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Validation of COAMPS(TM)/dust during UAE2

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THESIS

VALIDATION OF COAMPS™/DUST DURING UAE2

by

Darren D. Sokol

March 2005

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13. ABSTRACT (maximum 200 words)

Dust forecasting has become important to military operations over the past three decades. Rules of thumb have been the primary resource for forecasting dust. In recent years, algorithms for weather models have been created to produce atmospheric dust concentration forecasts and are now coming into use operationally. The question becomes how good are the models and what causes errors in their forecasts?

This study examines the accuracy of the U. S. Navy's Coupled Ocean Atmospheric Mesoscale Model dust module during the United Arab Emirates Unified Aerosol Experiment. The study also attempts to determine what causes any error if present. The primary method to verify the model's aerial coverage accuracy is through equitable threat score. Case studies are then conducted to verify the scores and identify sources of any errors identified.

Results indicate the model performs well with respect to sourcing dust plumes. Errors in modeled aerial coverage as compared to real world observations appear to be the result of an inability for the model to properly advect suspended dust near the surface layer. Unconfirmed dust plumes in the model seemed to be the result of inaccurate surface characteristics.

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VALIDATION OF COAMPS^{TM}/DUST DURING UAE2

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Submitted in partial fulfillment of the
requirements for the degree of

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from the

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ABSTRACT

Dust forecasting has become important to military operations over the past three decades. Rules of thumb have been the primary resource for forecasting dust. In recent years, algorithms for weather models have been created to produce atmospheric dust concentration forecasts and are now coming into use operationally. The question becomes how good are the models and what causes errors in their forecasts?

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Thank you to Dr Westphal and Dr Liu at Naval Research Laboratory for allowing me access to the model. It saved me from having to find a completely different topic when all other previous attempts to perform a study like this failed.

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I. INTRODUCTION

A. MOTIVATION

Throughout history, dust storms have played a significant role in military operations in desert regions. Accurately forecasting these conditions then becomes key to taking advantage of them. Not anticipating them can lead to disasters such as the 1980 failed attempt to rescue hostages in Iran. During this operation, helicopter pilots became disoriented and lost in a dust storm and were forced to turn back. While rendezvousing with C-130 aircraft there was a collision in low visibility conditions that claimed the lives of eight servicemen. More recently, Operation IRAQI FREEDOM encountered the "Mother of All Dust Storms." Although visibility was reduced to a few meters during the storm, the conditions were forecast far enough in advance for planners to react and plan accordingly.

Forecasting of dust storms is generally done using rules of thumb developed after years of experience in a region. Only within the past three years have operational dust models become available to military forecasters. Prior to this, atmospheric dust modeling was largely a research area. The emergence of operational dust models prompts the questions, how good are the dust models currently in use and what conditions result in poor or variable forecasts?

B. OBJECTIVES

Typical verification approach for dust models is to compare model forecast dust plumes to those observed in satellite imagery, to surface observations, or a combination of both. If the modeled plume is observed, it is considered a success.

Another method of verifying modeled fields where spatial coverage is important is to use equitable threat score (ETS). This method checks a forecast field against an observed field and assigns a score over the entire field.

In this thesis, the U. S. Navy's Coupled Ocean/Atmospheric Mesoscale Prediction System Dust Module (COAMPS™/dust) run by the Naval Research Laboratory (NRL) during the United Arab Emirates Unified Aerosol Experiment (UAE2) (August-September 2004) is studied to verify its accuracy. ETS for the dust concentrations are calculated over the entire period and select cases are further examined with satellite and surface observations.

This thesis begins with discussion of background material in Chapter II. The background material includes general rules of thumb for forecasting dust, a description of UAE2, a COAMPS/dust description, an explanation of ETS and bias, and a description of the software used. Chapter III covers the results of the verification. Conclusions and recommendations for further research follow in Chapter IV.

II. BACKGROUND

A. GENERAL RULES OF THUMB FOR DUST FORECASTING

Wilkerson (1991) provides 25 rules of thumb for forecasting dust storms. This thesis will only cover those relevant to this study:

1. The lifting threshold for fine dust is 15 knots (7.7 m/s).
2. The average height of a dust storm is 3,000 to 6,000 feet or approximately 900 to 800 hPa.
3. Suspended dust settles when winds drop below 15 knots (7.7 m/s).
4. Suspended dust settles at a rate of 1,000 feet per hour (8.5 cm/s). Settling occurs in areas where the dust was advected. Source areas clear instantly once winds drop below threshold speed.

For conversion of dust concentration to visibility, this thesis uses the general relationship found in the Air Force Weather Agency's analysis and verification of their Dust Transport Application as shown in Table 1. This analysis also found that under normal atmospheric conditions, a dust concentration of greater than 0.1 mg/m^3 would begin to produce hazy conditions (Wesely et al., 2004).

Visibility Range (NM)	**Dust Concentration (mg/m^3)**
<2	>2.5
2 – 4	2.5 – 1.8
4 - 6	1.8 – 1.0

Table 1. Relationship of visibility to dust concentration (After Wesely et al., 2004).

B. DESCRIPTION OF UAE2

United Arab Emirates Unified Aerosol Experiment is an international project to study atmospheric aerosols in the

Arabian Gulf region using satellite, airborne, and ground based sensors. These measurements were focused in the United Arab Emirates, the southern Arabian Gulf, and the northwestern Arabian Sea while this study focused on the larger southwest Asia region as a whole. Data was collected from 5 August to 30 September 2004. From Reid et al. (2005), there are four overarching goals for the experiment:

1. Evaluate and improve satellite aerosol and ocean products in this region.
2. Determine microphysical, optical, and transport properties of aerosol particles.
3. Understand how aerosol particles interact with the radiation budget in bright surface locations.
4. Model and explain the complex flow patterns in these coastal regions.

COAMPS/dust was run real time by the Naval Research Laboratory from 1 August to 30 September 2004 to support the experiment. A re-run of the model was later conducted to provide a uniform domain over the time period as the model domain was shifted during the experiment. It is the re-run model data that is used in this thesis.

C. DESCRIPTION OF COAMPS/DUST

COAMPS is a nonhydrostatic and compressible dynamics model in operational use by the U. S. Navy. Within COAMPS is a dust microphysical aerosol model (dust). This module uses the model’s meteorological fields at each time step and grid point (Reid et al., 2005; Liu et al., 2003). It produces dust concentrations at each point by solving a mass conservation equation with source production, transport, sedimentation, and wet and dry deposition terms. Operational forecasting started using this model in Southwest Asia in March 2003 (Reid et al., 2005).

Source production is calculated with a formula from Nickling and Gillies (1993) that describes vertical dust flux as proportional to the square of the surface wind stress. Source areas are based on 1 km resolution datasets from the U. S. Geological Survey and Walker et al. (2003). Dust emissions are restricted to areas where the soil is dry. The threshold used is a ground wetness index of 0.3, which is derived from long term dust modeling in Asia and calculated by COAMPS (Reid et al., 2005).

The transport is calculated using a 5th order flux-form scheme developed by Bott (1989a and 1989b). Sedimentation is determined by calculating the particle terminal velocity using Stokes' Law with a Cunningham correction (Reid et al., 2005). Dry deposition is determined by surface wind stress and 10 m wind speed (Stull, 1988). Wet deposition by precipitation is calculated through the scavenging rates of washout and rainout processes obtained from Pruppacher and Klett (1978).

Because no regular observations of atmospheric dust concentration are taken, the modeled fields are initialized with the previous run's 12 hour forecast dust concentration fields. This creates some issues for verification. First, there is no ground truth to compare against. And second, any errors in the field may cause erroneous verification. Also, these errors will continue to propagate in later runs of the model.

For UAE2, COAMPS/dust was run using 81 km, 27 km, and 9 km grids. The 27 km grid is used for this thesis in order to examine the regional accuracy of the dust forecast.

D. EQUITABLE THREAT SCORE AND BIAS

Equitable threat score is a statistical score to determine the accuracy of a forecast for a given field and a given threshold. It is defined as ETS = (H-CH)/(F+O-H-CH). F is the number of forecast points above a threshold, O is the number of observed points above a threshold, H is the number of correctly forecast points above a threshold, and CH is the chance or expected number of hits in a random forecast of F points for O observed points. CH is equal to F*O/NUM, where NUM is the total number of points in the given field. By using CH, ETS attempts to negate the reward achieved by random hits. ETS ranges from 0 to 1 with 1 being a prefect score (Rogers et al., 1996). The ETS is well suited to measure the skill with which the model forecasts the aerial coverage of dust.

Bias is the ratio of forecast points to observed points. In this thesis, if the coverage of forecast dust is too great, the bias is greater than 1. If the coverage of the forecast is too small, the bias is less than 1. With unity, the number of forecast points equals the number of observed points (Rogers et al., 1996).

E. SOFTWARE USED

VISUAL is a diagnostic and display program for gridded meteorological data (Nuss and Drake, 1995). This program was used to display COAMPS/dust data and create plots. It was also used to determine specific values at specific locations.

Two FORTRAN programs written by Prof. Wendell Nuss were used to calculate ETS from the gridded COAMPS/dust data and output this data in tabular form to a data file for further study.

MATLAB is a software package for technical computations, graphics, and animations (Pratap, 2002). It was used to calculate statistics from data generated by the FORTRAN programs and create graphs.

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III. RESULTS

A. STATISTICS

1. Equitable Threat Scores

Equitable threat scores for surface dust concentration were calculated for the 0.1, 1.0, 1.8, and 2.4 mg/m^3 thresholds at the 24, 36, and 48 hour forecasts. This includes 120 model runs during UAE2 from 0000UTC 1 Aug 04 to 1200UTC 30 Sep 04. Since no true verification data exists, the ETS was constructed by using the model initial dust distribution as the verification. As such, the ETS measures the divergence of dust forecasts that started at different times. The scores were then averaged by threshold and the results are shown in Figure 1.

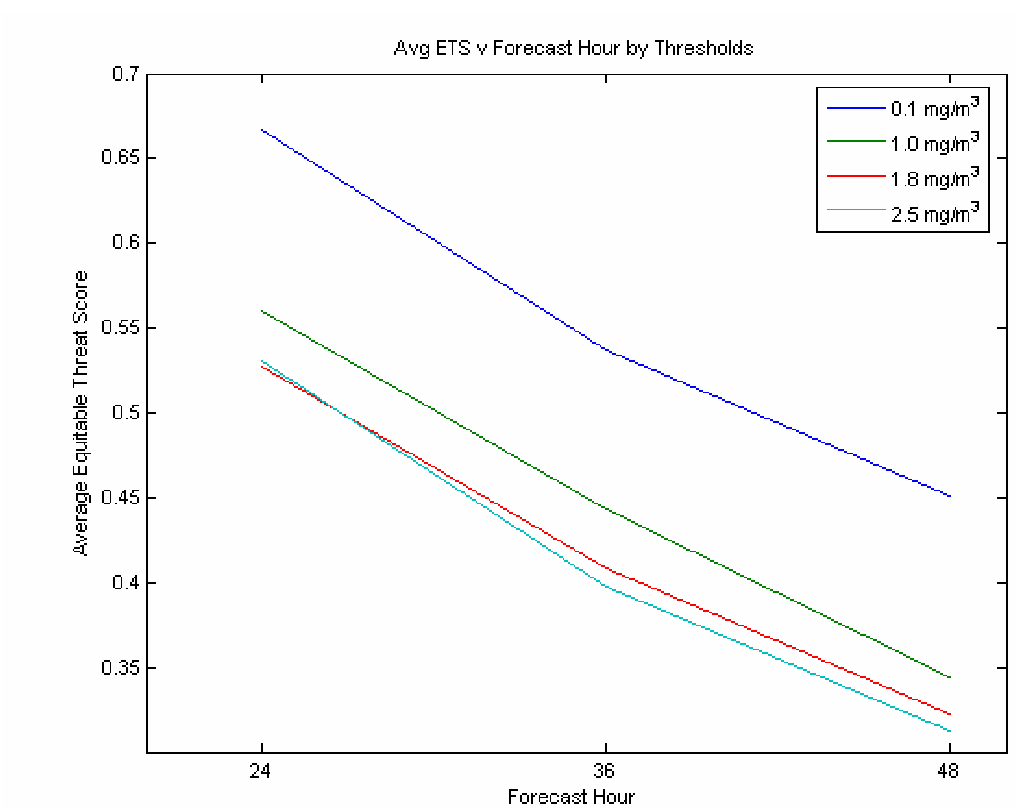

Figure 1. Average ETS versus forecast hour by thresholds.

The results indicate good performance for the lowest dust concentration threshold and shortest forecast. As the threshold increases, performance decreases. This is expected as the aerial coverage for higher concentrations decreases with the higher thresholds and it becomes more difficult to have the forecast and analysis fields overlapping to score hits. This trend also becomes an issue for operational forecasting since the highest thresholds represent the lowest visibilities. Forecasting the precise location of a significant impact caused by low visibility in dust becomes more difficult.

Also apparent from Figure 1 is the decrease in forecast accuracy as the length of the forecast increases. This is also expected as model performance does tend to decrease in time.

