7.8 Forecasting Dust Storms using CARMA-Dust Model and MM5 Weather Data

B. H. Barnum[1], N. S. Winstead[1], L., J. Wesely[2], Lt. Amy Hakola[2], P. Colarco[4], O. B. Toon[3], P. Ginoux[4], G. W. Brooks[2], L. Hasselbarth[1] and B. Toth[1]

1 Johns Hopkins University, Applied Physics Laboratory, Laurel, MD 20723
2 United States Air Force Weather Agency, Offut AFB, NE
3 University of Colorado, PAOS Group, Boulder, CO
4 NASA Goddard Space Flight Center, Greenbelt, MD

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) and the University of Colorado CARMA dust transport model.

In a unique study, AFWA undertook a 60 study to evaluate the effectiveness of the dust model to make short, medium and long-range (72 hour) forecasts of dust storms. The study is unique in using satellite and ground observations of dust storms and scoring the model 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 exceeding 68 percent over Northern Africa with a 16 percent False Alarm Ratio. Southwest Asia had average Probability of Detection values of 61 percent with False Alarm Rates averaging 10 percent.

Introduction

Dust storms throughout Saharan Africa, the Middle East and Asia are estimated to place more than 200 to 5000 million 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 in dust prone regions. The United States Air Force Weather Agency (AFWA) has supported the development of a dust forecast model with a 72 hour forecast capability. The dust model called CARMA (Community Aerosol and Radiation Model for Atmospheres), was developed by Professor Owen Toon and Dr. Peter Colarco at the University of Colorado, Boulder [*Toon et al., 1988, Colarco et al.*

2001]. The CARMA model has been modified by Johns Hopkins Applied Physics Laboratory to use daily Mesoscale Model 5th generation (MM5) weather forecasts run by the United States Air Force Weather Agency.

The latest version of the CARMA MM5 dust model can make 72 hour 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 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.

The forecast ability of the dust model was evaluated over a 3 month period 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 DMSP satellite imagery and ground observations. Each theater was broken into sub-regions for detailed evaluation of the short (6-12 hour), mid (30-36 hour) and long-term (54-60 hour) forecast ability of the model. Results of the study show the dust model has good skill in forecasting dust conditions for short and medium range and long range forecast periods.

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 use 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 hour forecast data for winds, pressure, temperature, rain, etc., are input into CARMA. The dust model outputs a set of dust concentration maps and vertical concentration profiles for each 3 hour time period during the 72 hour forecast.

The MM5 weather forecast data is run by United States Air Force Weather Agency (AFWA) for theaters worldwide on a daily basis, shown in Figure 1. The MM5 data is obtained directly from AFWA for the mesoscale theaters covering Saharan Africa and Middle East (T09a), Southwest Asia (T04a) and China (T06a). The MM5 model is run with 41 vertical sigma pressure coordinate levels with a 45 km horizontal grid spacing.

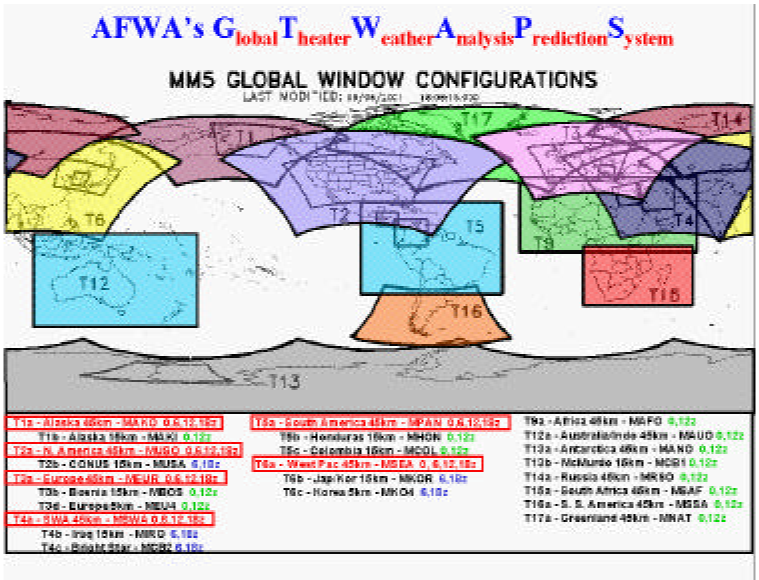

Figure 1 *Weather forecast data is run daily by the USAF Weather Agency for the theaters shown using MM5. Input meteorology used in CARMA is run with 45km grid resolution for Africa (t09a) and Southwest Asia (T04a).*

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 spacing as the 1^{o} x 1^{o} (111 km) Ginoux 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*].

Dust aerosols are lofted in the model by vertical advection and diffusion. The vertical diffusion is calculated in CARMA based on the MM5 input meteorology. CARMA calculates the vertical potential temperature, sensible heat flux, Monin-Obukhov length and friction velocity based on the MM5 input data, and estimates the vertical diffusion at 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 hour) "spin-up" period. The spin-up uses the first 24 hours of each daily 72 hour MM5 forecasts generated for each of the spin-up days. The data from the spin-up portion of the model is used as for the initial dust concentration condition at the beginning of the 72 hour 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 dust loading; however, the 2 day spin-up 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 cycle version was implemented.

