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MODELING ATMOSPHERIC DUST FOR RESPIRATORY HEALTH ALERTS

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1. INTRODUCTION

A major challenge for integrating satellite data into respiratory health alerts is to demonstrate that they improve dust predictions that could trigger respiratory responses. The body of medical and epidemiological knowledge linking dust and smoke to health responses is growing steadily (Pope, 1989, 2004; Schwartz and Dockery, 1992; Dockery et al., 1993; Pope et al., 1995; Griffin, 2007; NRC/IM, 2007). Through these linkages, it is increasingly clear to science and government that satellite observations can play a prominent role in forecasting short term weather episodes, and longer-term environmental changes that cycle over several human generations. Earth system scientists are finding quantitative measures for tracking health over regional domains.

2. OBJECTIVES

The focus of this report is on asthma as a rapidly growing chronic respiratory illness among children and elders in the southwestern U.S. This report examines the Dust Regional Atmospheric Model (DREAM) that predicts mineral dust entrainment based on observed surface conditions and NCEP/Eta atmospheric measurements.

DREAM was designed and evaluated for use in the western Mediterranean using the ECWMF medium range forecast model. It was adapted for use in the Southwest by nesting it within the NCEP/Eta global forecast model to create DREAM/Eta. A storm over the Southwest in December 2003 was used to baseline DREAM/Eta's performance before satellite data were assimilated. Model outputs were compared with standard products from surface synoptic sites, METAR reports, and local air quality networks to develop indices of agreement between observed and modeled DREAM/Eta meteorology and dust entrainment.

The research objective was to replace static surface parameters in the baseline DREAM/Eta with modern measurements of these parameters collected by Earth observing satellites to benchmark improvements in dust entrainment predictions.

A parallel effort engaged public health authorities in AZ, NM, and TX to guide the geospatial requirements in syndromic health surveillance; and, where possible, to identify cause-and-effect relationships between dust and human health responses. These communities included developers of syndromic surveillance systems, state and local departments of health, and regional air quality authorities (Morain and Sprigg, 2005).

3. MODELING SYSTEM

The DREAM/Eta model domain and the daily forecast domain are shown in Figure 1 (Yin et al., 2005 and 2007). A large model area is required to gather all the atmospheric parameters needed for accurate dust entrainment, transport, and deposition simulations. These domains are flexible and can be employed anywhere on the globe. However, the larger the domain, the longer it takes to create a forecast. Domains in Figure 1 have optimized the model run-time vs. domain size for the American SW. One of the difficulties in this region is the absence of ground-reporting air quality data from northern Mexico. The model can forecast dust patterns in Mexico, but the outputs cannot be verified or validated for that part of the domain. Furthermore, the outputs only represent mineral dust in the PM_{10} to $PM_{2.5}$ particle size range. This system is being expanded by linking outputs from the Community Multiscale Air Quality (CMAQ) model to those from DREAM/Eta to provide aerosol and ozone concentrations and durations.

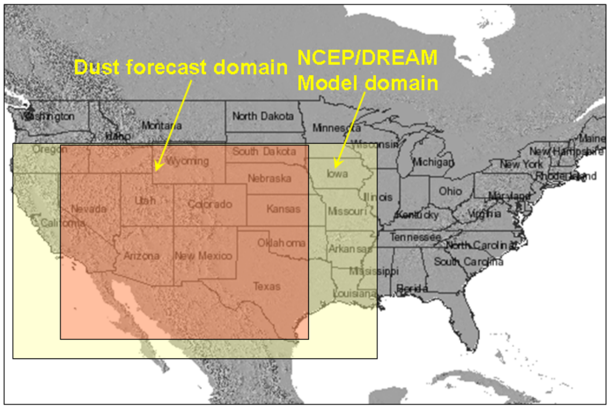

Figure 1. DREAM/Eta model and forecast domains.