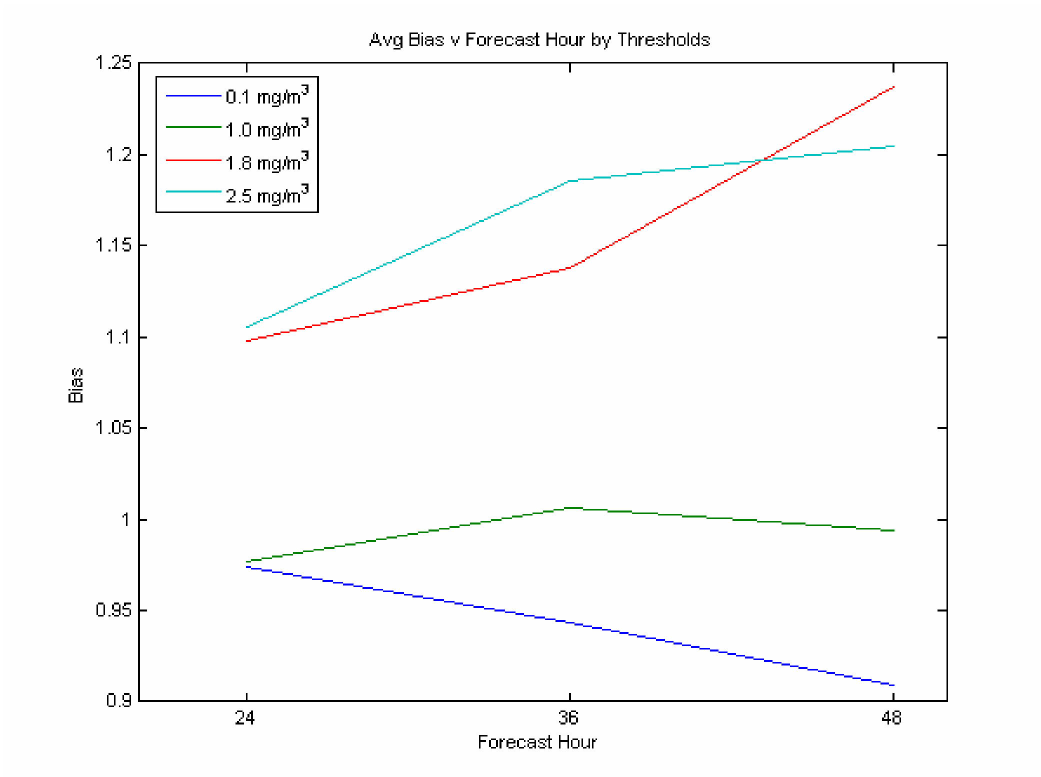

Figure 2. Average bias versus forecast hour by thresholds.

2. Bias

Bias was also calculated for the 0.1, 1.0, 1.8, and 2.4 mg/m^3 thresholds at the 24, 36, and 48 hour forecasts. The scores were then averaged by threshold and the results are shown in Figure 2.

No clear bias is detected. The 0.1 mg/m^3 threshold aerial coverage tends to be under-forecast slightly. The 1.0 mg/m^3 is very near unity. The 1.8 and 2.5 mg/m^3 thresholds aerial coverage is over-forecast slightly as the biases are only a few tenths off from unity. If the model is not significantly under or over-forecasting aerial coverage, what is causing the lower ETS?

3. Correlation to Wind ETS

The first inclination is that errors in the aerial coverage of the dust would be caused by differences in the wind forecast. Since the dust verification was simply a sequence of short term forecasts (12 hour), most of the deviation in dust is presumably due to the winds in longer term forecasts (24 to 48 hours). To verify this, ETS for wind speeds were calculated using 7.7 m/s as the threshold. The wind speeds were plotted against corresponding dust concentration ETS and correlation coefficients calculated (Figures 3 to 6).

Poor correlations between the areas of 7.7 m/s winds and dust concentrations were found. The correlation coefficients were near zero, ranging from -0.1215 to 0.0892. This is counterintuitive since a rule of thumb is 7.7 m/s wind speeds are needed to lift dust. Some of this difference is due to the fact that there are large areas in the model where winds exceed 7.7 m/s and no dust occurs. However, the model seemed to correctly predict the area of

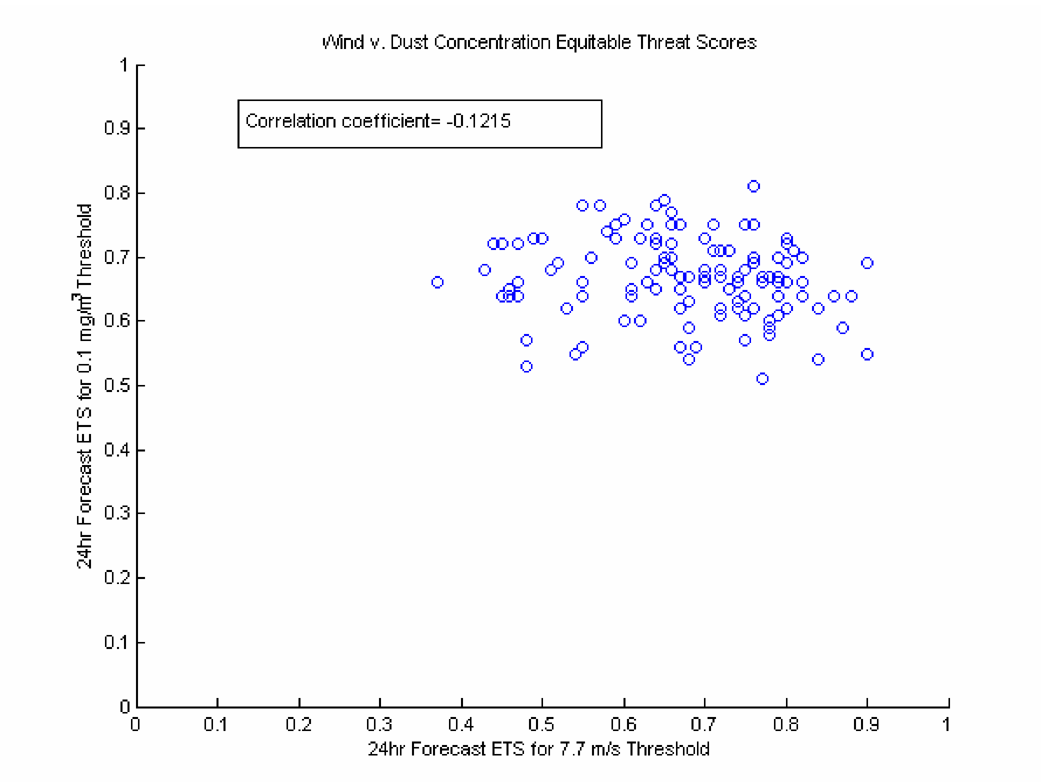

Figure 3. 7.7 m/s wind versus 0.1 mg/m^3 dust concentration ETS correlation plot.

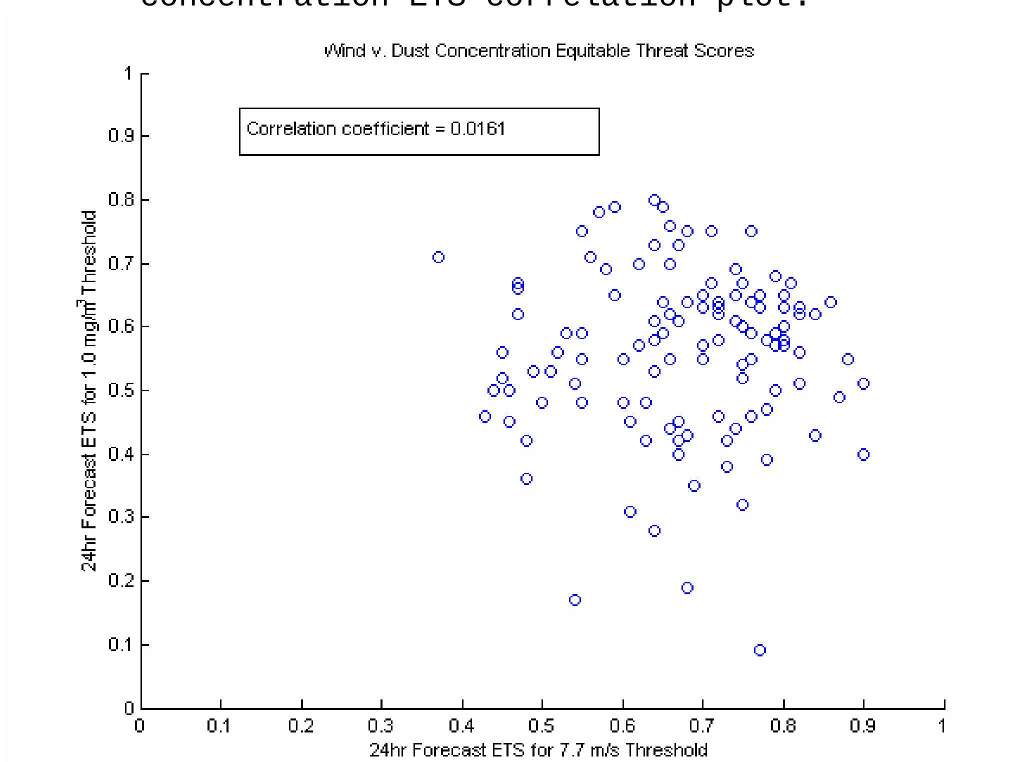

Figure 4. 7.7 m/s wind versus 1.0 mg/m^3 dust concentration ETS correlation plot.

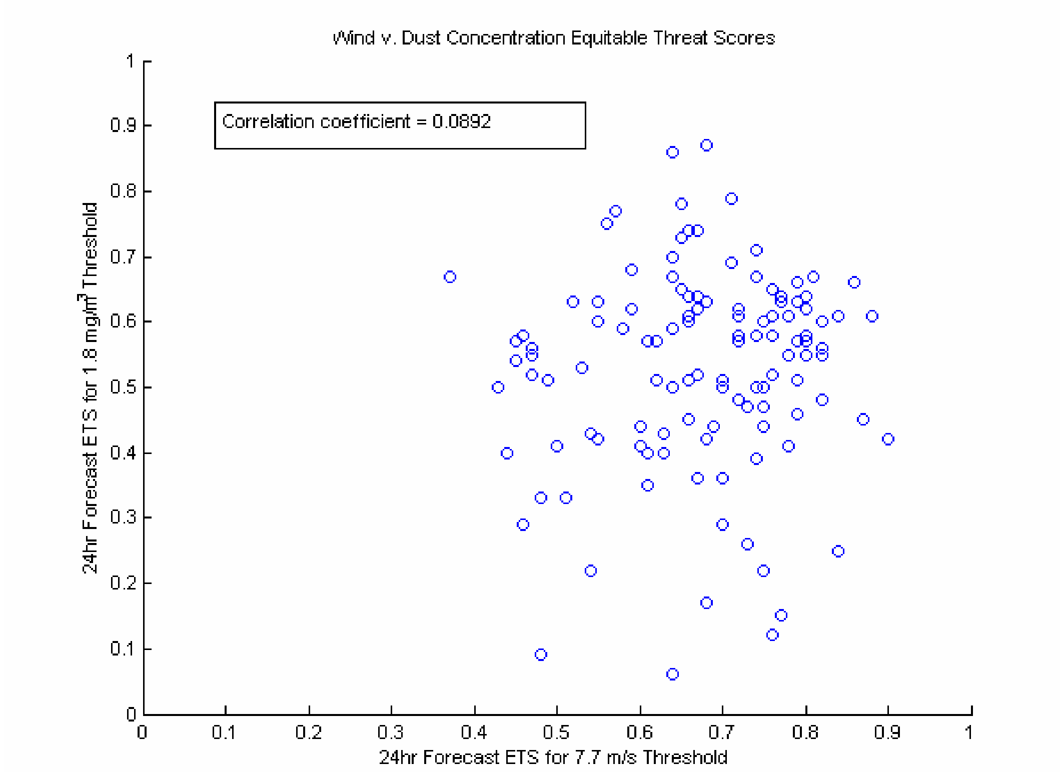

Figure 5. 7.7 m/s wind versus 1.8 mg/m^3 dust concentration ETS correlation plot.

