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Forecasting dust storms using the CARMA-dust model and MM5 weather data

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Abstract

An operational model for the forecast of dust storms in Northern Africa, the Middle East and Southwest Asia has been developed for the United States Air Force Weather Agency (AFWA). The dust forecast model uses the 5th generation Penn State Mesoscale Meteorology Model (MM5) as input to the University of Colorado CARMA dust transport model. AFWA undertook a 60 day evaluation of the effectiveness of the dust model to make short, medium and long- range (72 h) forecasts of dust storms. The study is unique in using satellite and ground observations of dust storms to score the model's effectiveness using standard meteorological statistics. Each of the main forecast regions was broken down into smaller areas for more detailed analysis. The study found the forecast model is an effective forecast tool with Probability of Detection of dust storm occurrence exceeding 68 percent over Northern Africa, with a 16 percent False Alarm Rate. Southwest Asia forecasts had average Probability of Detection values of 61 percent with False Alarm Rates averaging 10 percent.

Keywords: Dust storm forecasting; MM5 weather model; CARMA model; Skill scores; Mineral dust

Software availability

Name of Software: CARMA-Dust
Contact address: B. H. Barnum, Johns Hopkins Applied Physics, Laboratory, Laurel, MD 20723-6099, Tel.:+1-443-778-7082, fax:1+443-778-1899, email: ben.barnum@jhuapl.edu
Year first available: 2002
Hardware required: Sun or Pentium PC with 512 Mb RAM
Software required: Solaris Linux with IDL, Perl and F77 compiler with netCDF library.Program language: Fortran 77, Perl, IDL
Program size: 4 Mb
Availability and cost: contact the developer for further information.

1. Introduction

Dust storms throughout Saharan Africa, the Middle East and Asia are estimated to place more than 200–5000 million metric tons of mineral dust into the earth's atmosphere each year (Tegen and Fung, 1994). Dust storms directly affect visibility and impact daily commercial and military operations near desert regions. The United States Air Force Weather Agency (AFWA) has supported the development of a dust forecast model with a 72 h forecast capability. The dust model called Community Aerosol and Radiation Model for Atmospheres (CARMA), was originally developed by Professor Owen Toon and Dr. Peter Colarco at the University of Colorado, Boulder (Toon et al., 1988; Colarco et al., 2002).

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The CARMA model has been modified by Johns Hopkins Applied Physics Laboratory to make daily dust forecasts using weather forecast data generated by the United States Air Force Weather Agency MM5 weather model.

Several other dust aerosol models are being used for the daily forecasting of dust storms. These models are similar to the CARMA-Dust model, in that they use data from standard weather models such as ETA, NOGAPS or MM5. The University of Malta and the University of Athens uses a modified version of the Eta weather model to make dust forecasts over Northern Africa and the Mediterranean (Nickovic and Dobricic, 1996). The United States Naval Reasearch Laboratory makes daily forecasts of dust using the Navy Aerosol Analysis and Prediction System (NAAPS). The NAAPS aerosol model uses daily weather forecast products from the Navy Operational Global Atmospheric Prediction System (NOGAPS) (Hogan and Rosmond, 1991). A dust forecast model developed by Yaping Shao is being used to forecast dust storms over China and East Asia using weather data from the National Meteorological Center (CMA) of China (Shao, 2001; Lu and Shao, 2001).

Our goal in this paper is to evaluate how well CARMA does in making forecasts of dust storm occurrence using mesoscale weather forecast data. A direct comparison of the CARMA-Dust model to the other dust forecast models is beyond the scope of this paper. We believe, however, that the forecast statistics and capabilities of the CARMA model are representative of current dust models now in use worldwide.

The latest version of the CARMA MM5 dust model can make 72 h forecasts of surface and airborne dust concentrations in 3 different mesoscale theaters covering Saharan Africa and the Middle East, Southwest Asia and China. A new global dust source database developed by Dr. Paul Ginoux et al. (2001) is used in the CARMA model. The dust source model is based on topographical features associated with dust sources and has been further developed using TOMS satellite data (Prospero et al., 2002; Herman et al., 1997).

The forecast ability of the dust model was evaluated over a 60 day period, beginning February 15th, 2002, for two of the AFWA MM5 forecast theaters, Saharan Africa and Southwest Asia. The Middle East has been grouped with Southwest Asia for this evaluation. The model forecasts were compared with Defense Meteorological Satellite Program (DMSP) satellite imagery and ground observations. Each theater was broken into subregions for detailed evaluation of the short (6–12 h), mid (30–36 h) and long-term (54–60 h) forecast ability of the model. Results of the study show the dust model has good skill in forecasting dust conditions for short, medium and long range forecast periods.

2. CARMA MM5 dust forecasting

The Community Aerosol and Radiation Model for Atmospheres (CARMA) was originally developed by the University of Colorado and NASA Ames to be a scalable aerosol model to study a variety of atmospheric processes, such as cloud formation, smoke and dust aerosols (Toon et al., 1988). The version of CARMA developed for daily forecasting of dust has been modified to assimilate meteorological forecast data from the Penn State 5th generation Mesoscale Meteorology Model (MM5) (Anthes and Warner, 1978). The model also incorporates the global dust source database developed by Ginoux et al. (2001). The model uses 10 particle size bins which cover dust particles with radii from 0.5 μm to 10.0 μm. Following the model initialization, the MM5 72 h forecast data for winds, pressure, and temperature, at the surface and at 22 selected sigma pressure levels are input into CARMA. The dust model outputs a set of dust concentration maps and vertical concentration profiles for each 3 h time period during the 72 h forecast.

The MM5 weather forecast data is run by the United States Air Force Weather Agency (AFWA) for theaters worldwide on a daily basis (Fig. 1). The MM5 data is obtained directly from AFWA for the mesoscale theaters covering Saharan Africa and Middle East (T09a) and Southwest Asia (T04a). The MM5 model is run with 41 vertical sigma pressure coordinate levels with 45 km horizontal grid spacing.

The CARMA dust model reads in a subset of the MM5 data, using 22 vertical sigma pressure levels and a 90 km horizontal latitude, longitude grid spacing. This grid scheme was chosen to have approximately the same resolution as the $1° \times 1°$ (111 km) dust source database and to reduce the run time for daily forecasting. The vertical levels were chosen to optimize vertical resolution in the boundary layer, with 18 vertical levels used between the surface and the 500 mb pressure level. Vertical winds are calculated internally in CARMA for each grid location based on the divergence of the MM5 pressure fields at each sigma vertical pressure level using the method of Jacobson (1999). In the model, dust aerosols are lofted by vertical advection and diffusion. The vertical diffusion is calculated in CARMA using the MM5 input meteorology. The model calculates the vertical potential temperature, sensible heat flux, Monin–Obukhov length and friction velocity using the MM5 meteorological profile at each grid cell location. The model then calculates the vertical diffusion for each vertical level following the method developed by Zhang and Anthes (1982).