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 based on observed 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 331nm 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, such as the Lake Chad Basin. These sources areas are assigned a source strength value between 0 and 1.0. The data is given on a global 1°x1° grid and is then re-interpolated to the MM5 grid used in the CARMA dust model (Figure 2a and 2b).

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 1.21 times the mass of a particle in the preceding bin size [*Toon 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 0.1μm to 1.0 μm, silts are 1.0μm to 10 μm in particle radius and sand is any particle larger than 10.0 μm.

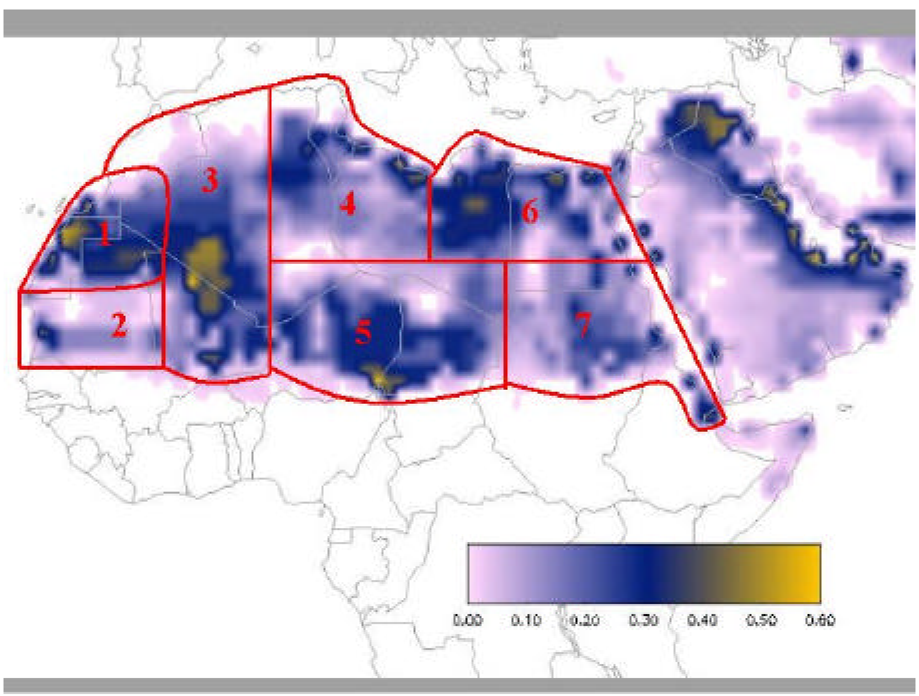

Figure 2a. *Dust source regions over North Africa and the Middle East on a 0 to .6 scale with 0 (white) being a non-source region and .6 (yellow) representing the most significant of source regions. The source regions are divided and grouped into distinct regions that are used for the computation of skill scores.*

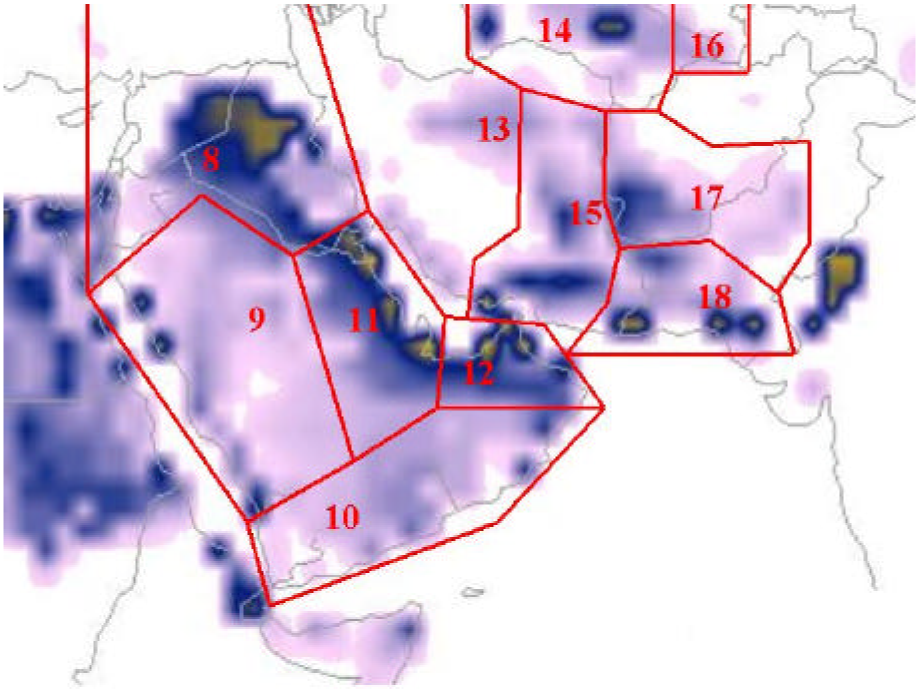

Figure 2b. *Dust source regions over the Middle East and Central Asia with white being a non-source region and yellow representing the most significant of source regions. The source regions are divided and grouped into distinct regions that are used for the computation of skill scores.*

Dust mobilization normally begins when the surface wind velocity exceeds a threshold wind speed and larger particles, which are not embedded in the soil matrix, are mobilized. The larger particles are then driven along the surface where they collide and liberate smaller particles from the soil matrix in a process called saltation [*Gillette 1981*]. The threshold wind speed calculated in CARMA follows the method developed by *Iverson and White* [1982], and is shown graphically in Figure 3. This method mobilizes larger sand particles at lower wind speeds. The threshold velocity used here differs from the threshold wind velocity equation originally used in the *Ginoux et al.* [2001] source flux model equation, which mobilizes smaller size particles first.