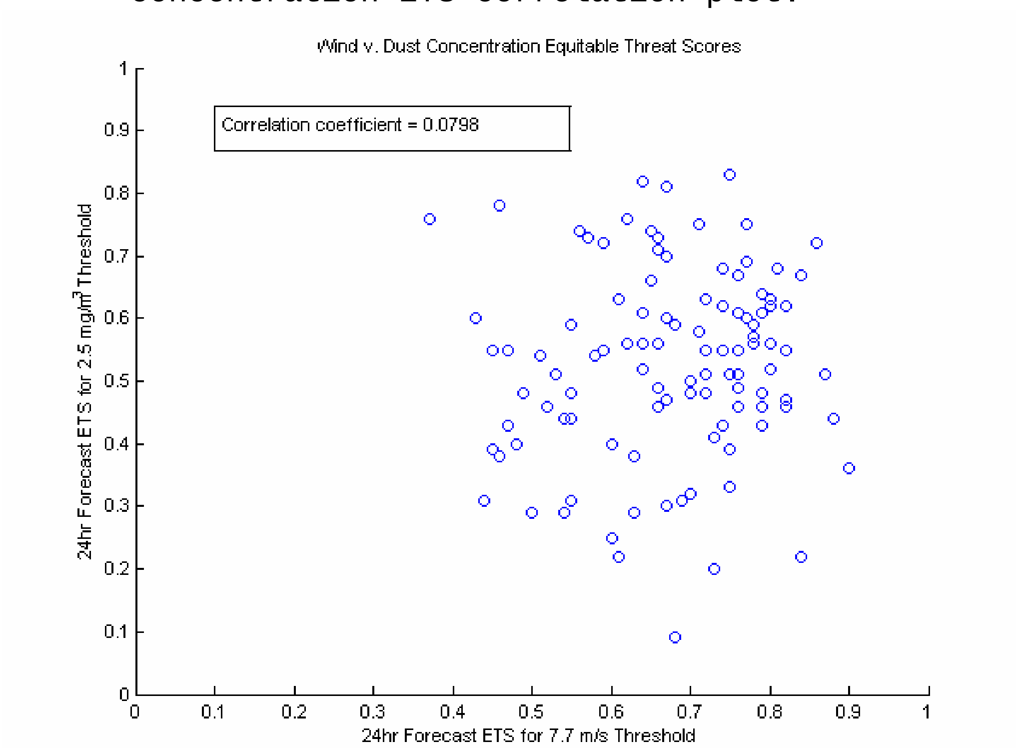

Figure 6. 7.7 m/s wind versus 2.5 mg/m^3 dust concentration ETS correlation plot.

higher winds rather well yet the dust coverage seemed to vary significantly. This could be due to a poor wind forecast in a critical source region which was not examined overall but will be addressed in specific events.

B. CASE STUDIES

Case studies were conducted for two reasons. First is to confirm the performance of ETS. Second is to determine possible reasons for poor performance. Five case studies are presented which encompass findings over the entire model period.

1. 7 Aug 04 – Best ETS

The model run with the valid time of 1200UTC 7 Aug 04 had the best ETS for its 24 hour forecast at the 0.1 mg/m^3 threshold. The ETS was 0.81.

Figure 7 is the surface plot showing the model's sea level pressure, surface winds, and surface dust concentration at the valid time. The surface plot indicates a large plume along the Afghan, Iranian, and Pakistani borders. Other plumes are also indicated in southern Pakistan, along the Oman coast, and scattered across Iraq and Saudi Arabia.

Figure 8 is a Moderate Resolution Imaging Spectroradiometer (MODIS) satellite image with an enhancement to highlight potential areas of suspended dust in the atmosphere (Miller, 2005). This image, from the Naval Research Laboratory (NRL), indicates a large dust plume along the Afghan, Iranian, and Pakistani borders which also extends into southern Afghanistan.

By comparing Figure 7 to Figure 8, the dust plume along the Iranian border in the model is confirmed. However, the model does not carry the plume into southern

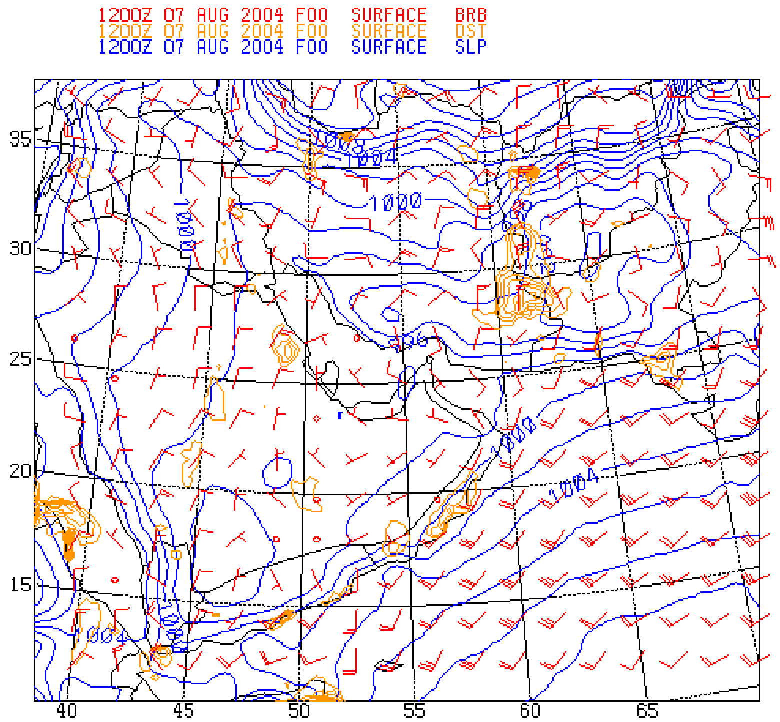

Figure 7. Surface plot for 1200UTC 7 Aug 04.

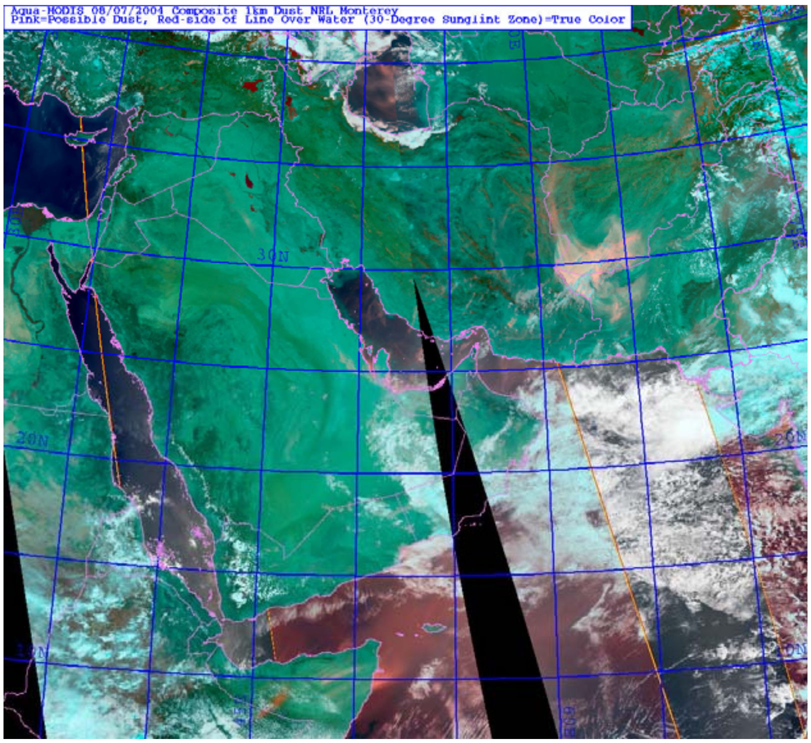

Figure 8. MODIS satellite image for 1330UTC 7 Aug 04 (From NRL, 2005).

Afghanistan as indicated in the satellite imagery. No other plumes from the model are verified in Figure 8.

Surface observations (Table 2) at the valid time support the satellite image. Zabol and Kandahar are both in the satellite indicated dust plume and are reporting either blowing or suspended dust as obstructions to visibility. Panjgur is also in the satellite indicated plume but only reporting haze as the obstruction to visibility. With visibility of only 1000 m, this haze is more likely suspended dust. No observations were found to support the other dust plumes indicated by the model.

Location	**Wind direction/speed**	**Visibility**	**Weather**
Zabol, Iran (31.3N 61.5E)	320/39kt	800m	BLDU
Kandahar, Afghanistan (31.6N 65.7E)	270/13kt	3200m	DU
Panjgur, Pakistan (27.0N 64.0E)	360/04kt	1000m	HZ

Table 2. Surface observations for 1200UTC 7 Aug 04.

Visually comparing the 24 hour forecast (Figure 9) to the initialization shows all predicted dust plumes were geographically well located. Stronger winds in Saudi Arabia are causing the larger dust concentrations in the 24 hour forecast. Winds above lifting threshold in Oman and southern Pakistan are coincident with erroneous dust plumes.

In order to compare wind forecasts for a valid time, composite plots were created to overlay all surface wind forecasts at the grid points. This makes consistent or

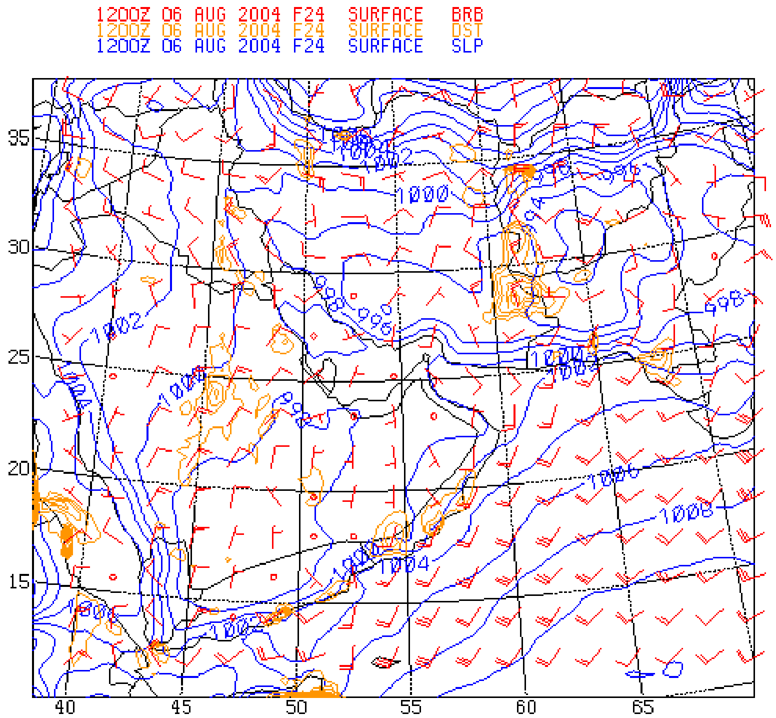

Figure 9. 24 hour surface forecast valid 1200UTC 7 Aug 04.

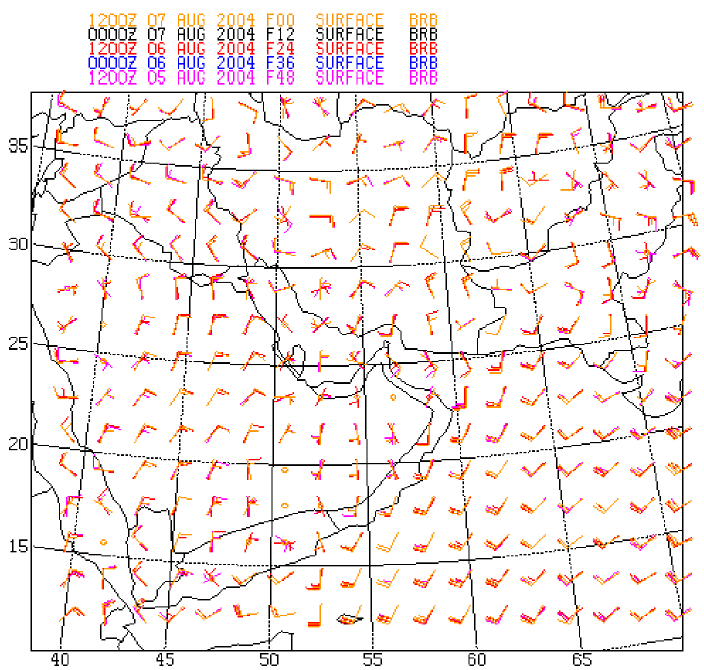

Figure 10. Composite of surface wind forecasts valid 1200UTC 7 Aug 04.

deviant forecasts easier to detect. Figure 10 is a composite of the surface wind forecasts valid at 1200UTC 7 Aug 04. Winds are fairly uniform over all forecasts.

This case indicates plumes from dust source regions are well forecast as long as the surface characteristics of the source region are properly identified in the model. From the observation at Kandahar there is an indication that the model may have some problems advecting suspended dust away from a source area.

2. 20 Sep 04 – Worst ETS

The model forecast with the valid time of 1200 UTC 20 Sep 04 had the worst ETS for its 24 hour forecast at the 0.1 mg/m^3 threshold. The ETS was 0.53.

Figure 11 is the surface plot showing the model's sea level pressure, surface winds, and surface dust concentration at the valid time. The model indicates very small areas of dust exceeding the 1.0 mg/m^3 contour in northern Saudi Arabia and southern Iraq. These areas are the remaining dust from a dust storm during the previous day.

Figure 12 is the MODIS imagery with dust enhancement for 1330UTC 20 Sep 04. The image indicates larger aerial coverage by the dust in northern Saudi Arabia and southern Iraq. It also indicates dust storms associated with convective cells in southern Afghanistan.

Comparing the surface plot to the satellite image, the model then appears to be under-forecasting the dust concentration in northern Saudi Arabia and southern Iraq at this time. The model has also missed the dust storms associated with the convection in southern Afghanistan.