The dust model forecast is initialized by running the model for a simulated 2 day (48 h) “spin-up” period. The spin-up uses the first 24 h of each daily MM5 forecast during the spin-up portion of the model run. The data from the end of the spin-up period is used as the

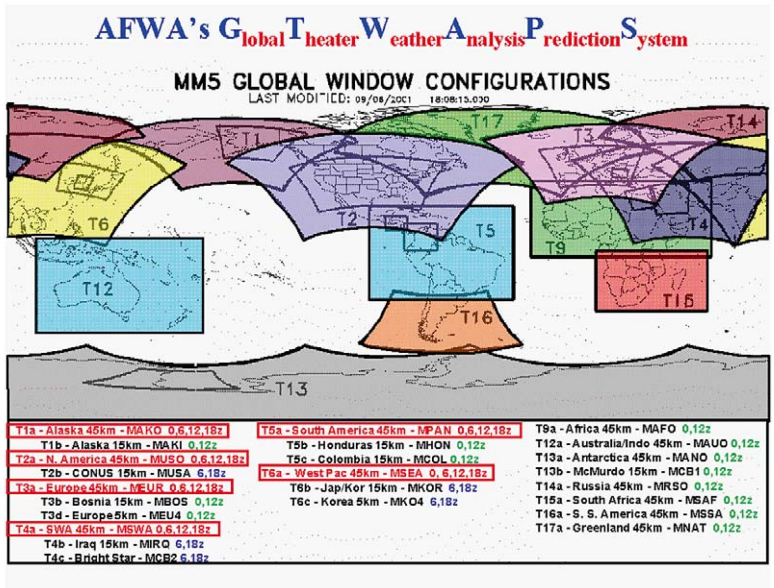

Fig. 1. Weather forecast data is run daily by the USAF Weather Agency for the theaters shown using MM5. Input meteorology used in CARMA is run with 45 km grid resolution for Africa (t09a) and Southwest Asia (T04a).

initial dust concentration condition at the beginning of the 72 h CARMA forecast. During model development, we compared 2, 5 and 10 day spin-up cycles for dust storm prediction. The use of 5 or 10 day forecasts were found to be better in a few cases over Saharan Africa for the prediction of total dust loading; however, the 2 day spin-up cycle was able to capture all of the main features required for dust forecasting. Since the model was to be used for daily operational forecasting at AFWA, the 2 day spin-up version was implemented.

2.1. Dust source model

The CARMA MM5 model uses a global dust source database originally described by Ginoux et al. (2001). The dust database was developed using topography and dust sources regions identified using satellite data from the Total Ozone Mapping Spectrometer (TOMS). The TOMS instrument measures the amount of ultraviolet absorption by dust aerosols by taking the ratio of 331 nm and 360 nm measured radiance to the calculated radiances based on a model Rayleigh scattering atmosphere (Herman et al., 1997). The database uses TOMS observed sources that are associated topographical depressions where sediments accumulate, such as the Lake Chad Basin. The source areas are assigned a source strength value between 0 and 1.0. The data is given on a global $1^\circ \times 1^\circ$ grid, shown in Fig. 1, and is re-interpolated to the MM5 grid used in the CARMA dust model.

The current implementation of the CARMA MM5 model uses 10 particle size bins, which cover particle sizes from 0.1 to 10 μm. Each of the bins are sized so that the individual particle mass in each succeeding bin has a mass ratio of 2.71 times the mass of a particle in the preceding bin size, as listed in Table 1 (Toon et al., 1988).

The model uses 3 dust particle size ranges or classes to describe soil fractional components consisting of clays, silts and sand. Each class is assigned a component fraction, which is 0.1 for clay, 0.33 for silt and 0.33 for sand. The clay component is any particle radius ranging from 0.1 μm to 1.0 μm, silts are 1.0 μm to 10 μm in particle radius and sand is any particle larger than 10.0 μm.

Dust mobilization normally begins when the surface wind velocity exceeds a threshold wind speed. At the threshold speed, larger particles, which are not embedded in the soil matrix, are blown along the surface in saltation where they collide and liberate smaller particles from the soil by sandblasting (Gillette, 1980). The threshold wind speed calculated in CARMA follows the method developed by Iversen and White (1982). The model mobilizes larger sand particles at lower wind speeds to simulate the sandblasting process. Fig. 3 shows the threshold wind speed versus particle size used in the model.

The surface dust flux in CARMA is calculated using the net MM5 wind velocity at 10 m above ground (agl). The flux equation follows the formulation based on Gillette and Passi (1988). The dust source model first calculates the mobilization threshold wind velocity at each grid location for each particle bin size. Where there is measurable accumulated precipitation in a 24 h period, the threshold wind velocity is set so that no dust flux is generated at the location.

The surface dust flux is then calculated for each particle size bin using the MM5 forecast 10 m wind speed using:

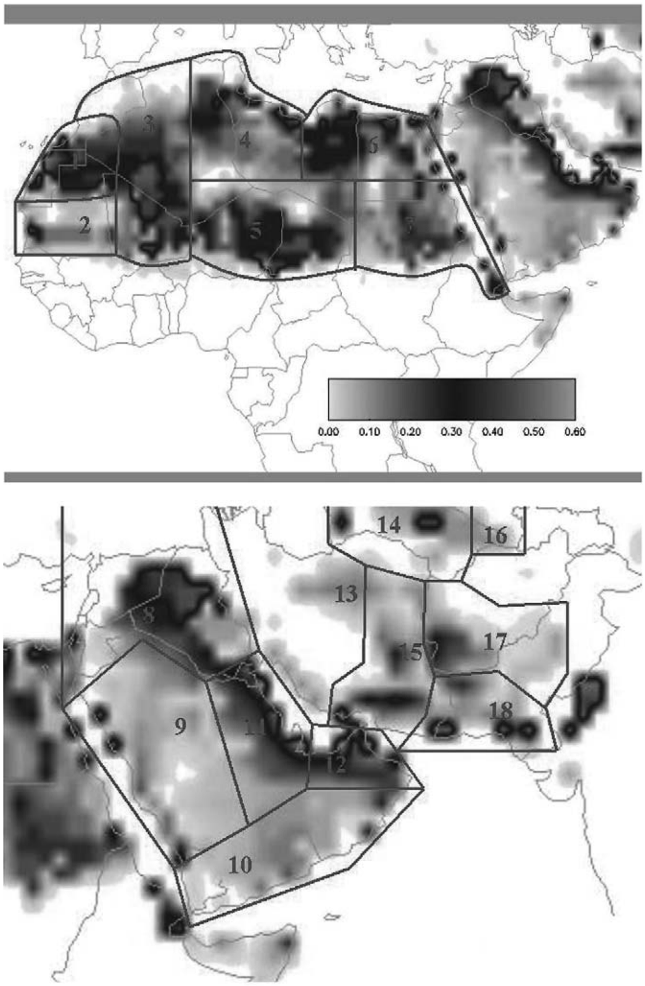

Fig. 2. (a) Dust source regions over North Africa and the Middle East on a 0–1.0 scale, plotted with 0 (white) being a non-source region and >0.6 (yellow) representing the most significant source regions. The mesoscale area is divided and grouped into distinct regions that are used for the computation of skill scores. (b) Dust source regions over the Middle East and Central Asia with white being a non-source region and yellow representing the most significant of source regions. The area is divided and grouped into distinct regions that are used for the computation of skill scores.

$$F_{(i,j,r)} = C*S_{(i,j,r)}*)w_{10m(i,j)} - u_{t(i,j,r)}*w_{10m(i,j)}{}^2.$$

where C is a model constant equal to 2.34 × E-17 µg s^2m^{-5}, used to control the total amount of dust flux emission. C depends on the particular weather model and grid scale used. $F_{(i,j,r)}$ is the surface dust flux in gm/m^2-s, at each of the i,j, grid locations and particle bin number r, $S_{(i,j,r)}$ is the Ginoux database source strength for each particle class size, $\boldsymbol{w10m}_{(i,j)}$ is the MM5 wind speed at 10 m agl, and $u_{t(ijr)}$ is the calculated threshold wind speed for each grid location and particle bin size (Ginoux et al., 2001; Chin et al., 2002).

Table 1
CARMA-Dust model particle bin sizes and estimated particle fall velocities at sea level. The 10 particle bins are sized such that the mass of a particle in the $i + 1$ bin is 2.71 times the mass of the particle in the preceding ith bin

Particle radius (in µm)	Particle mass (kg)	Particle fall velocity at sea level (m/s)
0.50	1.39×10^{-15}	0.0001
0.71	3.77×10^{-15}	0.0002
0.97	1.02×10^{-14}	0.0003
1.36	2.78×10^{-14}	0.0006
1.89	7.53×10^{-14}	0.0012
2.64	2.04×10^{-13}	0.0023
3.68	5.56×10^{-13}	0.0044
5.14	1.51×10^{-12}	0.0084
7.17	4.09×10^{-12}	0.0163
10.00	1.11×10^{-11}	0.0316

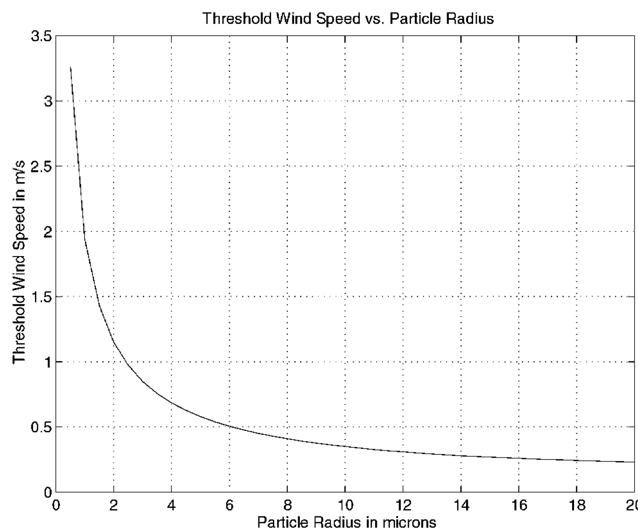

Fig. 3. Dust threshold surface wind velocity calculated in CARMA using the method described by Iverson and White (1982). Notice that smaller size dust grains require higher surface wind speeds to mobilize since they are embedded in the soil matrix until liberated by larger particles.

2.2. Dust deposition and advection

Dust deposition in CARMA is calculated using a 2 layer method described by Shao (2000). The particle vertical deposition velocity combines the effects of boundary layer turbulent motion, molecular diffusion and sedimentation. In this way, the particle deposition in the lowest model layer is controlled by the boundary layer meteorological conditions forecast by MM5. The particle sedimentation velocity is calculated at each model layer and particle size bin assuming rigid, spherical geometry using corrected drag coefficients developed by Prupacher and Klett (1997). In the current version of the dust model we only calculate dry deposition. However, dust flux is suppressed at locations wherever there is measurable accumulated precipitation in MM5. The dust flux is suppressed by making the surface threshold wind velocity infinite if there is accumulated precipitation within a 24 h time period within the grid cell.

The advection of dust in the CARMA model uses a horizontal transport method developed by Lin and Rood (1996). Horizontal advection rates are calculated using Piecewise Polynomial Method (Colella and Woodward, 1984). In order to satisfy the Courant (CFL) conditions, the model uses a time step of 1200 s, with meteorological conditions interpolated between each 3 h MM5 forecast.

2.3. Model output

The dust model forecasts are displayed as a set of color images showing total dust concentration at user selected altitudes, vertical profiles and total dust loading. The images are made for each 3 h interval in the 72 h forecast, an example of the African and Middle Eastern mesoscale theater (t09a) is shown in Fig. 4a and b.

3. Model forecast study

The dust model was installed and run daily at AFWA beginning February 2002. The forecast capability of the model was conducted by AFWA over a 66 day evaluation period beginning on the 8th of February through to April 15th 2002. The evaluation covered two mesoscale regions: Saharan Africa (t09a) and Southwest Asia (t04a) and the Middle East. Each mesoscale region was subdivided into smaller areas for more detailed evaluation.

The goal of the study was to determine how well the model could forecast dust storms and conditions of reduced visibility caused by dust. The study used satellite and ground based observations of dust storms to verify the presence or absence of dust storms.

3.1. Evaluation methodology

The AFWA study compared dust observation data with the CARMA model 72 h forecasts. The study used two separate analysis teams, one to run the dust model and prepare and analyze the forecasts, the second team prepared analysis of dust storm occurrences based on ground and satellite data. This was done in order to lessen possible human biases in the model evaluation.