The surface dust flux in CARMA is calculated using the MM5 wind speed at 10 meters agl. The flux equation follows the formulation based on *Gillette and Passi* [1998]. The dust source model first calculates the mobilization threshold wind velocity at each grid location for each particle bin size. At grid cell locations where there is measurable accumulated precipitation in a 24 hour 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 meter wind speed using:

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

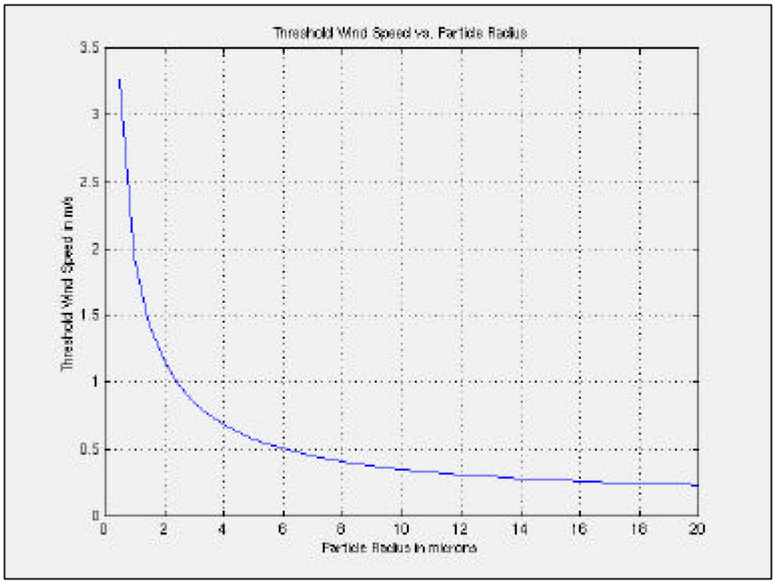

Figure 3 *Dust threshold surface wind velocity calculated in CARMA using the method described by Iverson and White [1982]. Notice that smaller size dust grains require higher surface wind speeds to mobilize since they are embedded in the soil matrix until liberated by larger particles.*

Where *C* is a model dimensional equal to 2.3xE-17 μgm s^2m^{-5}, used to control the total amount of dust flux emission, and 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 for each particle bin number *r*. $S_{(i,j,r)}$ is the Ginoux database source strength for the particle bin size, $w_{\mathbf{10m}(i,j)}$ is the MM5 wind speed at 10 meters, 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. 2001*].

Dust Deposition and Advection

Dust deposition in CARMA is calculated using a 2 layer method described by *Shao* [2000]. This method calculates the particle vertical deposition velocity adding together 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 and corrected drag coefficients developed by Pruppacher and Klett [*1978, 1997*]. In the current version of the dust model we calculate dry deposition only. 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 hour time period within the grid cell.

The advection of dust in the CARMA model uses a horizontal transport method a developed by Lin and Rood [*1996*]. Horizontal advection rates are calculated using Piecewise Polynomial Method [*Colela and Woodard, 1984*]. In order to satisfy the

Courant (CFL) conditions, the model uses a time step of 1200 seconds, with meteorological conditions interpolated between each 3 hour MM5 forecast.

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 hour interval in the 72 hour forecast, an example of the African and Middle Eastern mesoscale theater (t09a) is shown in Figure 3a and b.

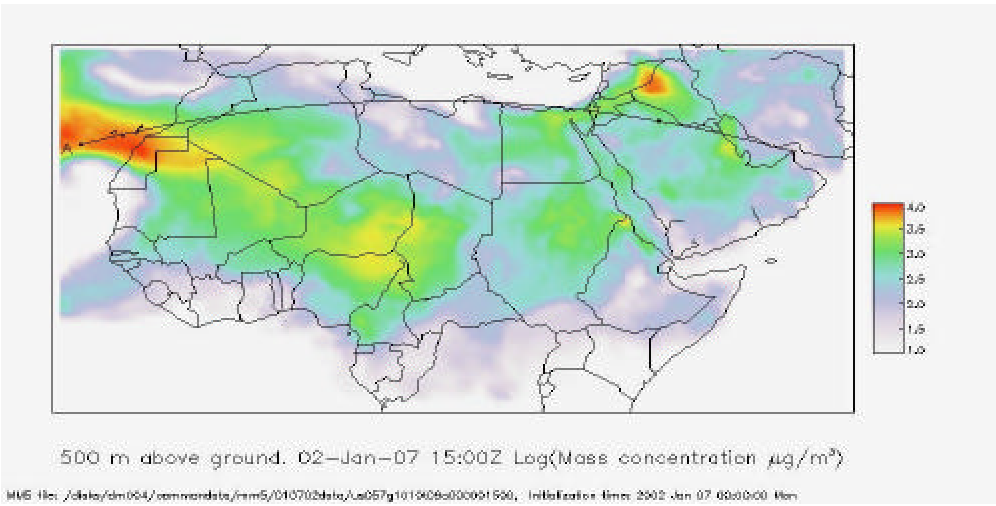

Figure 3a *Example of CARMA model output showing color map of total dust concentration at 500 meter altitude over Saharan Africa and Middle East for the dust storm during January 7, 2002. The maps show concentration using a log scale. The altitude "slice" and color bar levels are user selected.*