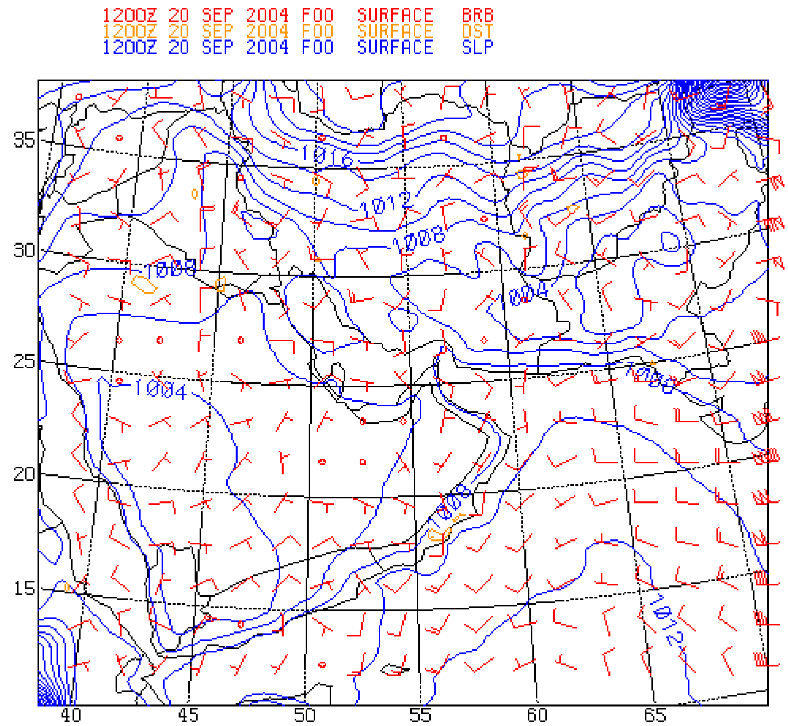

Figure 11. Surface plot for 1200UTC 20 Sep 04.

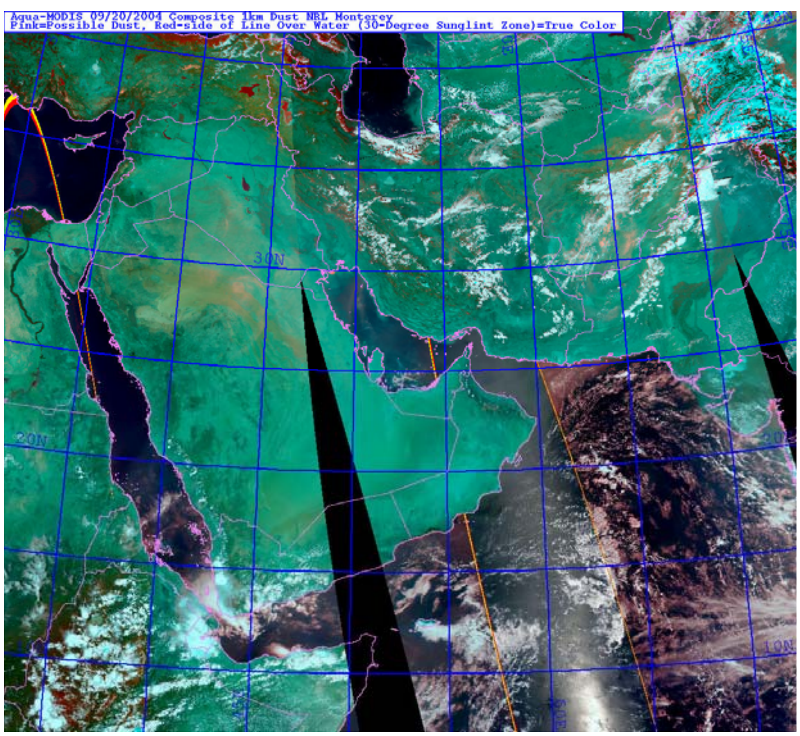

Figure 12. MODIS satellite image for 1330UTC 20 Sep 04 (From NRL, 2005).

Surface observations (Table 3) did not confirm the presence of suspended dust in northern Saudi Arabia as indicated by the model and satellite image. Hail was reporting ceiling and visibility okay. The dust in southern Afghanistan was confirmed as Kandahar reported suspended dust.

Location	Wind direction/speed	Visibility	Weather
Hail, Saudi Arabia (27.4N 41.7E)	270/08kt	MISSING	CAVOK
Kandahar, Afghanistan (31.6N 65.7E)	270/17G28kt	4800m	DU

Table 3. Surface observations for 1200UTC 20 Sep 04.

The 24 hour forecast (Figure 13) indicates that the model had previously settled the dust more quickly in northern Saudi Arabia and southern Iraq. The dust storms in Afghanistan were previously missed by the model.

The composite of the surface wind forecasts valid at 1200UTC 20 Sep 04 (Figure 14) shows more variability in the overall wind field forecasts. However, winds in the plume areas tend to be more consistent than the rest of the region. Most wind forecasts are also below the lifting threshold of 7.7 m/s.

With the poor performance in northern Saudi Arabia and southern Iraq, this case indicates that the model may be having difficulty with suspended dust. The missed dust storms in southern Afghanistan are more likely a result of the meteorological portion of the model missing the convection that occurred rather than errors in the dust module itself.

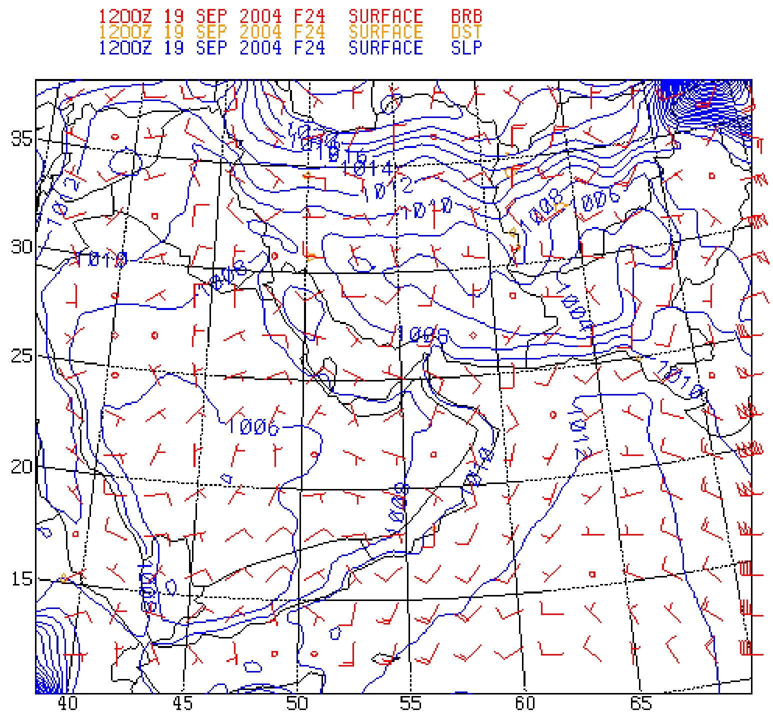

Figure 13. 24 hour surface forecast valid 1200UTC 20 Sep 04.

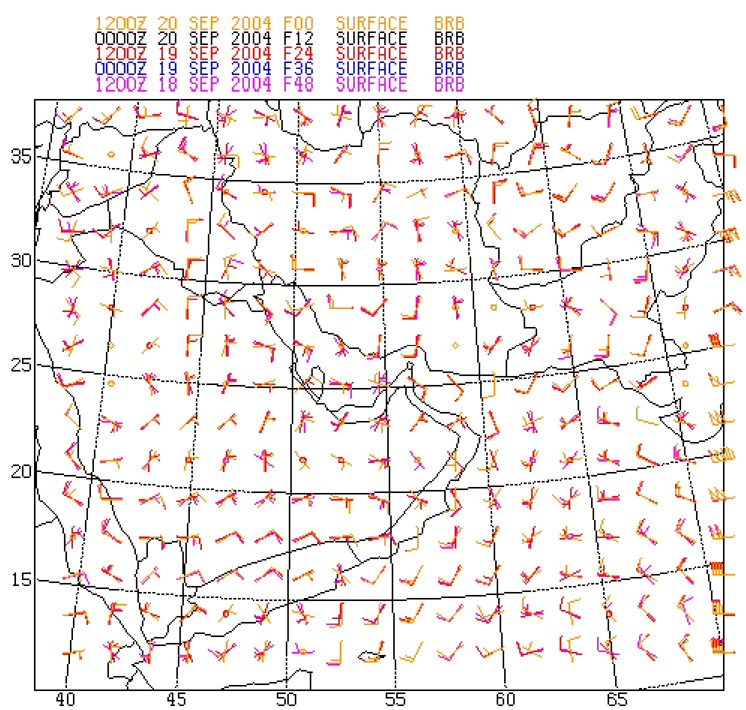

Figure 14. Composite of surface wind forecasts valid 1200UTC 20 Sep 04.

3. 18 Aug 04 – Largest Dust Area

The 1200UTC 18 Aug 04 case was chosen as this time had the most grid points observed where dust exceeded the 0.1 mg/m^3 threshold.

The valid time surface plot (Figure 15) shows a dust storm along the Afghan, Iranian, and Pakistani borders. Another dust storm is indicated from southeastern Iraq through Kuwait into northeastern Saudi Arabia. There is also a dust plume indicated from the east-central coast of Saudi Arabia towards the south. Again, there is a dust storm forecast along the coast of Oman.

The MODIS imagery (Figure 16) indicates a large plume along the Afghan, Iranian, and Pakistani borders which extends well into southern Afghanistan. There are dust plumes in southern Iraq, Kuwait, and eastern Saudi Arabia as well. No plume is indicated over Oman.

Surface observations (Table 4) confirm the dust plumes in Afghanistan, Iran, Pakistan, Iraq, Kuwait, and Saudi Arabia as all locations reported restrictions to visibility. Al Ahsa's visibility decreased within hours when the dust plume shifted east. No observations confirmed the plume in Oman.

Comparisons of the surface plot, satellite imagery, and surface observations indicate the model is over-forecasting the plume into south-central Saudi Arabia. The model is also under-forecasting the plume's extent into southern Afghanistan. The comparison also shows the satellite image is under estimating the intensity and size of the dust plumes in Iraq, Kuwait, and Saudi Arabia.

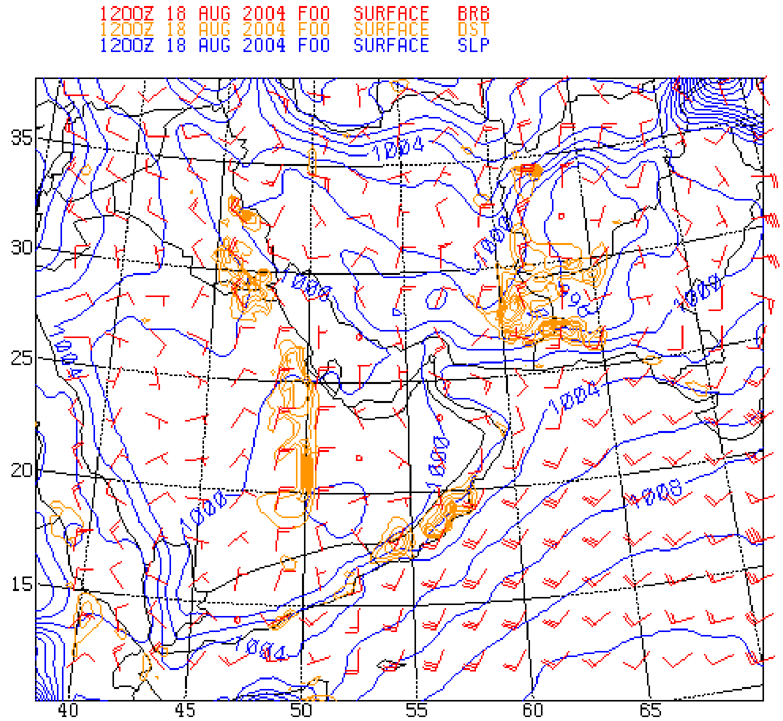

Figure 15. Surface plot for 1200UTC 18 Aug 04.

