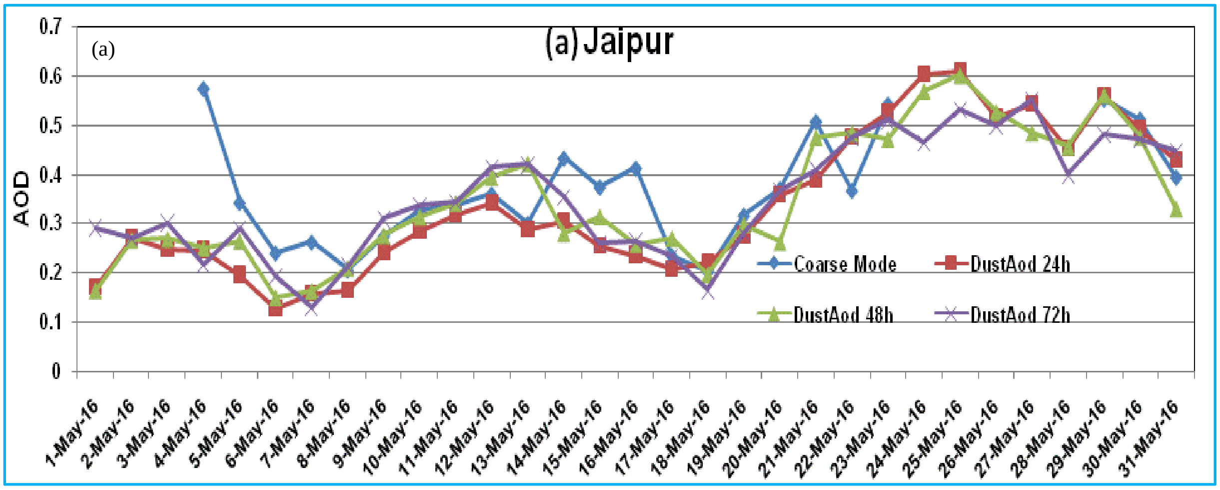
Figs. 3(a-d). Comparison of (a) MODIS AOD Observations with dust AOD (b) Day-1 (c) Day-2 and (d) Day-3 forecast from NCUM valid at 25th May, 2016

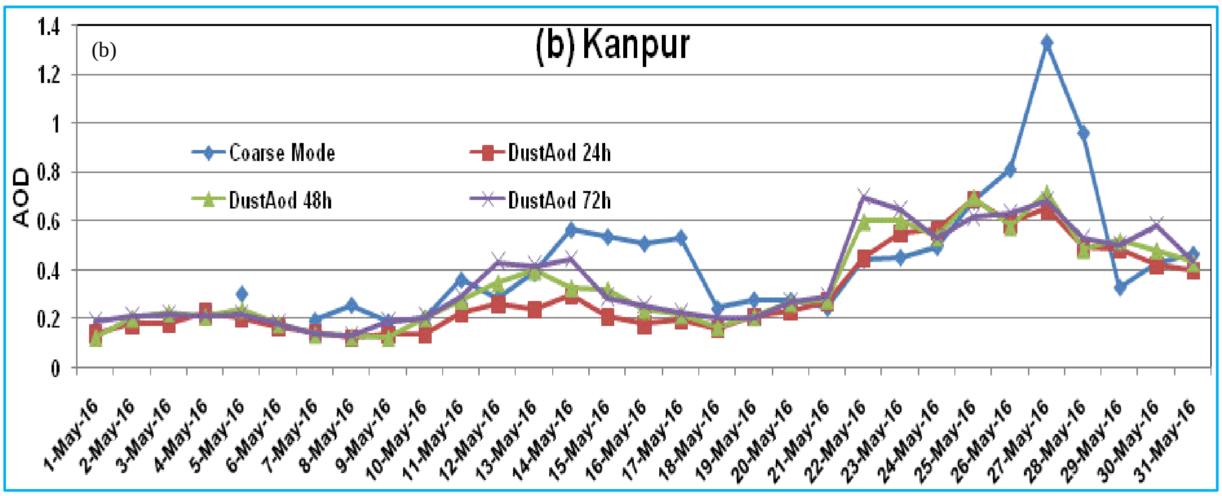
May respectively (Table 2). Fig. 1. shows the variation of OMI-AI over the Indian region from 20th-27th May 2016. The spread of dust storm over parts of north India is clearly seen with increasing values of AI on 21st, 23rd, 24th, 25th and 26th May. The AI values are high for these days in comparison to those observed for other days. The transport of dust is seen from western part (Thar desert) of the country. Very high values of AI of the order of 4.0 are observed from 24th May [Fig. 1(e)] which are spreading over eastern parts in the consequent days Figs. 1(f-h).

The analysis of wind fields at 700 and 925 hPa available from NCUM are used to study the movement of air mass over the northern parts of the country from 24th to 26th May, 2016 (Fig. 2). It is observed that wind speed at 700 hPa increases to higher values of the order of 14-16 ms^{-1} on 25th and 26th May causing the transport of dust from western to eastern parts of the country Figs. 2(b-c). However, the winds at lower levels 925 hPa do not favor dust transport Figs. 2(d-f). The analysis winds revealed that wind moved along the IG plains with greater wind speed (> 12 ms^{-1}) at higher altitudes than near the surface (925 hPa). This signifies that winds at or lower than 700 hPa is responsible for dust transport from north western part to north eastern part of the country.