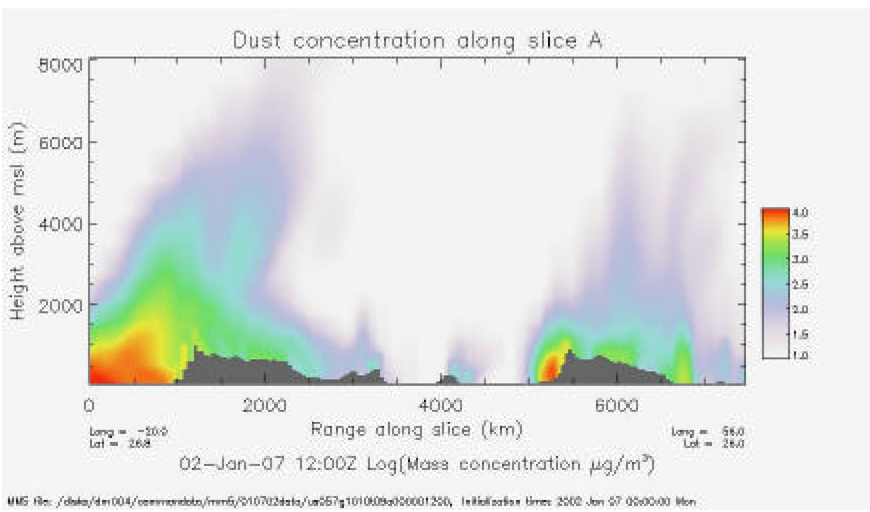

Figure 3b *Vertical cross section showing dust concentration along the line shown beginning at 'A' above in Figure 3a. The local terrain is shown in the map sections.*

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 60 day evaluation period beginning on the 8^{th} of February through April 15^{th} 2002. The evaluation covered two mesoscale regions: Saharan Africa and Middle East (t09a) and Southwest Asian (t04a). 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 forecasts dust storms and reduced visibility caused by dust. The study used satellite and ground based observations of dust storms to compare with the CARMA forecasts.

Evaluation Methodology

The AFWA study compared dust observation data with the CARMA model 72 hour forecasts. The study used two separate 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 $50\mu gm/m^3$ under normal atmospheric conditions, greater than $100\mu gm/m^3$ under hazy conditions, $1000\mu gm/m^3$ in reduced visibility and very hazy conditions, to $5000\mu gm/m^3$ and higher in severe dust storms [*Westphal, 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 1,800 to $3{,}500\mu gm/m^3$ shown as red areas on the log color dust maps as the threshold dust/no-dust forecast. Wherever model surface forecast concentrations exceeded 1800 $\mu gm/m^3$, 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 hr), medium (30-36hr) and long (54-60hr) 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 sub-regions as shown in figures 1a and 1b.

Model Evaluation Results

The average POD and FAR, CSI and POD-NE percentages for theater 9a are given in Table1, and the results for theater 4a are given in Table 2. The lowest CSI scores occurred in the Yemen and Oman sub regions where the POD's were only 19 percent, with a FAR of 0 percent. 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.

MM5 forecast Short /medium/long	*Probability of Detection (POD)%*	*False Alarm Ratio (FAR)%*	*Critical Success Index (CSI)%*	*Probability of Detection of NIL Event (POD-NE)*
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 1: *CARMA model average Probability of Detection and False alarm rate for short, medium (6-12hr) / medium (12-36hr) and long-range (48-60hr) forecasts. The model evaluation was done February 2002 to April 15, 2002. The sub-regions, 1-7, cover Saharan Africa and Sahel shown in Figure 2a .*

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

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)***
T4a Souwest 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

Table 1b: *CARMA model average Probability of Detection and False alarm rate for short, medium (6-12hr) / medium (12-36hr) and long-range (48-60hr) forecasts. The sub-regions, 8-18, cover the Middle East, Arabia and Southwest Asia (Iran, Afghanistan and Northern Pakistan), shown in Figure 2b.*

Discussion of Model Forecast Evaluation

The model has high POD scores in theater 9a averaging 69 percent for short range forecasts with a low average FAR of only 15 percent.

The highest forecast skill scores occur over Africa's regions 1, 3 and 5. Region 5, which covers Chan and Niger, has a short term POD of 95 percent. The case shown in Figure 4 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 over Tunisia observed in the satellite imagery, was not forecast by the dust model.