3.1 PARAMETER REPLACEMENTS

Several surface parameters in DREAM/Eta can be replaced with satellite data sets that can be temporally refreshed; or, that are more modern than those in baseline DREAM (Figure 2 and Table 1). The barren land category from the MODIS MOD12Q1 product (that is, the areas most subject to dust entrainment) was converted into a binary format to feature barren areas in the Southwest. This data set replaced the barren category used in the Olsen World Ecosystem (OWE) map for baseline DREAM.

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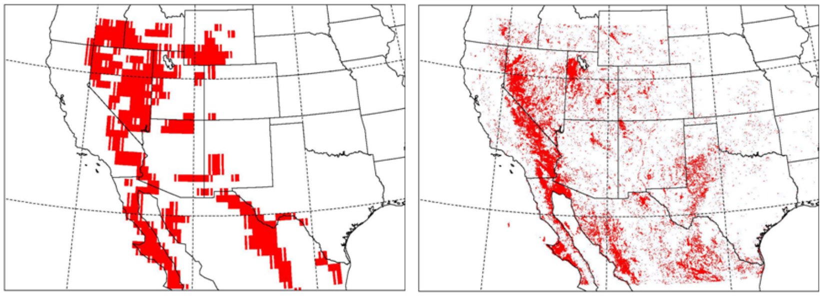


Figure 2. Comparison of potential regional dust sources. Left: Olsen Map of World Ecosystems; Right: satellite land cover from MOD12Q1 land cover product

Table 1. Baseline and replacement parameters

Baseline Surface Parameters	***Relevance to Dust Entrainment***	***Satellite Replacement Parameter***
ECWMF medium-range forecast	*Initial & boundary conditions; Res=1°*	*NCEP/Eta global forecast*
Olsen World Ecosystems; *Res= 10min.*	*Land cover; also affects* z_0	*MODIS MOD12Q1; Res.=1km*
USGS terrain data; Res.=1km	*Land form; also affects* z_0	*SRTM-30; Res.=1km*
Aerodynamic roughness length (z_0)	*Dust entrainment potential*	*Look-up table derived from MOD12*
Soil moisture simulated from soil texture classes; Res.=2min.	*Particle cohesion; entrainment potential*	*AMSR-E; Res.ca. 70km; Deemed too coarse*

Similarly, the USGS terrain data were replaced by higher quality digital terrain data collected by the Shuttle Radar Topography Mission (SRTM-30).

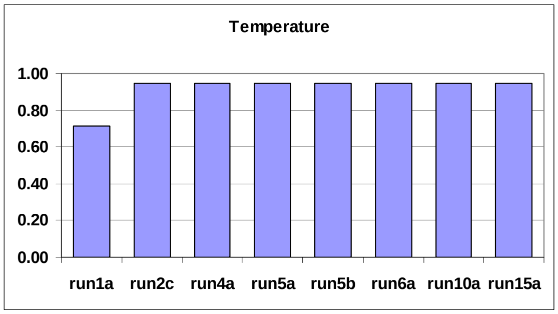
Aerodynamic surface roughness (z_0) is an important parameter influencing dust entrainment, but it is very difficult to measure directly from space. The baseline model simulated z_0 using the simplified simple biosphere (SSIB) land cover types. A modified version of this approach was used here by substituting MOD12Q1 data and developing a table look-up for estimating z_0.

Soil moisture was the last parameter tested for replacement. The baseline model simulated soil moisture by reducing 134 categories from the FAO map of world soils to Zobler/Cosby soil textures. The team attempted to use the Advanced Microwave Scanning Radiometer (AMSR-E) surface soil moisture product. Three DREAM/Eta model runs (#s 7a, 10a, and 15a) assimilated AMSR-E data but showed very modest improvements. The product's characteristics are considered too coarse for practical use in this application.

Overall, the parameter replacements that most improved DREAM/Eta performance were barren land dust sources derived from MOD12, the SRTM-30 and the z_0 look-up values.