AFWA personnel prepared hand drawn maps showing the locations of dust storms using high-resolution satellite loops, Defense Meteorological Satellite Program (DMSP) images, and ground observations. Dust concentrations vary from less than 50 $\mu g\ m^{-3}$ under normal atmospheric conditions, greater than 100 $\mu g\ m^{-3}$ under hazy conditions, 1000 $\mu g\ m^{-3}$ in reduced visibility and very hazy conditions, to 5000 $\mu g\ m^{-3}$ and higher in severe dust storms (Westphal, 1986; Westphal et al., 1987). Dust that reduces visibility and causes hazy conditions is often noted by local observers and can be seen in visible and infrared satellite imagery. The AFWA DNXT analysis team chose to use a value of approximately 1800–3500 $\mu g\ m^{-3}$ shown as red areas on the log color dust maps as the threshold dust/no-dust forecast. Wherever model surface forecast concentrations exceeded 1800 $\mu g\ m^{-3}$, it was considered to be a dust event and dust storm conditions were assumed to be present at the location. The model evaluation focused on the accuracy in forecasting the occurrence/non-occurrence of dust events rather than on their intensity.

The model was scored using meteorological "skill scores" over short (6–12 h), medium (30–36 h) and long (54–60 h) range forecasts. The skill scores used were Probability of Detection (POD), False Alarm Rate (FAR), Critical Success Index (CSI), and Probability of Detection of a NIL event (POD-NE) (Murphy and Winkler, 1987; Murphy and Epstein, 1989). Saharan Africa (t09a) was divided into 7 sub-regions and the Middle East/Southwest Asian theater (t04a) into 11 subregions as shown in Fig. 2a and b.

3.2. Model evaluation results

The average POD and FAR, CSI and POD_{Nil} percentages for theater 9a are given in Table 2a, and the results for theater 4a are given in Table 2b. The lowest CSI scores occurred in the Yemen and Oman sub regions where the POD's were only 19 percent, with a FAR of zero. This region of the Empty Quarter is a great sand desert, but is a relatively weak dust source in the Ginoux database. This desert region produces surface level sandstorms. Sandstorms typically have a lower TOMS AI, which is more sensitive to higher altitude dust concentrations.

Results of the AFWA study show the dust model has good skill in forecasting dust conditions over short (12 h) and medium (36 h) forecast periods. In Saharan Africa (t09a), the average POD for a 30–36 h forecast was 67 percent with a FAR of only 15 percent. Long range forecasts of 54–60 h had POD's of 59 percent with FAR's increasing to 18 percent, indicating decreasing forecast accuracy of the weather model by 60 h.

During the analysis and evaluation of the dust model a correlation was found between forecasted dust concentrations and ground observed visibility, shown in Fig. 5.

Reported surface visibility was found to be reduced in regions where the forecast ground aerosol concentrations were greater than 1000 $\mu g\ m^{-3}$. Analysis of surface visibility observations over Southwest Asia, indicate that a forecasted dust concentration of 2500 $\mu g\ m^{-3}$ (log 2500 = 3.4) or greater was sufficient enough to reduce visibilities to less than 2 miles.

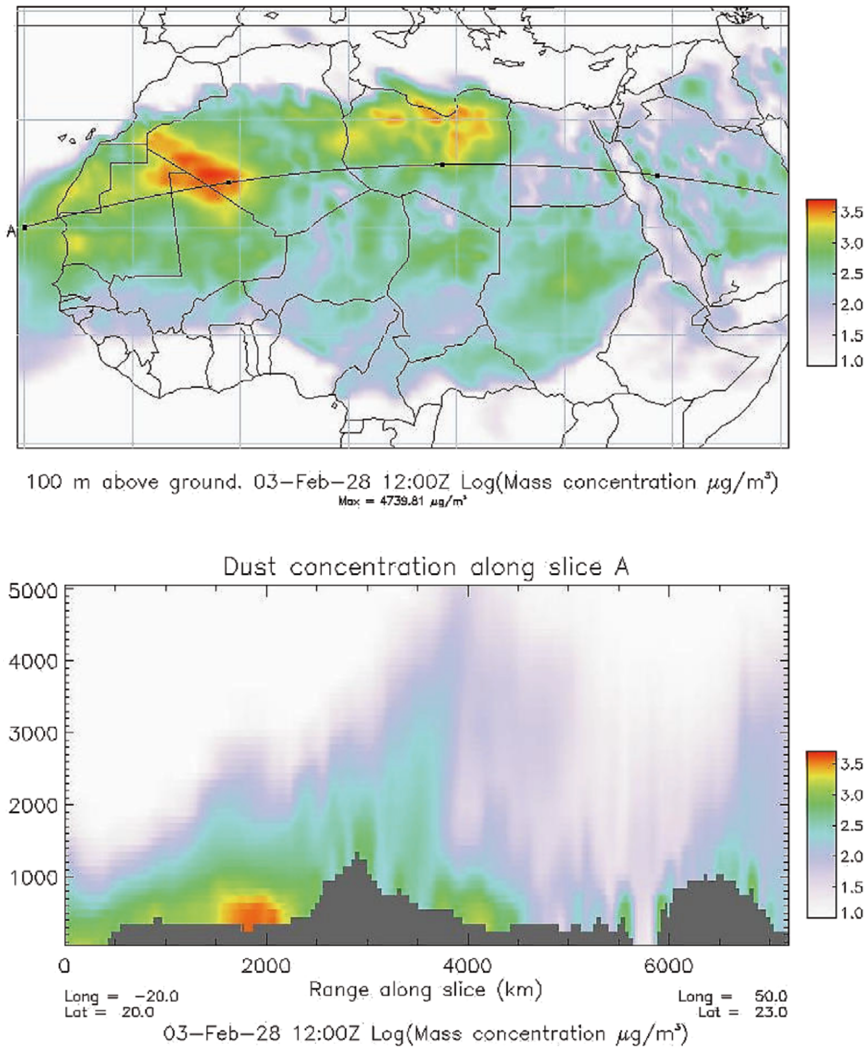

Fig. 4. (a) Example of CARMA model output showing color map of total dust concentration at 500 meter altitude over Saharan Africa and Middle East for the dust storm during January 7, 2002. The maps show concentration using a log scale with user selected color levels for the maps. (b) Vertical cross section showing dust concentration along the line shown beginning at ‘A’ above in Fig. 3a. The local terrain is shown in the map sections. Range along slice is in km, altitudes are in meters (msl).

3.3. Discussion of model forecast evaluation

Within the theater 9a Saharan forecast region, the model had an average short range forecast POD of 69 percent, with a low average FAR of 15 percent.