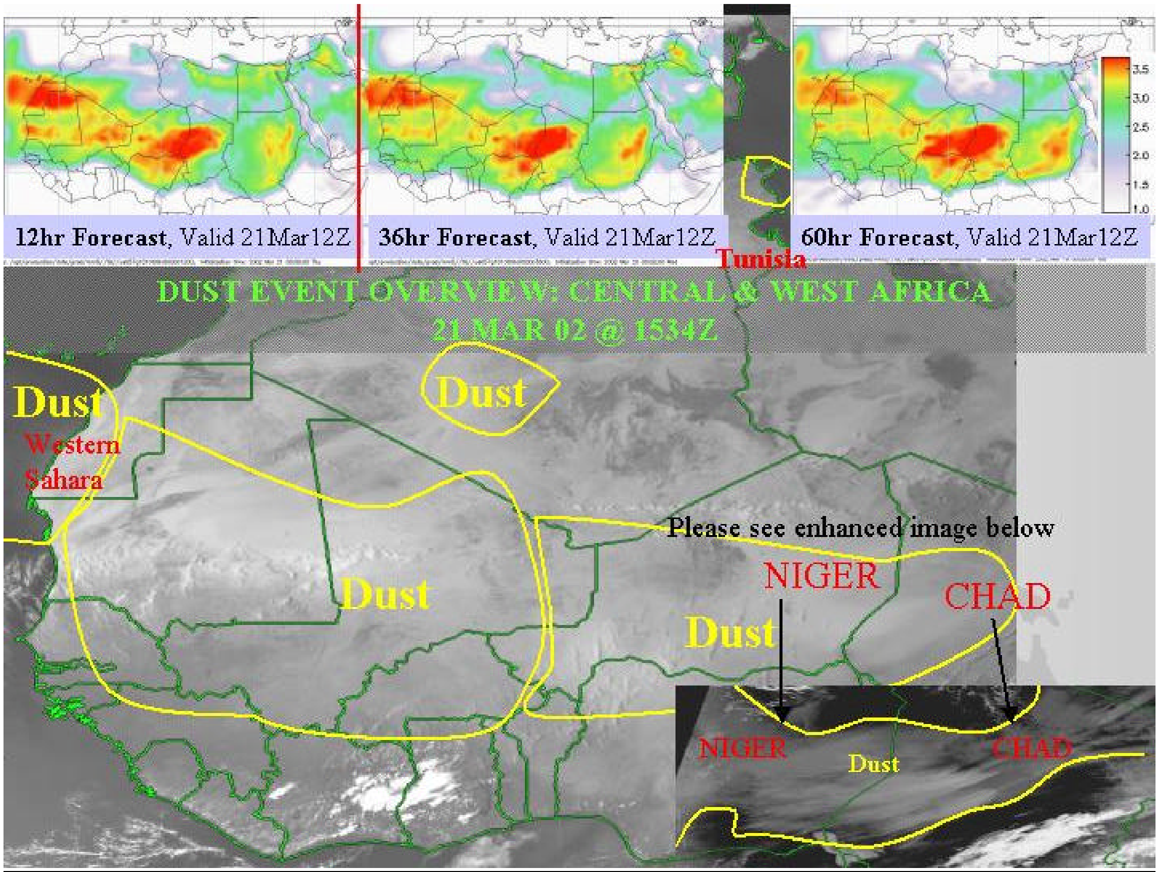

Figure 4. *Dust event during 21st March 2002 over West Africa. Dust model forecasts (top) and enhanced satellite imagery over Chad and Niger (bottom right). The model generally forecasted this event rather well, but slightly too far to the south. There is also a report of dust in Tunisia that was not forecasted.*

Southwest Asia had a 61 percent POD, with only a 10 percent FAR, with sub region 8 having a POD as high as 85 percent. Further evaluation revealed several regional tendencies. The model under-forecasts dust events in the Middle East countries of Jordan, Oman, Yemen and western Saudi Arabia, especially theater regions 9 and 10, which had POD's of 48 and 19 percent respectively. In Southwest Asia, under-forecasts occurred 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 forecast skill scores in these sub-regions are caused by the under representation of dust sources in the database at these locations. This is supported by the fact that there is more dust observed than forecasted, i.e. low POD scores in these sub-regions in Tables 1b.

The dust model also had low forecast scores over the southern coast of Yemen and Oman (Table 1b, region 10). Most of these dust events were generated by south winds off of the Arabian Sea. During the model evaluation, there was very little precipitation that fell over this region during the study, so it is unlikely that precipitation caused the under-forecasts. 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 region 10. A similar case example is shown for April 3, 2002, showing a Saudi Arabian duststorm, which is well predicted over eastern Saudi Arabia but is underestimated by the dust model across the central and western portions of the country (Figure 5). The observed and forecasted winds are nearly identical and are generally light across central Saudi Arabia at less than 15m/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 database. This region of Oman and Yemen is a great sand desert, known as the Empty Quarter [*Thesiger, 1959*]. The region is most noted for sand rather than dust storms. The DMSP satellite imagery however does not distinguish between sand and dust storms. The region may have lower measured aerosol indices in the TOMS AI satellite data. The TOMS satellite aerosol index is more sensitive to airborne small (.1 to 10 um) aerosols [*Colarco et al., 2002*].