3.2 MODEL PERFORMANCE

A pilot dust storm that occurred on December 15-17, 2003 was selected for testing the effects of replacing baseline parameters. The charts in Figure 3 show relative performance results for seven model runs for temperature, wind direction, wind speed, PM_{10}, and $PM_{2.5}$. Model run 1a is the baseline DREAM/Eta performance; the remaining seven represent model performance using various combinations of parameter replacements. Model runs 10a and 15a include AMSR-E data which actually reduced the model's performance for $PM_{2.5}$. Model run4a was selected as giving the best overall performance for both PM_{10} and $PM_{2.5}$ (Yin et al., 2005; Yin et al., 2007).



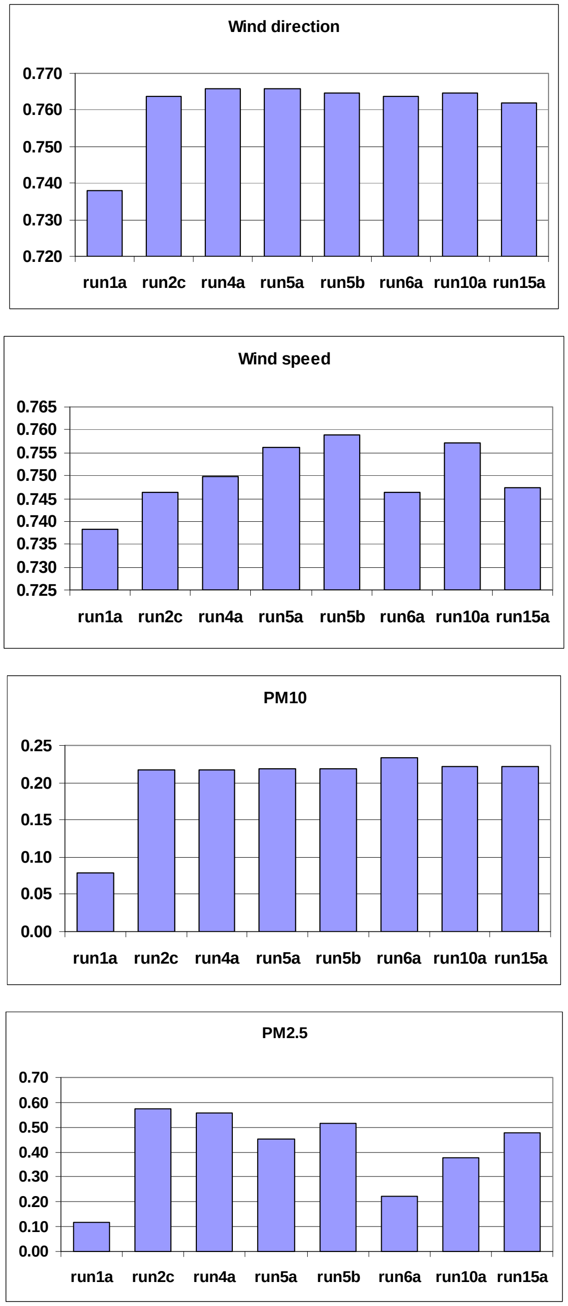


Figure 3. Baseline DREAM/Eta performance compared to seven parameter replacement model runs.

Surface wind speed, direction, and temperature change as weather systems pass through an area. Since these parameters also influence dust entrainment, the ability of DREAM/Eta to simulate these conditions is critical to both accurate weather forecasting and dust simulation. If the atmospheric parameters are altered by nesting a dust entrainment, transport and deposition module, then the model system performance is impaired. Table 2 compares the observed and modeled surface wind speed, direction, and temperature before and after parameter replacement. The indices indicate that DREAM/Eta's performance for wind speed and direction are not adversely affected by inserting the dust module; but that surface temperature was improved (0.71 vs. 0.95). The indices are for model run 2c (see figure 3), in which the only parameter replacement was the pattern of potential dust sources. The difference in model performance between the baseline DREAM/Eta (OWE) parameter and the MOD12 replacement parameter is evident in all of the model runs (compare model run 1a with 2c). The baseline model is therefore considered to simulate observed conditions fairly well; while the replacement of OWE with MOD-12 improved the simulation of surface temperature.