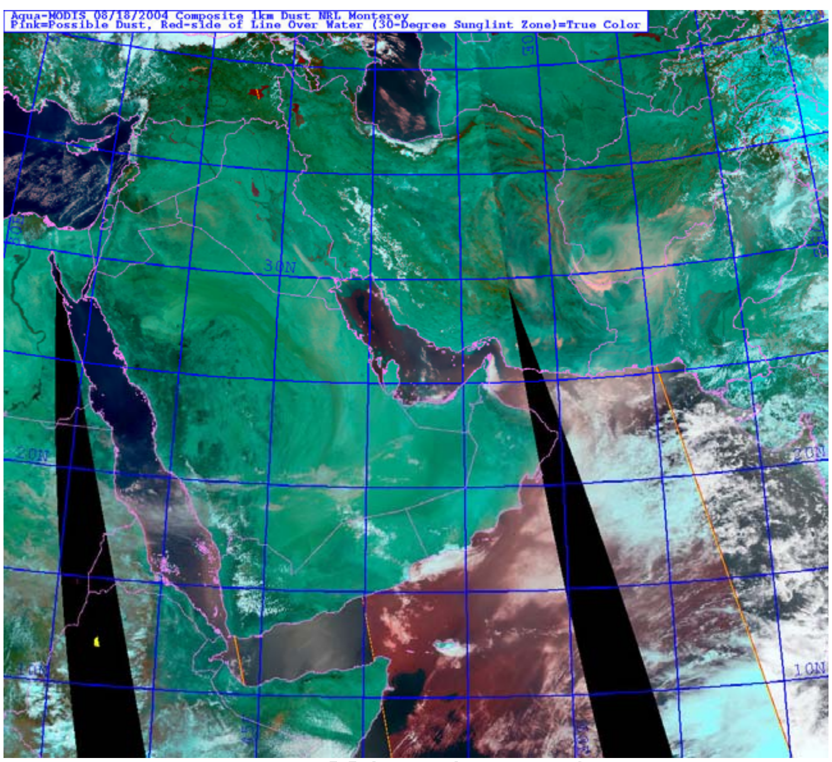

Figure 16. MODIS satellite image for 1330UTC 18 Aug 04 (From NRL, 2005).

Location	Wind direction/speed	Visibility	Weather
Al Ahsa, Saudi Arabia (25.3N 49.5E)	340/21kt	9000m	SKC
Kuwait City, Kuwait (29.2N 48.0E)	330/22kt	1400m	+BLDU
Zabol, Iran (31.3N 61.5E)	330/27kt	4000m	BLDU
Panjgur, Pakistan (27.0N 64.0E)	310/04kt	1000m	HZ
Kandahar, Afghanistan (31.6N 65.7E)	270/08kt	2400m	DU

Table 4. Surface observations for 1200UTC 18 Aug 04.

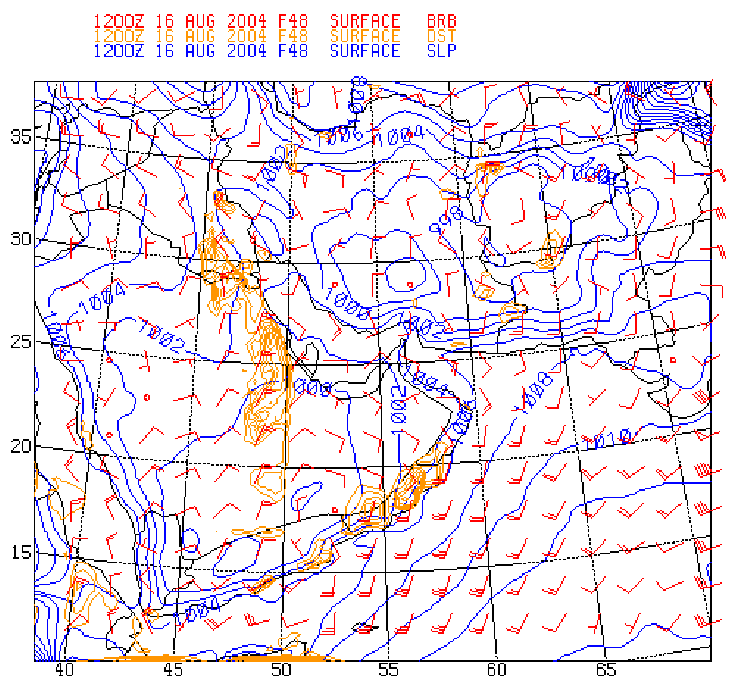

Figure 17. 48 hour surface forecast valid 1200UTC 18 Aug 04.

Figure 17 is the 48 hour forecast for the valid time of this case. The plume in Saudi Arabia covers more area and is shifted west from where it verifies. The plume in the border regions of Afghanistan, Iran, and Pakistan is drastically under-forecast. Table 5 provides the ETS for this forecast which are low, but follow the pattern identified in Figure 1. The biases are very near unity. Despite the differences in the plumes from forecast to initialization, the model forecast nearly the exact number of observed points. This illustrates that the plume placement and structure can vary substantially even though the area covered is about the same.

Figure 18 is the 24 hour forecast for this case. As the model runs progressed, they reduced the plume in Saudi Arabia and increased the plume in the border region. ETS

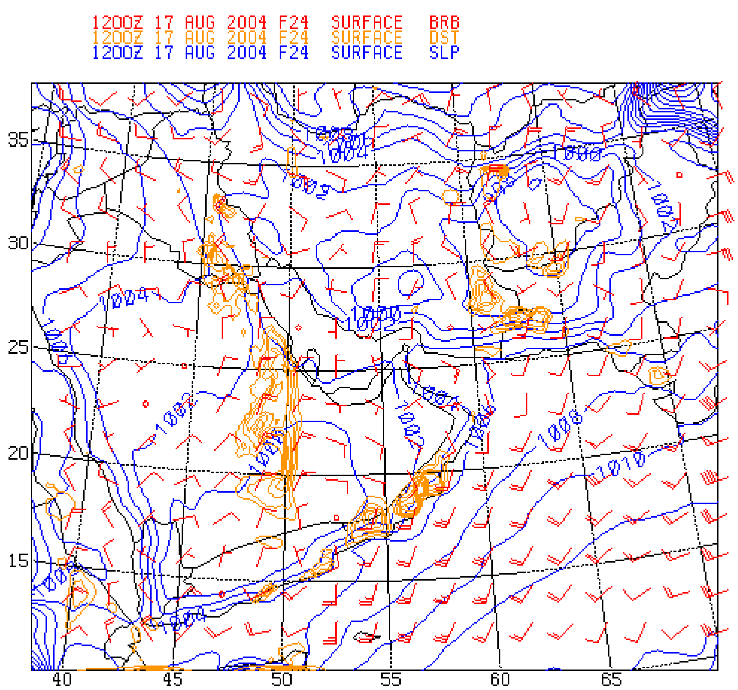

Figure 18. 24 hour surface forecast valid 1200UTC 18 Aug 04.

and bias statistics (Table 5) for this case are nearly identical to the averages of all the model forecasts (Figures 1 and 2).

Forecast Hour	Threshold	ETS	Bias
48	0.1 mg/m^3	0.52	0.99
48	1.0 mg/m^3	0.41	0.95
48	1.8 mg/m^3	0.36	0.97
48	2.5 mg/m^3	0.31	1.02
24	0.1 mg/m^3	0.67	1.00
24	1.0 mg/m^3	0.61	1.05
24	1.8 mg/m^3	0.52	1.00
24	2.5 mg/m^3	0.47	1.10

Table 5. ETS and bias for 18 Aug 04 case.

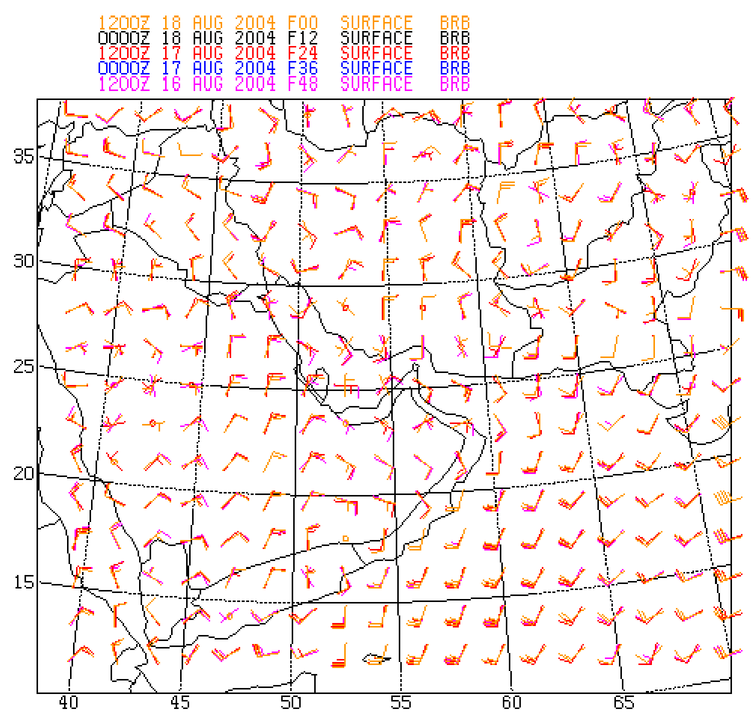

Figure 19. Composite of surface wind forecasts valid 1200UTC 18 Aug 04.

The composite of the surface wind forecasts in Figure 19 reveal consistent wind directions in all of the plume locations. There are some slight changes in speeds.

This case exhibited many of the characteristics of the model found to this point. If the source regions are accurately identified, the sourcing of dust plumes is fairly accurate. The model exhibits little bias and output improves as successive model runs get closer to specific validation times. Finally, despite accuracy in wind directions, the plumes still shifted over time. This was due to the slight changes in wind speeds. As the area of winds exceeding the lifting threshold shifted, the plumes shifted accordingly. This result illustrates that dust forecasts are closely tied to wind forecasts.

4. 12 Sep 04 – UAE2 Case

The 1200UTC 12 Sep 04 case was significant to UAE2 as a large dust plume from Iran crossed the Arabian Gulf and advected into the research area. Figure 20, the valid time surface plot, reveals a large dust plume from southern Iraq, through Kuwait, and along the west coast of the Arabian Gulf. This plume is not advected over water at the surface. Dust plumes are also indicated over the northern Iranian and Afghanistan border, the southern coast of Pakistan and Iran in vicinity of their shared border, and along the coast of Oman. No plume from Iran to UAE is detected.

The MODIS image (Figure 21) displays dust plumes from southern Iraq and Kuwait into the northern Arabian Gulf. A plume is also present from southern Iran, across the southern Arabian Gulf, and into UAE. The image indicates

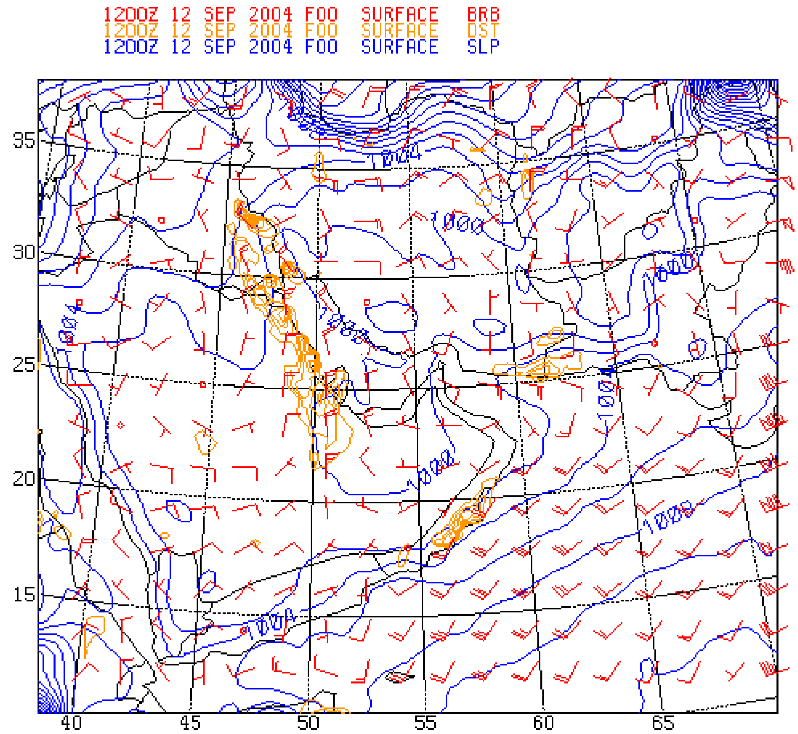

Figure 20. Surface plot for 1200UTC 12 Sep 04.

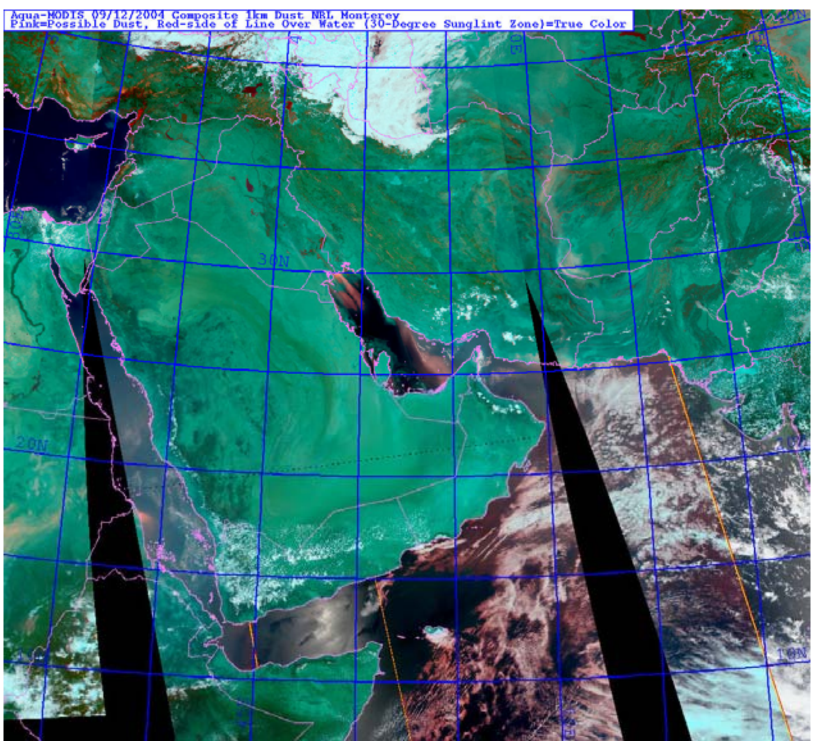

Figure 21. MODIS satellite image from 1330UTC 12 Sep 04 (From NRL, 2005)

another plume along much of the Afghanistan and Iran border. No plume is detected in Oman.