The dust model had the highest forecast skill scores over Africa’s regions 1, 3 and 5. In region 5, which includes Chad and Niger, had a short term POD of 95 percent. The case shown in Fig. 6 for March 21st, 2002, shows dust storms initiated by strong easterly winds. Lofted dust plumes extend off of the west coast of Africa and out over the Atlantic Ocean. In this example, the dust storm visible in the satellite imagery over Tunisia was not forecast by the dust model.

Southwest Asian theater (t04a) had a 61 percent POD, with only a 10 percent FAR. The highest average POD skill score of 85 percent occurred in sub-region 8. Further evaluation revealed several regional tendencies. The model had lower forecasting skill scores for dust events in the Middle East countries of Jordan, Oman, Yemen and western Saudi Arabia, especially sub regions 9 and 10, which had POD’s of 48 and 19 percent respectively.

In Southwest Asia, low skill scores occurred within the Amudarya valley of northern Afghanistan in sub-regions 16 and 17 where POD’s were 38 and 39 percent for short range model forecasts. The lower skill in forecasting in this region is primarily caused by an underestimate of dust sources in the dust source database at these locations. A case example is shown in Fig. 7, for a dust event over the Amudarya valley on 27 March, 2002.

On this day east winds lifted dust in the Amudarya valley and carried it westward. The model does predict dust to the northwest of the Amudarya valley where a more significant dust source region is indicated in the database (compare Fig. 2b, region 14 and region 16).

Table 2a
CARMA model average Probability of Detection (POD) and False alarm rate (FAR) for short, medium (6–12 h)/medium (12–36 h) and long-range (48–60 h) forecasts. The model evaluation was done February 2002 to April 15, 2002. The sub-regions, 1–7, cover Saharan Africa and Sahel shown in Fig. 2a

MM5 forecast short /medium/long	Probability of detection (POD)	*False alarm ratio* (FAR)	Critical success index (CSI)	Probability of detection of NIL event POD_{NIL}
T9a Africa	68/ 67/ 59	16/ 15/ 18	60/ 60/ 52	78/ 80/ 78
Region 1	81/ 78/ 67	25/ 30/ 38	64/ 58/ 47	80/ 74/ 69
Region 2	57/ 57/ 48	11/ 07/ 13	53/ 54/ 45	83/ 89/ 83
Region 3	77/ 72/ 66	23/ 24/ 28	62/ 59/ 53	47/ 47/ 45
Region 4	62/ 68/ 51	14/ 10/ 11	56/ 63/ 48	83/ 87/ 86
Region 5	95/ 92/ 84	14/ 10/ 11	82/ 83/ 76	77/ 85/ 85
Region 6	71/ 63/ 42	10/ 11/ 08	66/ 59/ 58	88/ 88/ 92
Region 7	44/ 47/ 42	10/ 09/ 10	42/ 44/ 40	88/ 90/ 90

Table 2b
CARMA dust model average Probability of Detection and False Alarm Rates for short, medium (6–12 h), and long-range (48–60 h) forecasts. The model evaluation was done February 2002 to April 15, 2002. The sub-regions, 16–18, cover Middle East, Arabia and Southwest Asia, shown in Fig. 2b (Iran, Afghanistan and Northern Pakistan)

MM5 forecast:short/med. /long(6-12) (30-36) (5460)	Probability of detection (POD)%	False alarm ratio (FAR)%	Critical success index (CSI)%	Probability of detection of NIL events POD_{NIL}%
T4a Southwest Asia	61/ 62/ 52	10/ 9/ 7	56/ 56/ 49	88/ 89/ 92
Region 8	85/ 78/ 65	19/ 19/ 12	72/ 71/ 59	62/ 58/ 75
Region 9	48/ 52/ 54	0/ 0/ 0	48/ 52/ 54	100/100/100
Region 10	19/ 17/ 9	0/ 0/ 0	19/ 17/ 9	100/100/100
Region 11	81/ 81/ 69	0/ 0/ 0	81/ 81/ 69	100/100/100
Region 12	76/ 82/ 71	12/ 17/ 7	68/ 72/ 69	69/ 69/ 85
Region 13	83/ 83/ 75	42/ 42/ 33	59/ 59/ 56	83/ 83/ 86
Region 14	60/ 53/ 40	33/ 27/ 20	45/ 42/ 33	77/ 82/ 86
Region 15	71/ 87/ 64	7/ 7/ 7	67/ 81/ 60	95/ 95/ 95
Region 16	38/ 23/ 31	15/ 15/ 8	33/ 21/ 29	92/ 96/ 96
Region 17	39/ 43/ 39	0/ 0/ 0	39/ 43/ 39	100/100/100
Region 18	64/ 58/ 46	8 / 4 / 4	59/ 56/ 44	87/ 93/ 93

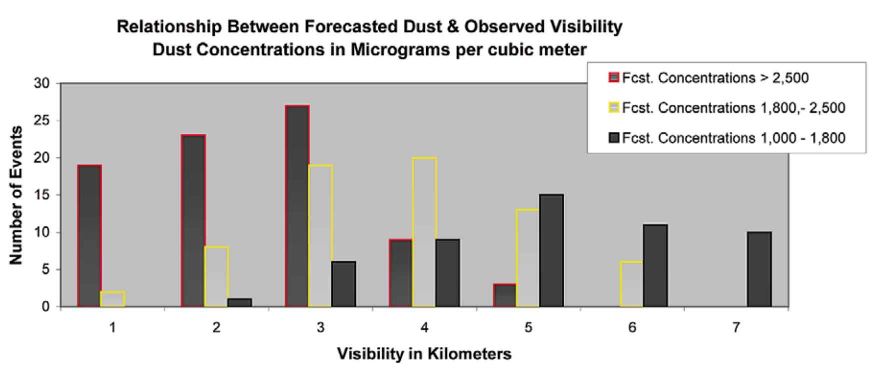

Fig. 5. Ground reported visibility and the CARMA forecasted dust aerosol concentrations showed good correlation during the evaluation period over Southwest Asia (Theater 4a).