Table 2. DREAM/Eta performance before and after parameter replacement. Baseline indices are shown in normal font; Replacement indices in bold, blue font.

Metrics	**Wind sp (m/s)**	**Wind dir. (°)**	**Temp. (K)**
Mean Observed	5.53	231.40	276.74
Mean Modeled	4.65 **4.37**	226.60 **230.38**	275.56 **277.48**
Mean Bias	-0.88 **-1.16**	-4.80 **-1.02**	-1.20 **0.72**
Mean Error	1.97 **2.03**	51.76 **47.85**	4.09 **2.67**
Agreement index	0.74 **0.75**	0.74 **0.76**	0.71 **0.95**

Visualizations of the model output before and after parameter replacement are shown in Figure 4 for PM_{10}. DREAM/Eta with baseline parameters (model run 1a) gives a generalized picture of the storm compared to its companion produced using satellite data (model run 4a)

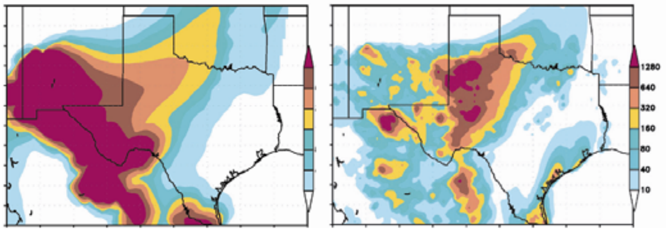


Figure 4. Comparison of dust storm patterns before (left) and after (right) parameter replacements for the storm of 15-17 Dec. 2003.

3.3 VERIFICATION AND VALIDATION

Model dust concentrations have been, and continue to be, verified and validated using three different techniques: (a) indices of agreement between modeled and observed patterns generated from METAR and radiosonde reports; (b) comparisons between modeled and observed AIRNow and other ground-based CAM networks; and (c) by calculating model skill and threat scores using the Point-Stat tool developed for use in WRF.

For verification and validation, DREAM model runs were compared to observed PM_{10} data during dust events in the model domain (Morain and Sprigg, 2007). A regional dust episode occurred on January 4-6, 2007 (*High Winds Aren't Over Yet*, L.A. Times, January 6, 2007, p. A1). Using DREAM/Eta in a hind-casting mode, the event was modeled and the results compared to seven PM_{10} AIRNow stations plotted geographically from west (left) to east (right). Figure 5 shows a 72-hour plot for each station for January 4-6, 2007. The event occurred around 23:00 UTC on January 5th at most stations. Southern California was affected most, but the observed and modeled data show a dust gradient from east to west, with the exception of Riverside where no significant dust was recorded. Dust concentrations are shown for model run 15a and 20a. Both runs overestimated concentrations significantly; but, they are less pronounced in run 20a. Run 15a included AMSR-E data while 20a used the baseline DREAM default parameter. Some of the improvement in run 20a was realized by adjusting the bin size for PM_{10}. Other versions used a broader bin size that apparently contributed to even more serious over-prediction.

The data suggest that timing of peak hour concentrations is rather good, but that predicting the magnitude of the concentrations is rather poor. This is partly accounted for by the fact that monitors are direct, in situ sensors, while the satellite sensor records an atmospheric depth (in this case, approximately 100m). It may also be that ground stations malfunction under extreme conditions.