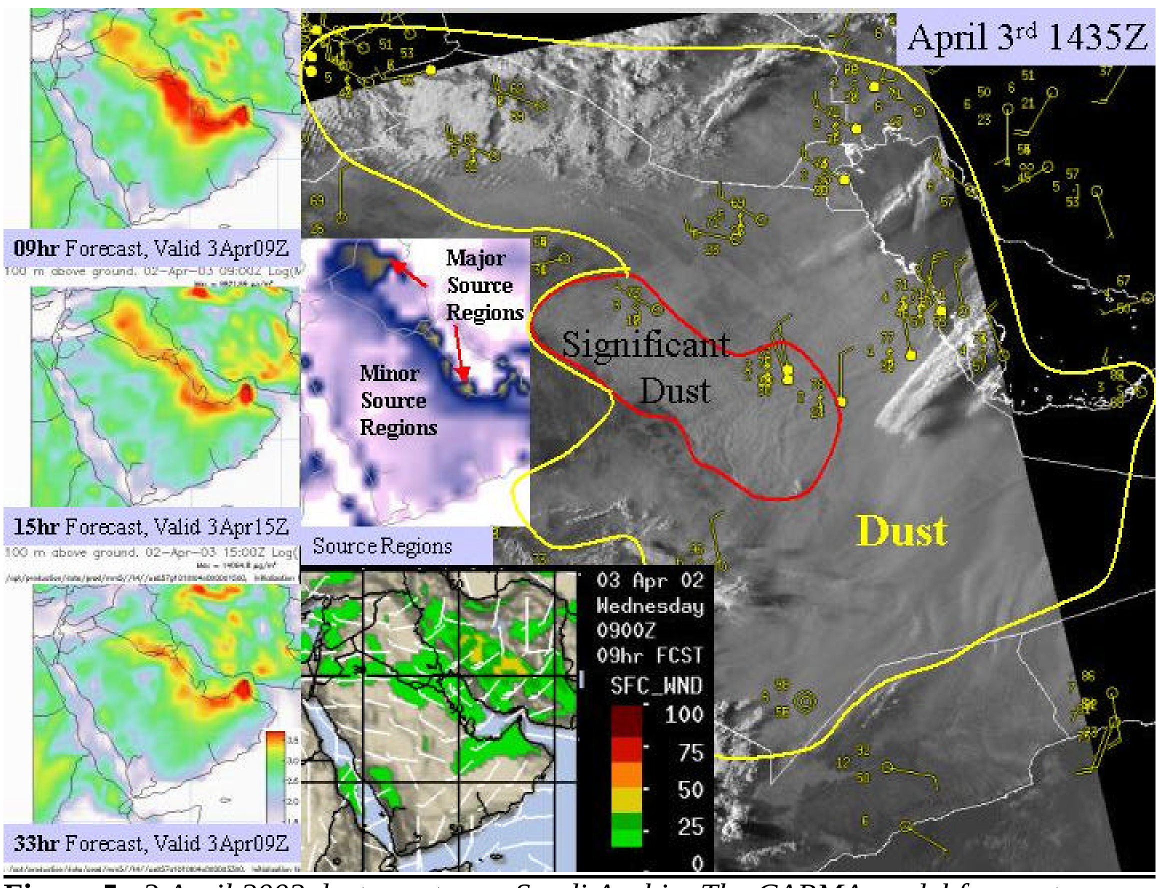

Figure 5. *3 April 2002 dust event over Saudi Arabia. The CARMA model forecasts are shown on the left. MM5 forecasted winds, which are incorporated into the model, are shown bottom center. The Ginoux database dust source, center panel, are indicated by the shades of purple to yellow with yellow being 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.*

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 hour period is most likely caused by MM5 wind forecast data. Figure 6 shows an example where stronger forecast surface winds using the 12 hour MM5 data resulted in an accurate dust forecast for the dust event during the 7th of April 2002. The 60 hour MM5 wind fields cause the CARMA model to miss the verified dust event over Syria and Iraq, verified by satellite data. It is not possible to directly verify the MM5 wind predictions for Iraq due to a complete absence of reported observations over the country.