The dust model had low forecast scores in region 10 over the southern coast of Yemen and Oman (Table 2b). Most of these dust storms were generated by southerly winds off of the Arabian Sea. During the model evaluation, there was very little precipitation over this region during the study, making it unlikely that precipitation caused the low forecast skill scores. Meteorological data did not show the presence of surface inversions, which would have inhibited dust from being elevated, so this is not a likely explanation. The low POD scores over Yemen and Oman are thus likely due to the weak representation of dust in the Ginoux source database in

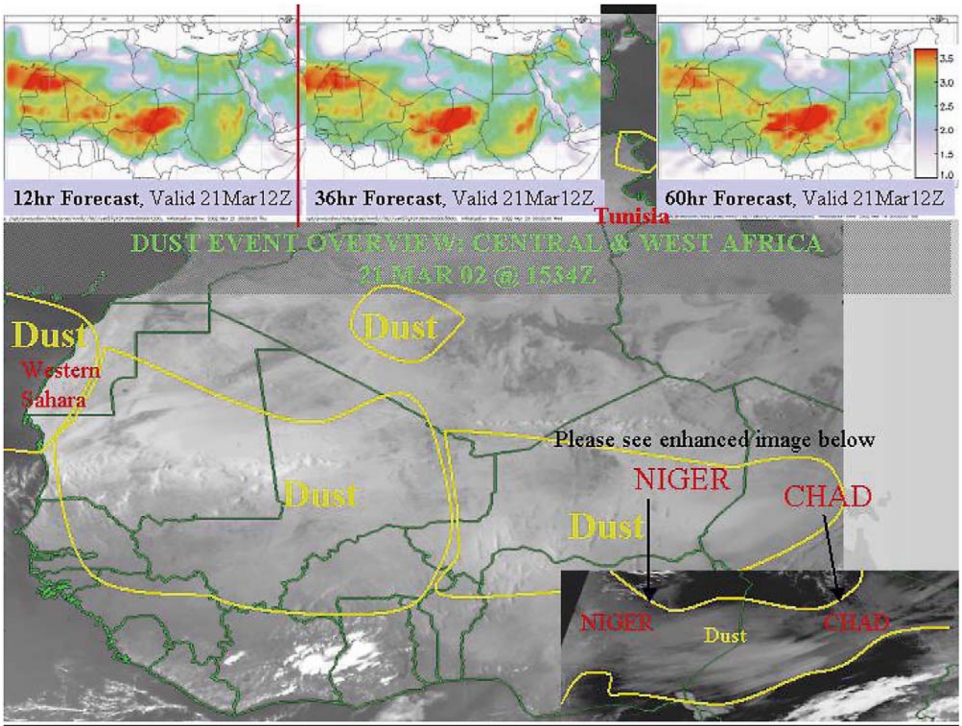

Fig. 6. Dust event during 21st March 2002 over West Africa. Dust model forecasts (top) and enhanced satellite imagery over Chad and Niger (bottom right). The model generally forecasted this event rather well, but slightly too far to the south. There is also a report of dust in Tunisia that was not forecasted.

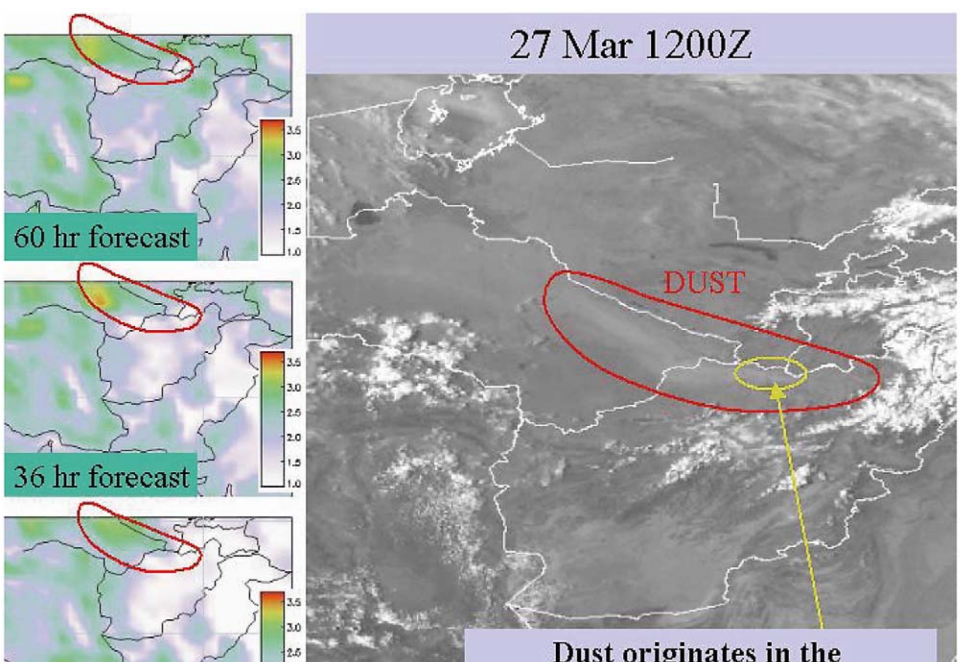

Fig. 7. 27 March 2002 dust event across the Amudarya valley of northern Afghanistan. CARMA predicted dust downwind but missed the origin of the dust event, which is likely due to the model's weak representation of sources in the Amudarya valley.

region 10. A similar case example is shown for April 3, 2002, showing a Saudi Arabian dust storm, which is well predicted over eastern Saudi Arabia but is underestimated by the dust model across the central and western portions of the country (Fig. 8).

The observed and forecasted winds are nearly identical across central Saudi Arabia at less than 15 m/s. Observed visibilities within the outlined dust contour ranged from 1 to 6 miles. The CARMA model indicates some dust over central Saudi Arabia, although it is under-forecasted due to under representation of the sources in the Ginoux source database. This region of Oman and Yemen is a great sand desert, known as the Empty Quarter where sand storms rather than dust storms usually occur (Thesiger, 1959). The DMSP satellite imagery however does not distinguish between sand or dust storms. Sand storms in this region would have lower measured aerosol indices (AI) in the TOMS satellite data. TOMS AI is more sensitive to small airborne particles (0.1–10 μm) than larger sand particles near the surface (Colarco et al., 2002).

MM5 weather model output wind speeds are sometimes in error and this has a direct effect on dust forecasts. Iraq, Jordan, Syria, and the southern coast of Pakistan are the regions that experienced the greatest variability in skill scores from the short to long-term forecasts. Since the predefined dust source regions do not change over time, this decrease in forecast accuracy over a 72 h period is most likely caused by MM5 wind forecast data. Fig. 9 shows an example where the stronger forecast surface winds using the 12 h MM5 data resulted in an accurate forecast for the dust event during the 7th of April 2002.

The 60 h MM5 wind fields cause the CARMA model to miss the dust event over Syria and Iraq verified by satellite data. It is not possible however to directly verify the MM5 wind predictions for Iraq due to a complete absence of reported observations over the country.