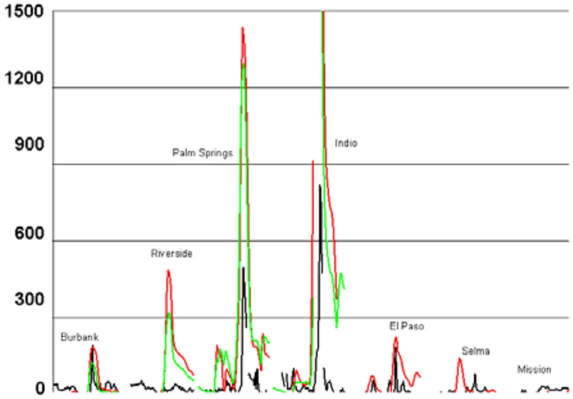
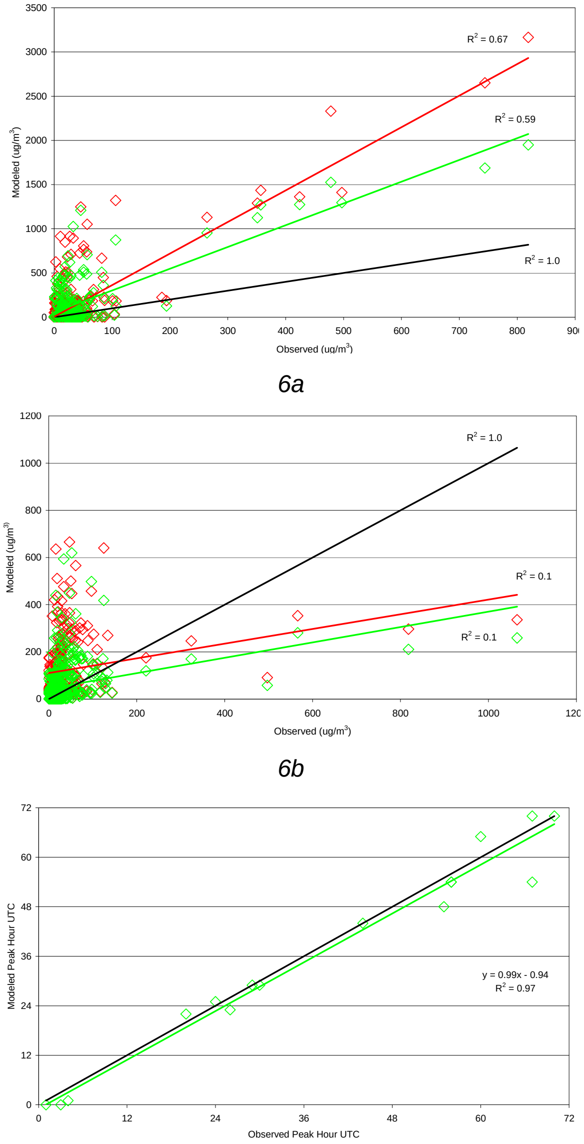


Figure 5. Regional dust storm of Jan 4-6, 2007 showing peak hour and peak concentration at seven stations from CA to TX for model run 15A (red) and 20a (green)

Figure 6 shows the magnitude and time correlations for modeled and observed PM_{10} on Jan 4-6, 2007, and for a second storm on February 23-25, 2007. Hourly values were compared to the measured AIRNow data. Magnitude correlations are skewed toward the modeled data axis, illustrating the model's tendency to over-predict. Predicting magnitude from one run to another is indicated between runs 15a and 20a. For the January storm, run 15a was best (R^2=0.67 vs. 0.59 for 20a); for the February storm R^2 was the same (0.1). Timing correlations for both cases were quite good (R^2 = 0.95 and 0.97 respectively). Statistical data are given in Table 3.