Surface observations (Table 6) confirm the plumes from southern Iraq and Kuwait. Bahrain’s visibility observation decreased to 5000m in suspended dust a few hours later, verifying the plume is over the gulf. Despite the UAE observations missing weather, an assumption can be made that it is suspended dust from the plume from Iran.

Location	**Wind direction/speed**	**Visibility**	**Weather**
Kuwait City, Kuwait (29.2N 48.0E)	340/23kt	2500m	+BLDU
Bahrain, Bahrain (26.3N 50.7E)	320/21kt	MISSING	CAVOK
Ras Al Khaimah, UAE (25.5N 55.9E)	310/11kt	6000m	MISSING
Sharjah, UAE (25.3N 55.5E)	330/08kt	7000m	MISSING

Table 6. Surface observations for 1200UTC 12 Sep 04.

Comparisons of the model data, satellite image, and surface observations were made. The modeled plumes from southern Iraq and Kuwait are verified. However in actuality, these plumes did go over water rather than staying along the Saudi Arabian coast as indicated. The southern portions of this plume were not verified. The plume from southern Iran and into UAE is verified and thus a miss for the model. The modeled plume in Oman is not confirmed through satellite and surface observations. The dust areas along the eastern Iranian borders are confirmed.

In order to further examine the vertical extent of the plumes over the Arabian Gulf, plots were made of the 930hPa and 850hPa levels (Figures 22 and 23). These plots reveal the model did bring the plumes from southern Iraq and Kuwait over water, but at altitude only. The model also continued to produce higher than observed dust concentrations along the Saudi Arabian coast. The plume from southern Iran is still not detected in the model.

The composite of the surface wind forecasts (Figure 24) reveals little variability in the forecasts in the regions where dust plumes were confirmed. The winds in areas where plumes were not confirmed tend to vary in both speed and direction over time.

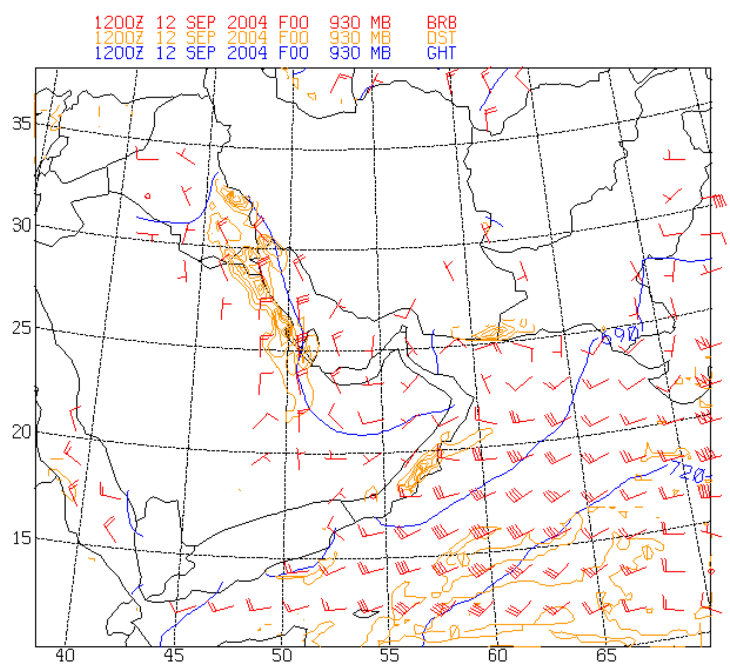

Figure 22. 930hPa plot valid 1200UTC 12 Sep 04.

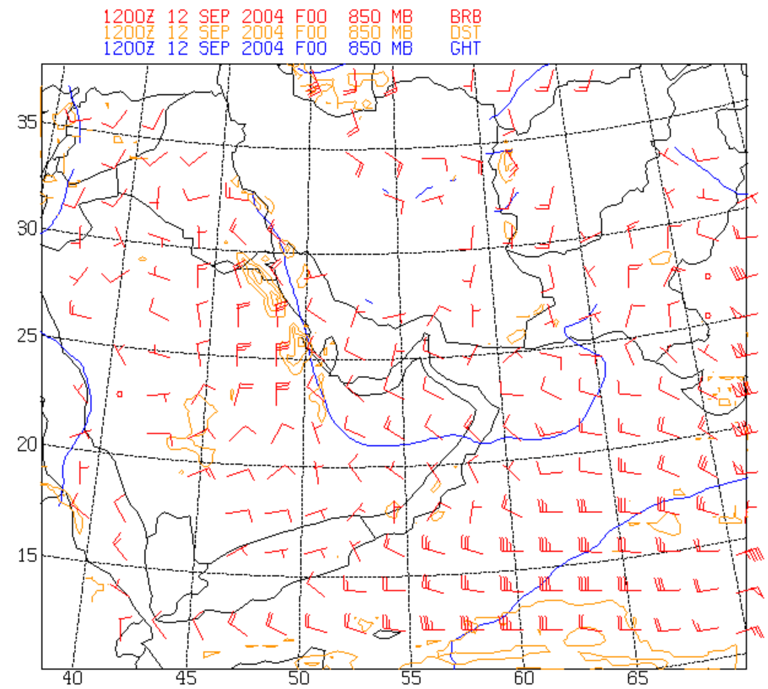

Figure 23. 850hPa plot valid 1200UTC 12 Sep 04.

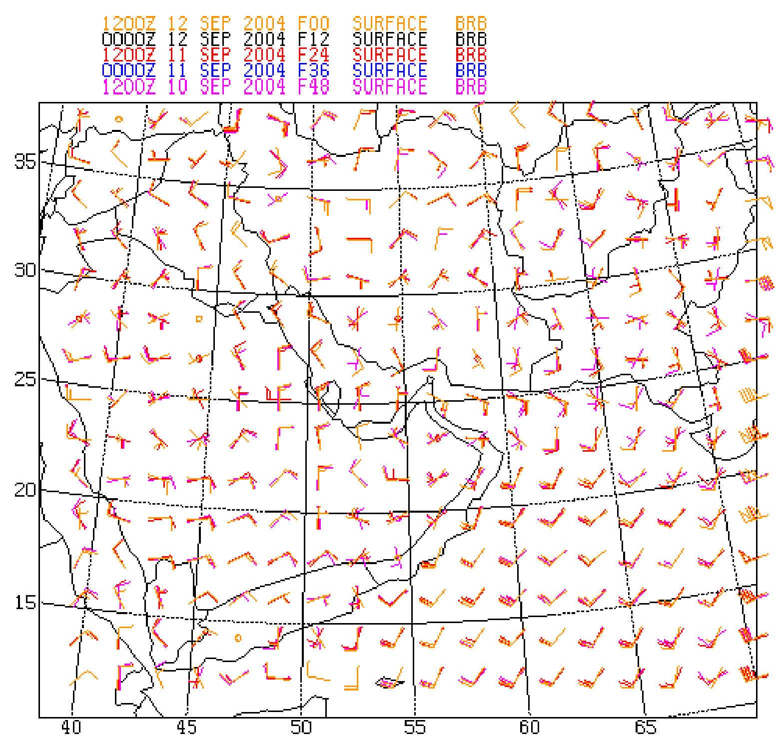

Figure 24. Composite of surface wind forecasts valid 1200UTC 12 Sep 04.

To check the initialization of the dust concentrations in the model, the previous model run's 12 hour forecast was plotted (Figure 25). The sea level pressure and wind fields have only minor differences from the forecast. The dust concentrations were identical. When the initialization of the 0000UTC model run was plotted (Figure 26) to check the evolution of the dust plumes, an unexpected picture was revealed. Figure 26 shows small, intense plumes scattered through Iran to include one in the source region of the plume from Iran to UAE. There is no hint of plumes from southern Iraq and Kuwait, which is confirmed through surface observations for 0000UTC. This different picture is a result of an interaction between the 9km and 27km grids.

Through correspondence with Liu (2005), it was learned that during this experiment the model for was run with dust concentrations being sent from the 27km grid to the 9km grid for initialization. After the 9km grid calculations were complete, the 9km grid dust concentrations were sent back to the 27km grid. This only occurs at the 0000UTC time steps. The dust concentrations displayed in Figure 26 are then primarily from the 9km grid. The 27km grid model would then quickly damp these plumes in favor of its own dust concentrations. This could be in response to differences in the surface classifications between the two grids. Since it appears that the model may have difficulty with the advection of suspended dust, if the 27km grid has a different surface type than the 9km grid and it does not have a good dust source, any new plumes would damp or disperse in the 27km grid.

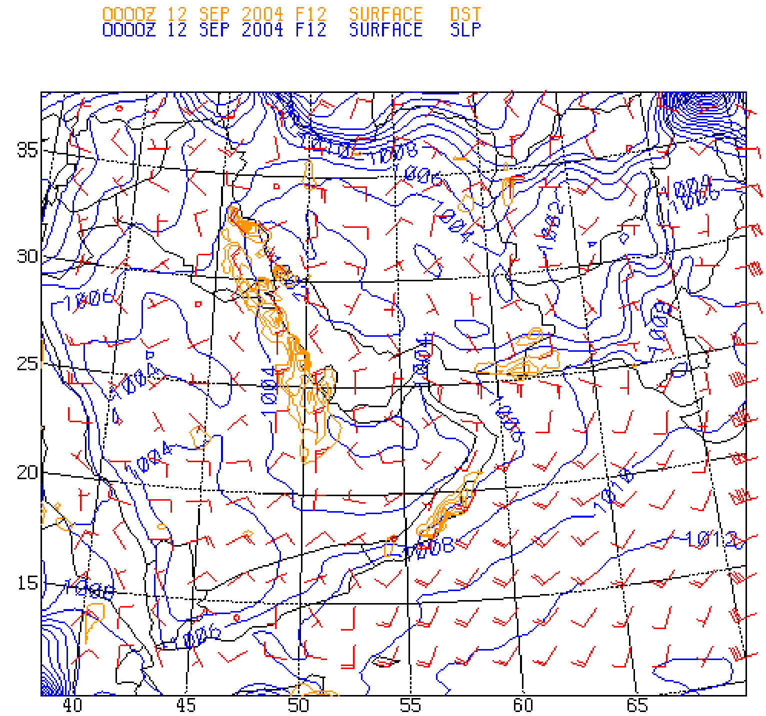

Figure 25. 12 hour surface forecast valid 1200UTC 12 Sep 04.

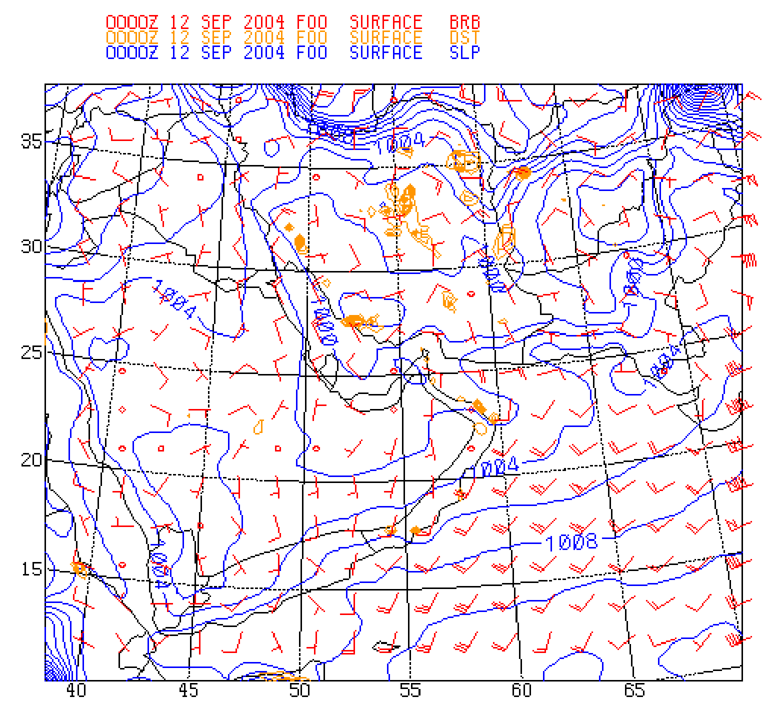

Figure 26. Surface plot valid 0000UTC 12 Sep 04.