4.2. *Verification of dust AOD from NCUM with MODIS Observations during the dust storm event*

The forecast of dust AODs from NCUM are verified against MODIS AOD observations for dust storm of





Figs. 4(a&b). Time series of Day-1, Day-2 and Day-3 Dust AOD forecast with Aeronet observations at (a) Jaipur and (b) Kanpur during May 2016

TABLE 3

Correlation coefficient for Day-1, Day-2 and Day-3 Dust AOD forecast with aeronet observations at Jaipur and Kanpur

Location	Correlation Coefficient		
	Day-1	Day-2	Day-3
Jaipur(26.90° N,75.80° E)	0.71	0.65	0.61
Kanpur(26.51° N, 80.23° E)	0.70	0.69	0.65

25th May, 2016 which was experienced over Jaipur and Lucknow. The dust storm was observed at 1500 UTC over Jaipur as moderate and light over Lucknow at 1600 UTC (Table 2).

Fig. 3 shows the comparison of observed AOD from Modis with Day-1, Day-2 and Day-3 dust AOD forecast obtained from NCUM valid at 1500 UTC of 25th May. Higher AODs ranging from 0.8-1.0 are observed over regions nearby Delhi, Jaipur and Lucknow on 25th May [Fig. 3(a)]. These high values of AODs in this region are due to enhanced dust loading during pre-monsoon season.

Day-1 forecast of dust AOD based on 0000 UTC 24th May initial conditions also show high values of dust AOD ranging from 0.5-0.8 over major parts of the north India, the values of dust AOD ranging from 0.8-1.0 are predicted for regions near Delhi and Lucknow [Fig. 3(b)]. The spatial distribution of dust AODs in Day-2 [Fig. 3(c)] and Day-3 [Fig. 3(d)] forecast are also in agreement with the observations.

4.3. *Verification of dust AOD from NCUM with Aeronet observations during the dust storm event*

Aeronet is a global network which have ground based measurements of aerosol optical properties (Holben *et al*., 1998). The data of Aeronet stations at Jaipur and Kanpur is available during the study period. These stations lie along the path of dust transport over plains of north India and thus considered for model evaluation. The present study utilizes level 1.5 daily Aeronet data for validation of model forecast. The Aeronet data does not directly retrieve the dust AOD. However, as coarse mode particles dominate in the mineral dust (Dubovik *et al*., 2002), the coarse mode optical depth from Aeronet can be utilized as dust AOD at these stations.

Fig. 4 shows the comparison of observed coarse mode AOD with Day-1, Day-2 and Day-3 forecast of dust AOD from NCUM for the month of May 2016 at Jaipur and Kanpur. There is a good agreement between observed and predicted values at both the stations. Jaipur observed dust storms on 2nd, 10th, 12th, 16th and 25th May (Table 2) which is well captured by the model with prediction of high values of dust AOD(>0.3) and matching with observations [Fig. 4(a)]. Similarly, the observed values of AOD are matching with predicted values of AOD over Kanpur for 23rd and 25th May [Fig. 4(b)] when Lucknow observed dust storm (Table 2). A good correlation of the order of 0.7 is obtained between the observed and predicted values up to Day-3 forecast at both the stations (Table 3). For some days at both the stations the model forecast is under predicted as compared to observations. The under prediction becomes higher at Kanpur which is the region away from dust source.

Thus, the model is able to predict the high values of AODs in the spatial forecast and also over the specific locations during the dust events. An under prediction is observed in the model predicted values of AODs at both the Aeronet stations. These differences may be due to the fact that regions of dust sources in arid and semi-arid regions of northwest India may not be properly represented in the model. Another limiting factor of the model is that it does not account for any local dust due to unavailability of local dust inventory for Indian region. The horizontal resolution of the model is 17 km which is relatively coarser resolution to capture the dust raised by local convective events. Further, the lack of assimilation of dust/aerosol optical depth in the present assimilation system which prepares the initial condition of NCUM may have contributed to the under prediction of AODs by the model.

5. Conclusions

The main objective of the study is to forecast the dust events observed over northern plains of India during the pre-monsoon season of 2016. The dust AOD forecasts from operational global unified model of NCMRWF (NCUM) are used to forecast the transport of dust over the northern plains of India. The ground based and satellite observations are analyzed to identify the dust events over plains of north India. The results of study may be concluded as:

(*i*) Six dust events are identified over northern plains of India based on the meteorological observations available from METARS of three stations Jaipur, Delhi and Lucknow during March-May 2016. The dust event on 25th May was experienced over Jaipur and Lucknow and Delhi experienced dust event on 23rd May. The dust storm event of moderate intensity was experienced over Jaipur on 25th May, 2016 whereas Delhi and Lucknow experienced light dust storm on 23rd and 25th May respectively. This event is identified based on the observations from OMI and from the analysis winds of NCUM. The higher values of AI are observed from OMI during 24th - 27th May indicating the movement of dust storm from western to eastern parts of the country.

(*ii*) The analysis winds from NCUM at 700 and 925 hPa suggest that dust is transported over plains of north India from 24th - 27th May by high altitude winds (700 hPa) of the order of 14 ms^{-1}. Thus, model is able to capture the transport of dust during the event.

(*iii*) The comparison of spatial forecast of AOD from NCUM with MODIS observations shows that the model is able to capture the high values of AODs observed over northern plains of India on 25th May in its Day-1, Day-2 and Day-3 forecast.

(*iv*) The comparison of model predicted AODs with Aeronet observations at Jaipur and Kanpur shows that model is able to capture the high values of AOD during the dust storm events of 2nd, 10th, 12th, 16th and 25th May in Day-1, Day-2 and Day-3 forecast.

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