6a

6b

6c

Figure 6. PM_{10} magnitude correlations for dust storms of Jan 4-6, 2007 (6a) and Feb 23-25, 2007 (6b) for model runs 15a (red) and 20a (green); and timing correlation for the storm of Feb 23-25, 2007 (6c)

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Table 3. Agreement indices for storms of Jan 4-6, 2007 and Feb 23-25, 2007

Metric	Jan 4-6, 2007 N (7 sites, 446 obs)	Feb 23-25, 2007 N (7 sites, 346 obs)
Mean	29.2 obs.; 26.3 model	34.1 obs.; 59.3 model
Mean bias	2.8	-25.0
Mean error	26.0	56.o
Norm mean bias	10.8	42.4
Norm mean error	76.2	67.7
Fractional bias	12.1	9.7
Fractional error	88.1	122.0
Agreement index	0.63	0.42

To augment point-by-point correlations, the Point-Stat tool in the Model Evaluation Tools (MET) was used to evaluate model performance in forecaster terms[1]. Although it was specifically designed for application to the WRF it can be used to evaluate simulations from models such as DREAM/Eta.

The Point-Stat tool provides categorical verification for modeled forecasts at observation points. It matches gridded forecasts to point observation locations using several interpolation approaches. One is intrinsic, as in the case of rainfall, where the observation points either have rain or no rain; another uses a 'rain threshold' such as 0.01 to verify the model's ability to predict measurable rainfall. To evaluate DREAM/Eta's performance as a forecast tool, EPA's 24-hour standards for $PM_{2.5}$ (35 ug/m3) and PM_{10} (150 ug/m3) particulates were used as a 'dust threshold'. The verification stats were formulated using a contingency table where "M" represents the modeled hourly forecasts of $PM_{2.5}$ and "O" represents the AIR-Now hourly observations; the two possible M and O outcomes were represented by zero (no) if the EPA standard was not attained; and, one (yes) if the outcome exceeded the 'dust threshold'. Table 4 shows Point Stat results for the Phoenix area between January and April, 2007. The Skill score suggests that DREAM/Eta detected roughly 66 percent of the dust storms passing over the Phoenix area.

Table 4. Point Stat tool performance statistics for the Phoenix metro area, Jan-Apr 2007

N=111; Hits=64; Misses=24; False alarms=10; Non-events=13		
Accuracy	Proportion hits + non-events	.69
PoD	Proportion correctly forecasted	.71
PoFD	Proportion falsely forecasted	.06
Threat score	Proportion successfully modeled (ignores non-events)	.29
Skill score	How well does model discriminate events and non-events	.65

4. RESPIRATORY HEALTH APPLICATIONS

There is now a four year archive of daily model runs for V&V analysis. These daily model runs have attracted the attention of health communities in the Southwest from AZ, NM, and West TX. The communities include: (1) school nurses and public school districts developing Asthma Action Plans; (2) print and broadcast media; and (3), epidemiologists from university hospitals and State departments of health who need access to archived dust data for use in longitudinal and etiological analyses. Visualizations of dust storm movements are interesting to the first two communities because they can see the forecasted distribution and generation of dust patterns. These animations help build user-confidence, especially if they confirm user experiences. Once confidence and confirmation are achieved, these communities would rather have information delivered to them via print and broadcast media or by fax, twitter, or text messaging for broader distribution to affected populations. The third community is less interested in daily forecasts. Their statistical analyses are based on long-term data sets aggregated into summaries for analysis against reported health outcomes.

4.1 HEALTH ALERTS

Forty-eight-hour forecasts of atmospheric dust are produced daily for the forecast domain beginning at 00.00 hours UTC. They are shown at http://phairs.unm.edu, and http://nmtracking.unm.edu. Figure 7 captured a storm crossing southeast Arizona and southwest New Mexico, Jan 6-8, 2008. Individuals in Wilcox and Silver City couldhave viewed an animation of the DREAM/Eta forecast that ran from 5:00pm (local time) on Jan 6th through about midnight on Jan 8th. The image in Figure 7a is a clip from the animation centered on the hours of peak dust concentration. Figure 7b shows the peak hour and magnitudes for Wilcox Playa (blue curve) and Silver City (red curve). Each of the locations had a peak hour storm separated by a 2-4 hour time difference. There was a precursor, lower concentration episode at both locations, but Wilcox Playa was eventually hit with three episodes over the forecast period. It is interesting that Silver City, at a higher elevation and surrounded by forested terrain, recorded the highest concentration over a longer period than did Wilcox Playa.