This case highlighted two consistent trends in the model over the verification period. First, the importance of properly identifying surface types for dust source regions is fundamental to obtaining accurate forecasts. If the dust source is not correct, the model results will produce erroneous plumes such as over Oman or plumes may be missed such as from Iran to UAE. Second, the model has difficulty advecting dust, especially near the surface. This may be due to the model overestimating sedimentation and dry deposition. In the case of the plumes from southern Iraq and Kuwait, the dust lofted higher into the atmosphere was able to advect downstream. However dust concentrations near the surface were too low as shown by the lower than expected visibilities if the dust concentrations were accurate. Also, the failure to advect the dust from Iran to UAE even though the 9km grid detected the source and provided large concentrations to the 27km grid illustrates this difficulty.

This case also shows that given the initial dust analysis is from the previous 12 hour forecast, the accuracy of the plumes at the 12 hour mark is very critical to subsequent forecasts. The evolution of plumes from 24 to 48 hour forecasts compared to the analysis shows that the evolution of dust in the model can evolve very differently. This is true even when the winds seem to be rather similar. These differences which arise due to the physical processes in the dust module impact the accuracy of the plume used to initialize the next forecast cycle. If the plume decays too quickly, then the model must spin things up again which may account for some of the low ETS.

5. 28 Aug 04 – Consistent Performance Period

While examining ETS graphs for the 1.0 mg/m^3 threshold (Figure 27), a period of consistent performance was observed between forecast cases 40 and 60. This period was from 1200UTC 24 Aug 04 to 1200UTC 1 Sep 04. This performance was above average and found in the 24, 36, and 48 hour forecast ETS. The peak of this period corresponded to the valid time of 1200UTC 28 Aug 04. The initialization for this case is examined as well as the forecasts resulting from this initialization.

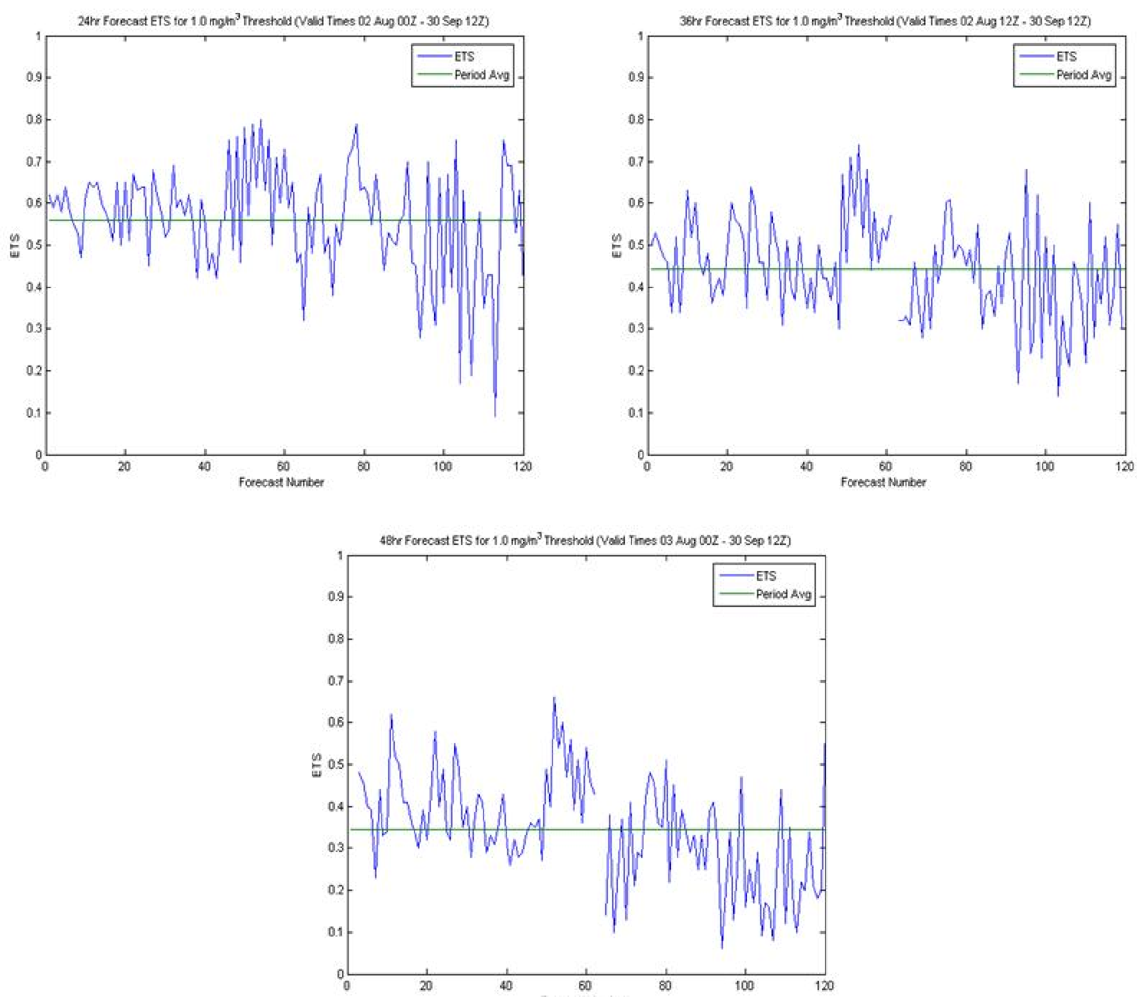

Figure 27. Graphs of ETS for 1.0 mg/m^3 threshold.

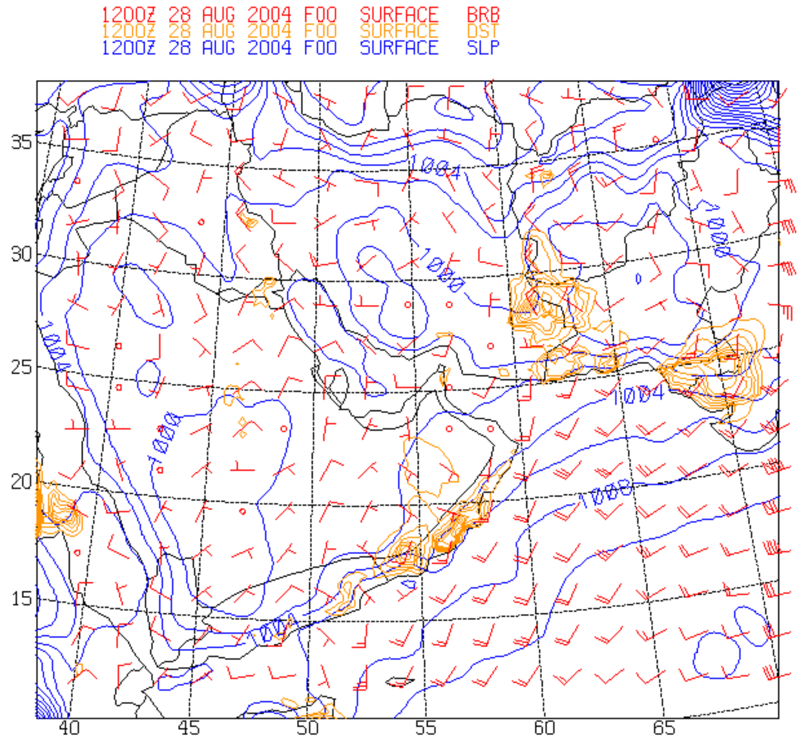

Figure 28. Surface plot for 1200UTC 28 Aug 04.

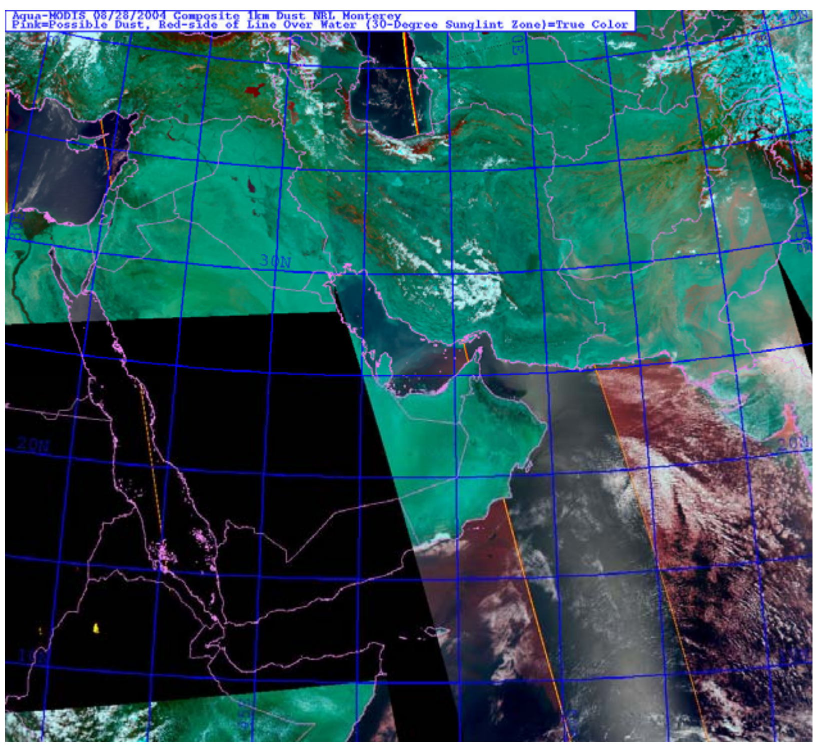

Figure 29. MODIS satellite image from 1330UTC 28 Aug 04 (From NRL, 2005).

The initialization surface plot of 1200UTC 28 Aug 04 (Figure 28) reveals three large dust plumes. The first plume is along the Iranian borders with Afghanistan and Pakistan. The second is in southern Pakistan. The last plume is once again in Oman.

Figure 29 presents a different picture of the dust coverage. Plumes are present along the Iranian border, but not to the extent as indicated by the model. Suspended dust appears to be present from southern Pakistan extending northward through most of Pakistan and into eastern Afghanistan. No plume is detected in Oman.

Observations (Table 7) support the MODIS image dust coverage. Zabol reported blowing dust and the haze in Hyderabad could be the result of suspended dust. No other locations reported dust of any kind.

Location	**Wind direction/speed**	**Visibility**	**Weather**
Zabol, Iran (31.3N 61.5E)	340/25kt	8000m	BLDU
Kandahar, Afghanistan (31.6N 65.7E)	280/14G20kt	9999m	SKC
Panjgur, Pakistan (27.0N 64.0E)	310/10kt	9999m	SKC
Hyderabad, Pakistan (25.5N 68.3E)	250/20kt	4000m	HZ

Table 7. Surface observations for 1200UTC 28 Aug 04.

Comparisons of the model, satellite image, and observations reveal the plume modeled in Oman is not confirmed. The plume along the Iranian border and the plume in southern Pakistan are verified as over-forecast.

At Hyderabad the model produced a dust concentration of 4.21mg/m^3, which should produce a much lower visibility than what is observed. It also does not appear to handle the advection of suspended dust northward into Pakistan.

The 24 hour forecast from 1200UTC 28 Aug 04 (Figure 30) continues the three previously identified dust storms. The aerial coverage of the plumes in and around Pakistan is similar. The plume in Oman is reduced in aerial coverage as well as in overall intensity.

MODIS imagery (Figure 31) indicates an intense plume generated along the Afghan and Iranian border and extending into southern Afghanistan. The suspended dust across much of Pakistan has apparently settled. No other significant plumes are detected.

Surface observations (Table 8) once again agree with satellite observations. Of note though, surface visibilities at Kandahar begin to decrease at 1300UTC in suspended dust.

Location	**Wind direction/speed**	**Visibility**	**Weather**
Zabol, Iran (31.3N 61.5E)	310/29kt	8000m	BLDU
Kandahar, Afghanistan (31.6N 65.7E)	210/08kt	9999m	SKC
Panjgur, Pakistan (27.0N 64.0E)	310/06kt	9999m	SKC
Hyderabad, Pakistan (25.5N 68.3E)	230/20kt	4000m	MSG

Table 8. Surface observations for 1200UTC 29 Aug 04.