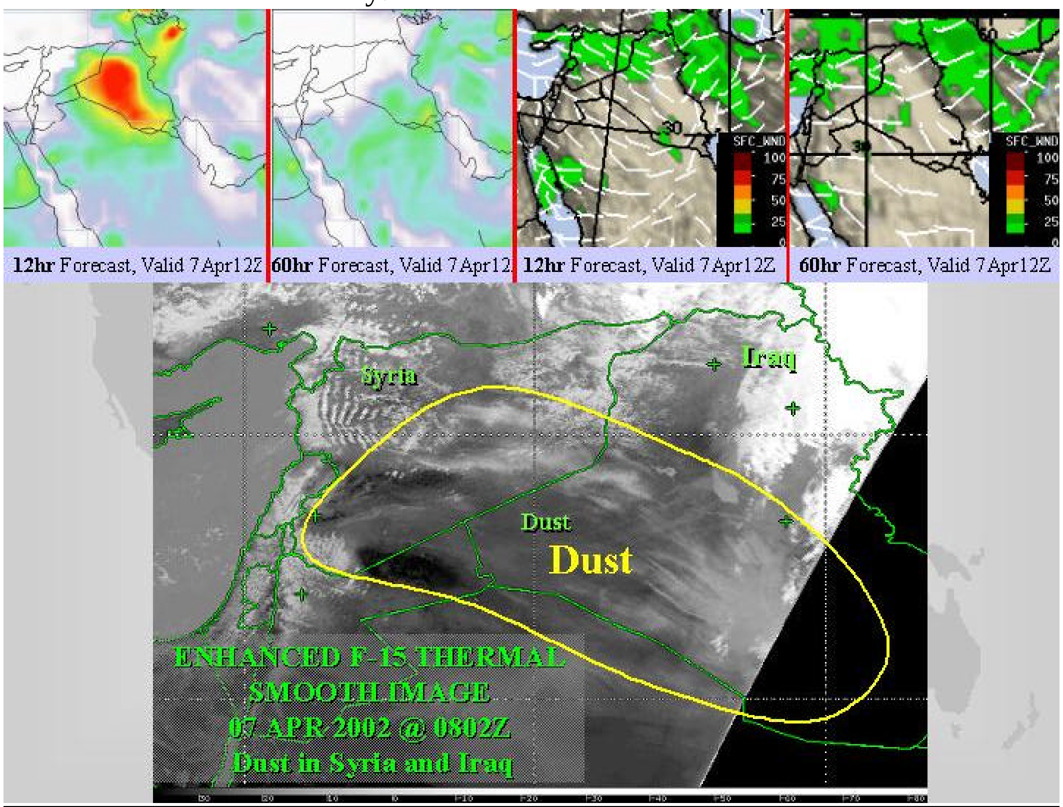

Figure 6. *7 April 2002 Middle East dust event. DTA forecasts (top left), MM5 45km wind forecasts (top right), Satellite verification (bottom). The 12hr DTA forecast more accurately predicted the Iraqi dust event due to the more accurate MM5 winds, which were incorporated in the shorter forecast projection.*

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 (Figure 7).

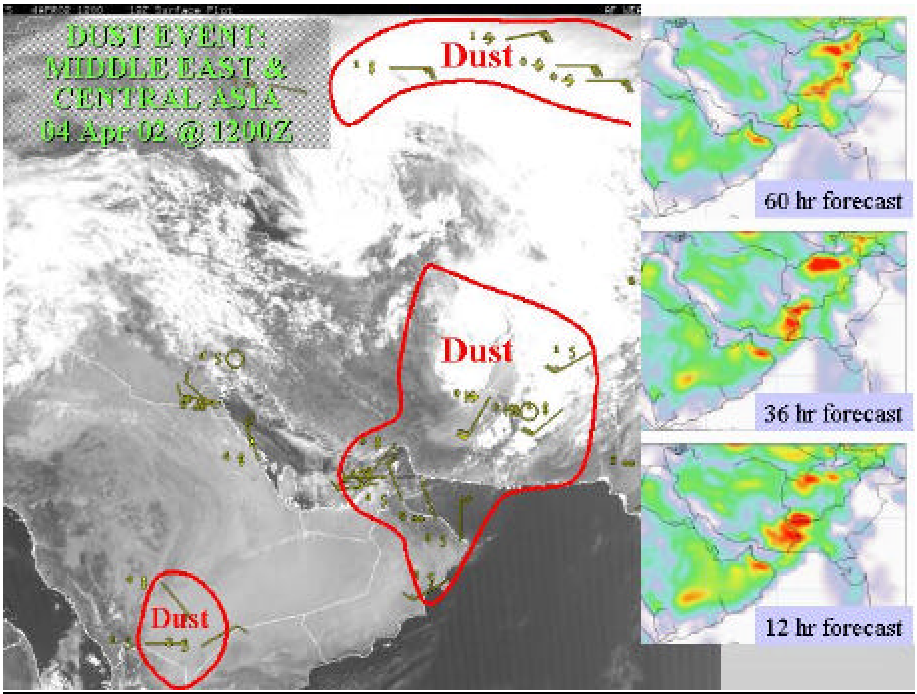

Figure 7. *April 4th, 2002 dust event over Central and Southwest Asia. DTA forecast (right). Visibility reports of 1 mile or less are present in all 3 of the contoured regions. The lack of observations over Afghanistan coupled with cloud cover prevents DTA verification over northern Afghanistan on this day.*

The strong surface winds and thunderstorm outflows elevated a substantial amount of dust causing many visibility reports of 0 to 2 miles. Where observation data has been available, the dust model was accurate in forecasting the position and intensity of these intense dust clouds.

Mid-latitude cyclone synoptic events over Africa (t09a) are well forecasted by the MM5 weather model and result in high confidence for dust forecasts under these conditions. A case with a mid-latitude extra-tropical cyclone located over the Mediterranean Sea during March 9th, 2002 is shown in Figure 8. This weather system caused blowing dust visible off of Egypt's northern coast. The dust model did not forecast significant dust over Saudi Arabia on March 9th. As stated earlier, this is likely due to weak representation of sources in central Saudi Arabia.