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[1] Developed by NCAR for use in WRF

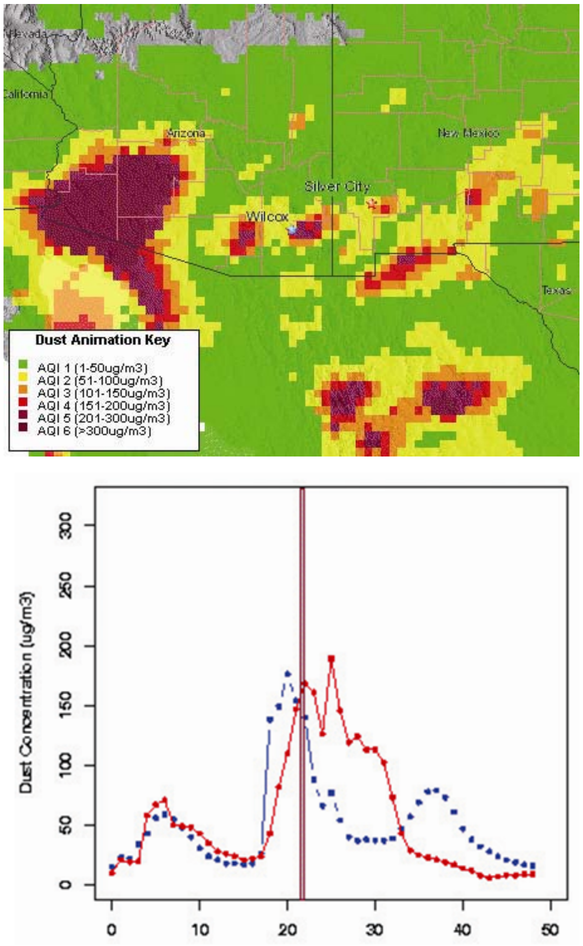

Figure 7a (top) shows the dust pattern at about 1pm on Jan 7th in terms of EPA AQI categories. Fig. 7b (bottom) shows the timing of peak dust concentrations over the forecast period. The pattern in 7a is for the hour shown on the vertical bar in 7b.

School nurses in the Albuquerque Public Schools prefer an air quality alert system that obviates referring to websites. It favors a daily written synopsis of dust and air quality conditions across the district. They have developed an Asthma Action Plan that has three categories of symptoms. Least threatening to the asthmatic is the green "zone" in which the teacher observes student respiratory behavior and suggests appropriate actions. The yellow zone of moderate asthma symptoms is addressed by a school nurse or other medical provider; and the most severe, or red zone conditions, are addressed by emergency response units. This three-color scheme could provide the basis for health-based daily air quality forecasts sent via email to Asthma Registry nurses, Asthma Allies, the local chapter of the American Lung Association, and the print and broadcast media.

Using Figure 7b as an example, a synopsis of dust forecasts might look as follows:

Wilcox vicinity: For January 6-8, expect moderate windblown dust late in the evening on the 6th, dissipating gradually through the night but increasing and peaking in concentration to unhealthy levels between 12N and 3PM on the 7th. There is a chance for moderate dust between 6-8AM on the 8th.

Silver City vicinity: For January 6-8, expect conditions as in Wilcox on the 6th. For the 7th, expect a sharp rise in dust concentration between noon and 7PM and remaining high until after midnight. Expect diminishing dust on the 8th.

4.2 EPIDEMIOLOGY

The NM-Environmental Public Health Tracking System (EPHTS) has been developed by the New Mexico Department of Health and EDAC/UNM under a grant from CDC that contributes data and statistics to CDC's national tracking network (EPHTN) (Budge et al., 2006).