Dust storms associated with the passage of strong mid-latitude cyclones are well forecasted by MM5 and the dust model. A mid-latitude cyclone passed through the theater 4a forecast region during April 4th, 2002. The mid-latitude cyclone increased surface winds over much of Southwest and Central Asia leading to the formation of intense dust storms (Fig. 10).

The strong surface winds and thunderstorm outflows elevated a substantial amount of dust causing many visibility reports of 0–2 miles.

The dust model accurately forecasted the positioning and relative intensity of these dust clouds under these meteorological conditions. Mid-latitude cyclone synoptic events over Africa (t09a) are also well forecasted by the MM5 weather model resulting in high confidence dust forecasts under these types of weather conditions.

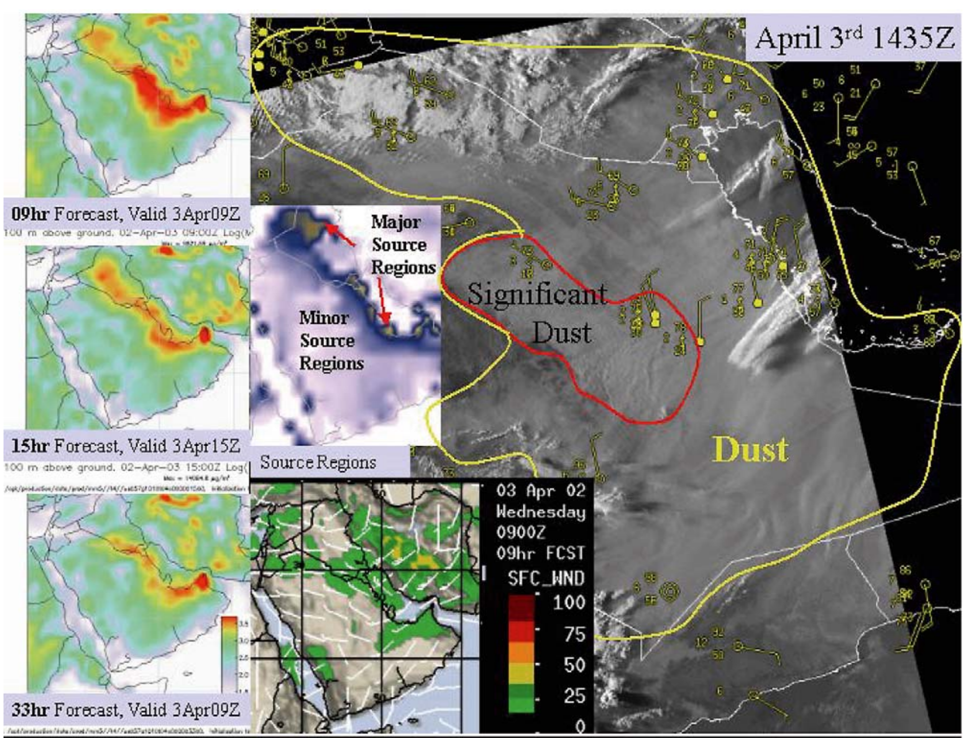

Fig. 8. 3 April 2002 dust event over Saudi Arabia. The CARMA model forecasts are shown on the left. MM5 forecasted winds, which are used in the model, are shown bottom center. The Ginoux database dust source, center panel, are indicated by the shades of purple to yellow with yellow being the most significant source regions. Regions of blowing dust are indicated by satellite and observations and are enclosed within the yellow and red outlined areas.

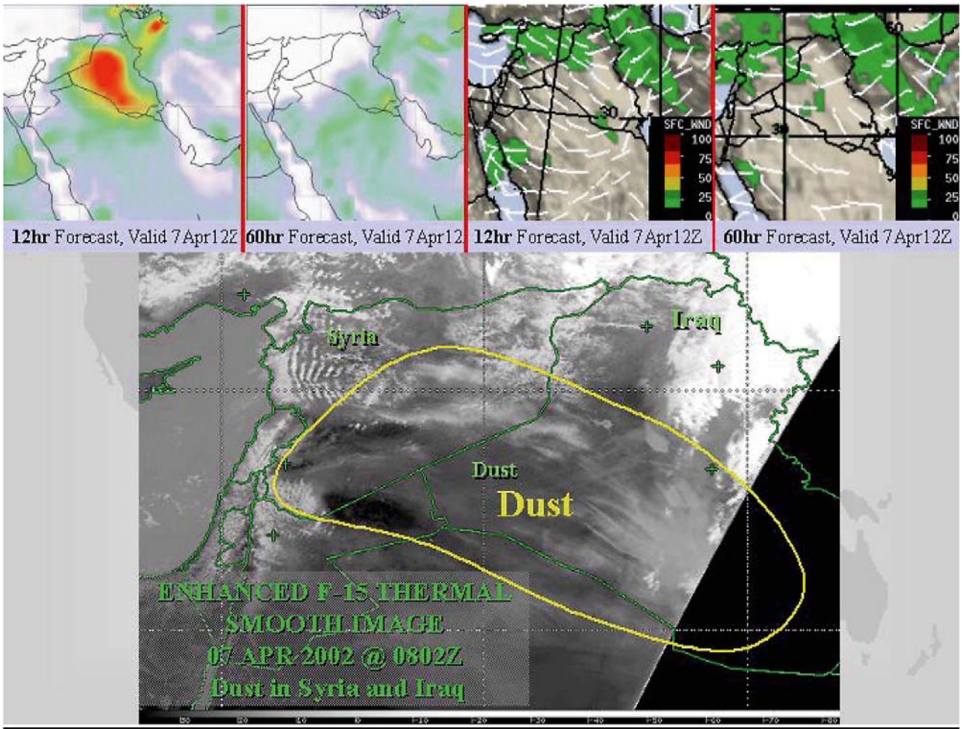

Fig. 9. 7 April 2002 Middle East dust event. CARMA-DUST forecasts (top left), MM5 45 km wind forecasts (top right), Satellite verification (bottom). The 12hr CARMA-DUST forecast accurately predicted the Iraqi dust event due to the more accurate MM5 winds, which were incorporated in the shorter forecast projection.