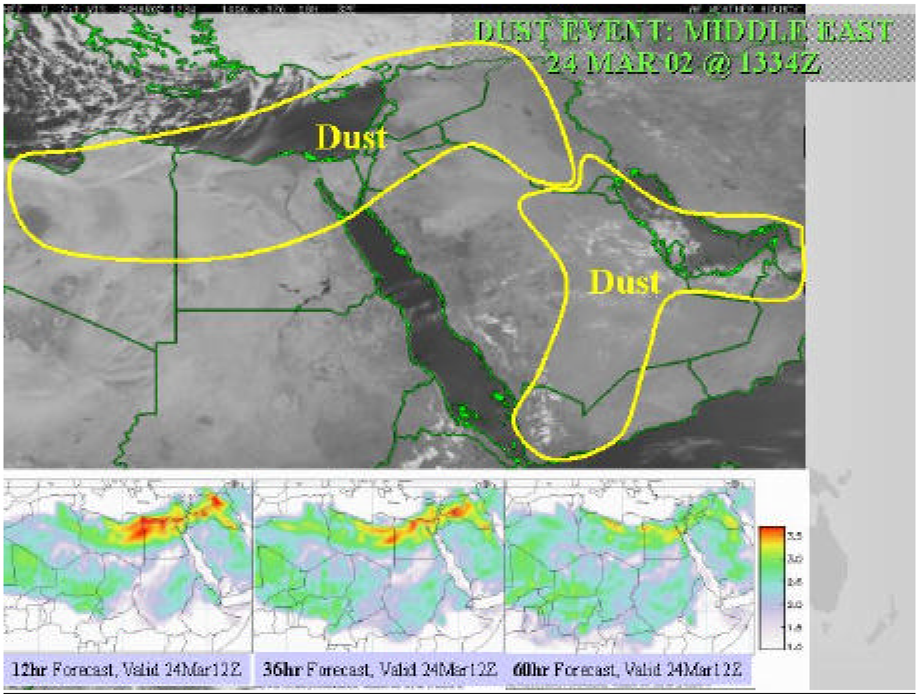

Figure 8. *March 24th, 2002 dust event across Northern Africa and Southwest Asia. Dust can be seen blowing off the northern coast of Egypt, which was well forecasted by the model. The dust model did not forecast dust or sand storms over central Saudi Arabia, Yemen and Oman.*

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, however some regions are underestimated in the database model. The study made by AFWA 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 add 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.

References

Anthes, R. A., and T. T. Warner, 1978: Development of hydrodynamic models suitable for air pollution and other meso-meteorological studies. *Mon. Wea. Rev*., **106**, 1045-1078

Colela, M and Woodard, J., Comp. Phys., 54, 174-201, 1984

Colarco, P. R., O. B. Toon, O. Torres and P. J. Rasch, 2002, Determining the UV imaginary index of refraction of Saharan dust particles from TOMS data and a tree dimensional model of dust transport, *J. Geophys Res*. (in press)

Lin, S. and R. Rood, Multidimensional flux-form semi-lagrangian trasport schemes, *Mon. Weather Review*, **124**, 2046-2070, 1996.

Ginoux P. M., Chin, I., Tegen, J., Prospero, B. Holben O. Dubovik and S. J. Lin. 2001. Sources and global distributions of dust aerosols simulated with the GOCART model, *J. Geophys. Res., 106*, 24698-24712.

Herman, J., P. Bhartia, O. Torres, C. Hsu, C. Seftor, and E. Celarier, 1997, Global distribution of UV-absorbing aerosols from Nimbus 7/TOMS data, *J. Geophys. Res*., **102**, 16911-16922.

Jacobson, Mark Z., 1999, Fundamentals of Atmospheric Modeling, *Cambridge University Press*, Cambridge, United Kingdom

Murphy, A.H., and R.L. Winkler, 1987: A general framework for forecast verification. *Monthly Weather Review*, **115**, 1330-1338.

Murphy, A.H., and E.S. Epstein, 1989: Skill scores and correlation coefficients in model verification. *Monthly Weather Review*, **117**, 572-581.

Prupacher H. R. and J. D. Klett, Microphysics of Clouds and Precipitation, *Kluwer Academic Publishers*, Dordrecht, 1997.

Tegen I and Fung, I., 1994, Modeling of mineral dust in the atmosphere: Sources, tranport and optical thickness, *J. Geophys. Res.*, **99**, no d11, 22897-22914, 22897-914

Thesiger, Wilfred, 1959, Arabian Sands, Penguin Books, London, England.

Toon, O. B., R. P. Turco, D. Westphal, R. Malone and M. S. Liu. 1988, A Multidimensional Model for Aerosols: Description of Computational Analogs, *J. Atm. Sci*., **45**, no. 15 pg 2124-2143.

Weseley J, Hakola A., Brooks, G. 2002, Numerical Modeling of Severe Duststorms over Africa and Southwest Asia, USAFETAC/TN-02/004

Westphal, D., 1986, A numerical investigation of the dynamics and microphysics of Saharan dust storms, Thesis, Pennsylvania State University Department of Meteorology.

Zhang, Dalin and Richard A. Anthes, 1982, A High-Resolution Model of the Planetary Boundary Layer –Sensitivity Tests and Comparison with SESAME-79 Data, *J. Applied Met.*, **21**, 1594-1609