Daily $PM_{2.5}$ concentrations from April 2009 were used in a pilot epidemiological study to identify statistically what areas of NM might have the greatest potential for dust-related health issues (Figure 8). The measure is the proportion of days that 24-hour average $DUST_{2.5}$ was greater that $35ug/m^3$. This concentration was used because it corresponds to the Federal 24-hour standard for $PM_{2.5}$. While it is not a health threshold, it is believed to represent a concentration that is greater than acceptable. Up to one-third of the days were forecasted to exceed $35ug/m^3$. Of particular interest for EPHTS is Lea County in southeastern NM, where some of the highest rates of asthma hospitalization occur.

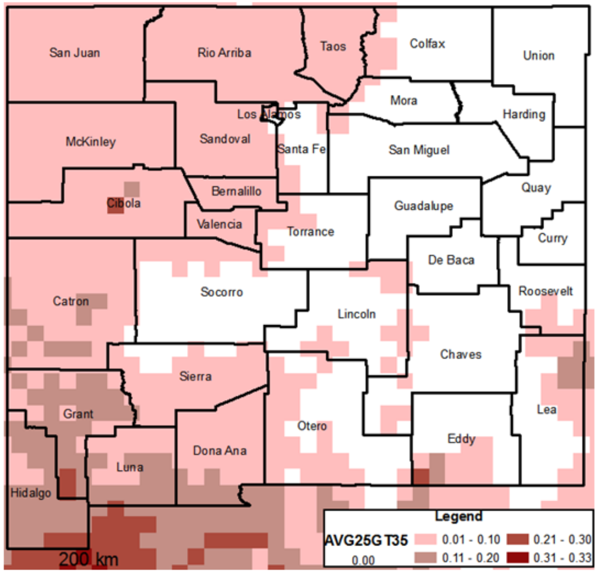

Figure 8. Daily modeled concentrations of $PM_{2.5}$ were used to develop a state-wide picture of dust exposure levels > $35ug/m^3$ across New Mexico for April 2009

A companion effort funded by NASA to UNM/EDAC has added raster and tabular data providers to the architecture to feed air quality data, graphics, and visualizations for epidemiological research. A variety of client services is included in the architecture to discover, extract, process, and deliver products on demand. Among these are time and date-range data sets and visualizations for PM_{10} and $PM_{2.5}$ outputs from daily DREAM/Eta model runs.

Authorized user communities have access to other EPHTS/N products, including:

Data Tables: (1) All PM_{10} and $PM_{2.5}$ data for all sites in the archive across the model domain, or for selected sites and for a specific date range; (2) Create a table of observed and modeled dust concentrations for: (a) a specific date, hour, and particle size category across the domain; (b) a 48 hour dust model run for all stations; (c) at a single station for a 48 hour DREAM/Eta model run; or (d), at a single station for a user-defined date and time range.

Statistics: Generate statistics for a single station for a 48 hour model run, or for a user-defined date range.

EPTHS is continuing to: (a) Explore the use of other metrics for health assessment; (b) evaluate seasonal dust patterns; and (c), develop methods for using higher resolution forecasts for dust and other particulates modeled by CMAQ.

5. CONCLUSIONS

The DREAM/Eta model system holds promise for accurately forecasting many of the PM_{10} dust events across the Southwest. Dust concentrations appear to be less accurately forecasted but this may be due in part to differences between in-situ ground samplers and samples detected through an atmospheric depth. The peak hour of dust events is detected very well for heavy dust events, but further work is needed to assess concentrations and timing on days that are essentially dust-free.

The availability of daily 48-hour dust forecasts, and the accumulation of these records into long-term archives, could provide environmental information for immediate health alerts by respiratory health providers, broadcast and print media, and related communities monitoring health. As the quality and reliability of forecasts improve, archives will be available for linking long term dust exposures to chronic respiratory health outcomes for populations at risk.

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7. ACKNOWLEDGEMENTS

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