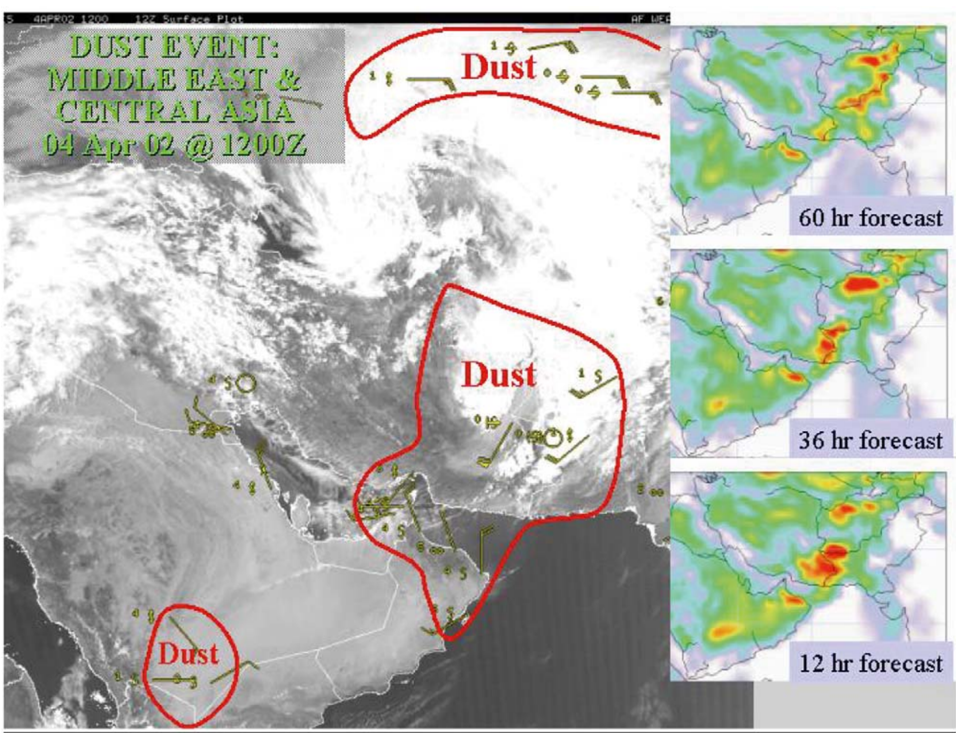

Fig. 10. April 4th, 2002 dust event over Central and Southwest Asia. CARMA-DUST forecast (right). Visibility reports of 1 mile or less are present in all 3 of the contoured regions. The lack of observations over Afghanistan coupled with cloud cover prevents CARMA-DUST verification over northern Afghanistan on this day.

An example with a mid-latitude extra-tropical cyclone located over the Mediterranean Sea during March 24th, 2002 is shown in Fig. 11.

The weather system caused blowing dust visible off of Egypt's northern coast. In this case again, the dust model did not forecast significant dust over Saudi Arabia. As stated earlier, this is likely due to weak representation of sources in central Saudi Arabia.

4. Conclusion

The CARMA dust model has been successfully adapted to use MM5 weather forecast data for operational prediction of dust storms. In the qualitative study conducted by AFWA, the model has been shown to have good skill over the Saharan African theater and Southwestern Asia. The global dust source database developed by Ginoux et al. has been especially accurate for forecasting in Saharan Africa. The source strength of some regions are underestimated in the Ginoux et al. database, such as Saudi Arabia and portions of the Amudarya Valley. The study made by AFWA however did not discriminate between dust storms and sand storms in the satellite data analysis. The dust database model developed by Ginoux et al. (2001) relies on the UV TOMS Aerosol Index, which is more sensitive to lofted dust than lower altitude sand storms. This may explain the low dust model scores in Saudi Arabia.

The next phase of the dust project will integrate the Continental United States, Eastern Asia and China as operational dust forecast theaters. More studies are underway to evaluate and improve the predicted dust concentrations with data from the Puerto Rican Dust Experiment and ground based aerosol measurements from China and White Sands, New Mexico.

Appendix A

Contingency table and definitions used to derive Probability of Detection (POD), False Alarm Ratio (FAR), Critical Success Index (CSI), and Probability of Detection Nil event (POD_{NIL}) values given in Tables 2a and 2b.

		Observed dust events	
		Yes	No
Carma-dust forecasted events	YES	X	Z
	NO	Y	W

$POD = X/(X + Y)$; $FAR = Z/(X + Z)$; $CSI = X/(X + Y + Z)$; $POD_{NIL} = W/(W + Z)$.

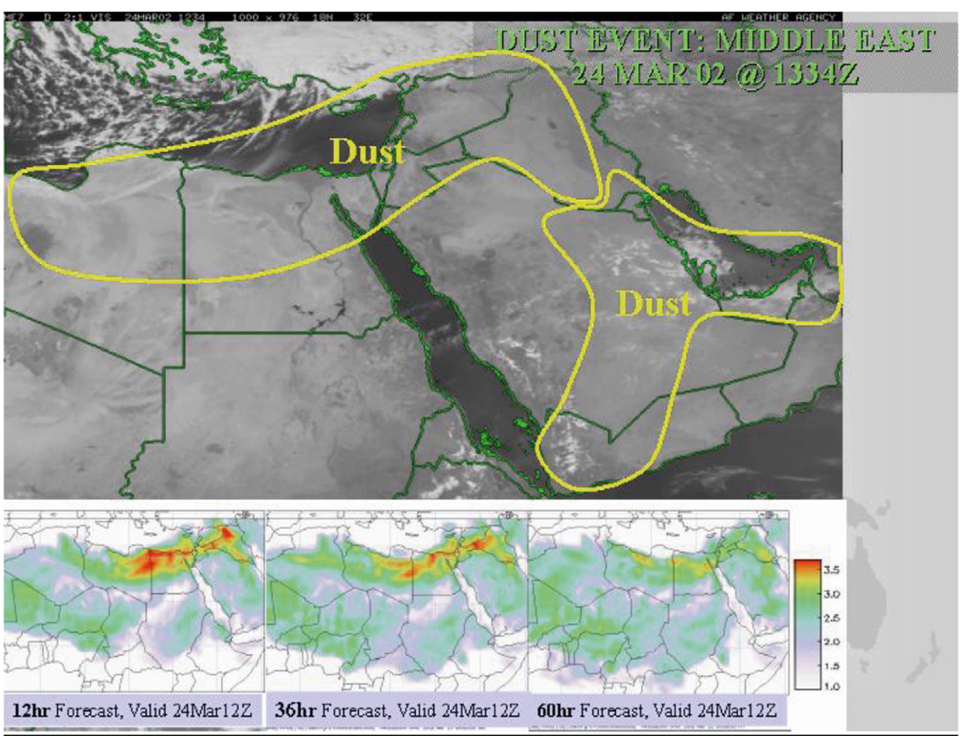

Fig. 11. March 24th, 2002 dust event across Northern Africa and Southwest Asia. Dust can be seen blowing off the northern coast of Egypt, which was well forecasted by the model. The dust model did not forecast dust or sand storms over central Saudi Arabia, Yemen and Oman.

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