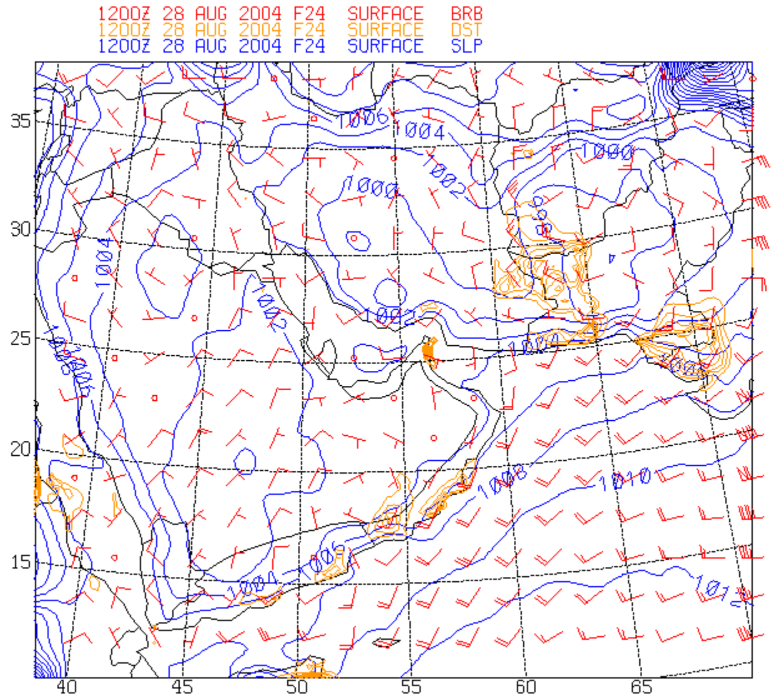

Figure 30. 24 hour surface forecast valid 1200UTC 29 Aug 04.

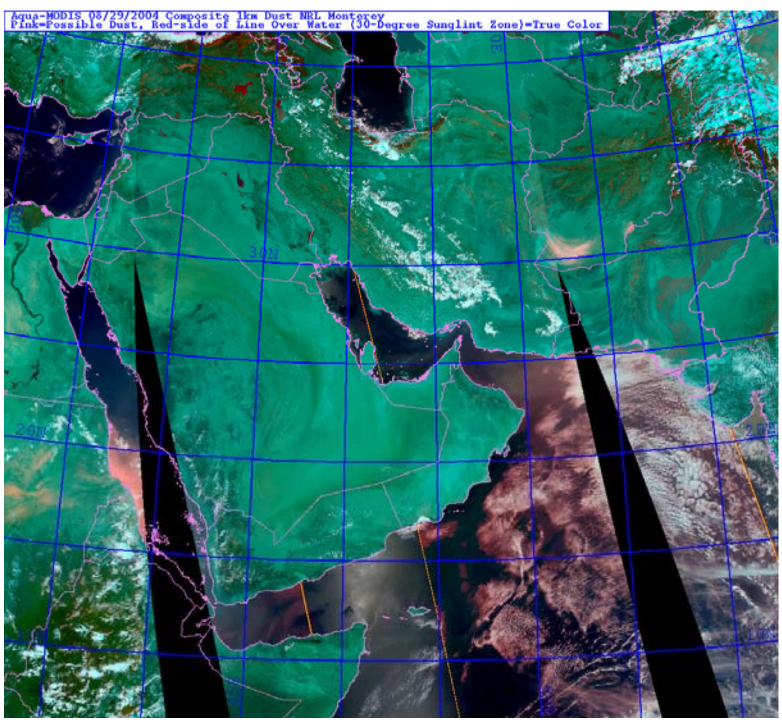

Figure 31. MODIS satellite image from 1330UTC 29 Aug 04 (From NRL, 2005)

Yet again in comparisons of observations to the model, the model is shown to have over-forecast dust concentrations. It also does not appear to have accurately advected dust. With observations decreasing in Kandahar an hour after the valid time, one would expect the edge of the dust plume to be closer to Kandahar than what it was forecast. Especially since the wind forecasts verify with respect to the surface observations.

The 36 hour forecast (Figure 32) displays a different picture of dust concentrations than the previous two images. This is a result of the feedback from the 9km grid. There is no longer any sourcing of dust along the Iranian border and in southern Pakistan. There are some plumes indicated in central Pakistan and Afghanistan.

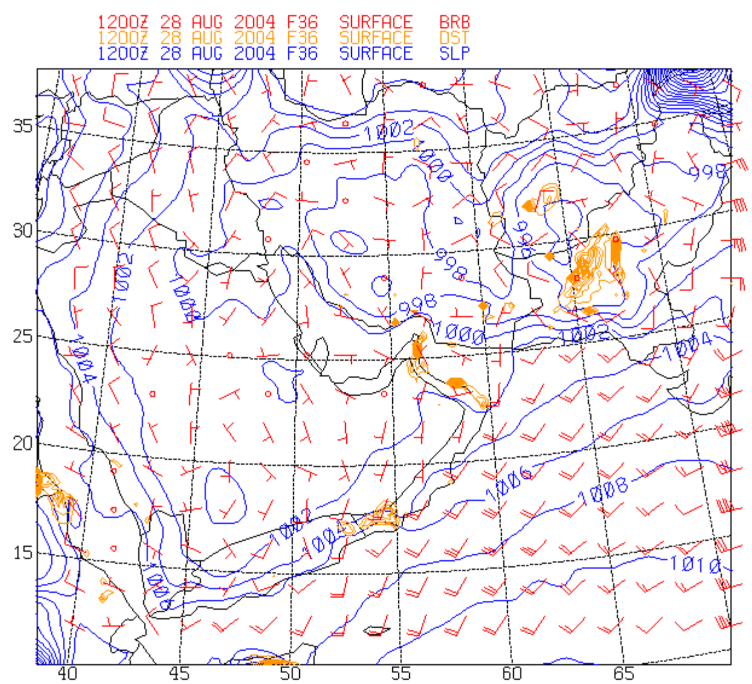

Figure 32. 36 hour surface forecast valid 0000UTC 30 Aug 04.

Location	Wind direction/speed	Visibility	Weather
Zabol, Iran (31.3N 61.5E)	340/21kt	8000m	BLDU
Kandahar, Afghanistan (31.6N 65.7E)	VRB/05kt	4800m	DU
Panjgur, Pakistan (27.0N 64.0E)	000/00kt	2000m	MSG
Hyderabad, Pakistan (25.5N 68.3E)	MSG	MSG	MSG

Table 9. Surface observations for 0000UTC 30 Aug 04.

No MODIS imagery was available for this time but surface observations (Table 9) indicate sourcing of dust is still occurring along the Iranian border as Zabol reported blowing dust. Suspended dust from this area has extended across southern Afghanistan as Kandahar reported low visibility. No observation from Hyderabad was available.

It is difficult to compare observations and the model during this time step as contamination from the 9km grid has produced a much different forecast from what was previously being forecast. The light winds forecast by the 27km grid match those observed. However, the wind forecasts in the 9km grid must be different in order to produce dust plumes as displayed. Also, it would appear that dispersion of these plumes is not accurate. Despite Kandahar having visibility reduced to around 4800m in suspended dust from 1500UTC 29 Aug 04 to 0800UTC 30 Aug 04, dust concentration at this forecast step was only 0.06 mg/m^3.

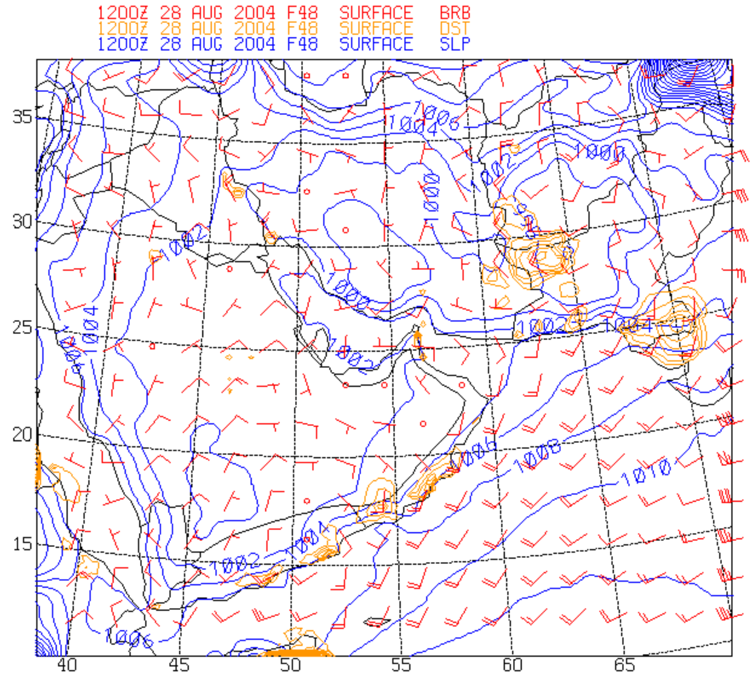

Figure 33. 48 hour surface forecast valid 1200UTC 30 Aug 04.

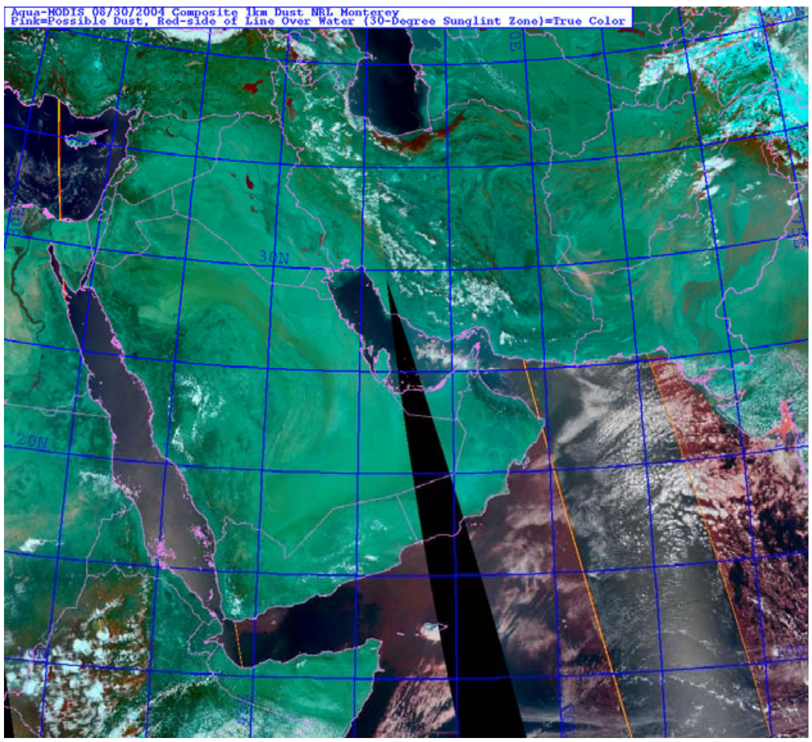

Figure 34. MODIS satellite image from 1330UTC 30 Aug 04 (From NRL, 2005)

The 48 hour forecast (Figure 33) returns to the patterns seen in the initialization and the 24 hour forecast. MODIS imagery (Figure 34) indicates a plume in southwestern Afghanistan extending into Pakistan. No other areas of dust are identifiable.

Surface observations (Table 10) support the sourcing of dust for the plume in southwestern Afghanistan. Suspended dust has settled out at Kandahar. Of note, this is the only observation of blowing dust at Hyderabad despite winds observed well above the lifting threshold and forecasts of dust concentrations from 2.67mg/m^3 to 6.10mg/m^3 over this case.

Location	**Wind direction/speed**	**Visibility**	**Weather**
Zabol, Iran (31.3N 61.5E)	330/19kt	8000m	BLDU
Kandahar, Afghanistan (31.6N 65.7E)	280/05kt	9999m	SKC
Panjgur, Pakistan (27.0N 64.0E)	310/06kt	9999m	SKC
Hyderabad, Pakistan (25.5N 68.3E)	210/32kt	4000m	BLDU

Table 10. Surface observations for 1200UTC 30 Aug 04.

Comparisons of observations and model data at this time step reveal no new information. This case underscores what was found in the previous cases. Accurate surface characteristics are key to accurate dust forecasts and the model has difficulty in the transport of suspended dust. The high ETS suggest excellent and consistent plumes but the observations tend to show less than ideal performance.

The consistent ETS but over-forecast plumes again highlight the impact that the initial dust distributions may have on the forecast. Also shown in this case is the feedback from the 9km grid can cause erroneous forecasts as illustrated by the 36 hour forecast in this case.

IV. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Overall performance of the model is encouraging. With respect to the creation of dust plumes, the model performs very well. Only a few confirmed dust events were completely missed. It does have a tendency to forecast erroneous plumes in consistent locations, those being central Saudi Arabia, the coast of Oman, and southern Pakistan.

Wind fields are generally well forecast, especially above the lifting threshold. Minor changes in the wind field speeds near the lifting threshold do indicate that these speed forecasts are important to accurate dust forecasting. This indicates that other reasons are responsible for errors in this model.

The transport and evolution of suspended dust is poorly handled by the model near the surface. On numerous occasions in this study, observations indicated suspended dust had traveled farther than the model predicted. The transport term in the dust module equation does not seem to be the culprit for these errors as dust is transported away from source areas at altitude. Reasons for this error could then be sedimentation or dry deposition occurring too quickly near the surface. This would also explain why dust plumes from the 9km grid are removed within the 27km grid once they are separated from their sources.

B. RECOMMENDATIONS

It is recommended that studies be conducted to check surface characteristics in source regions. Without a correctly identified source area, the forecasts will never improve. A second reason would be to check for inconsistencies between grid levels. As shown, when a 9km plume was transferred to the 27km grid, the plume was dissipated. Would this happen if the source characteristics were more consistent between the different grid spacings?

Another recommendation is for further research into whether sedimentation and dry deposition are occurring too quickly in the near surface layers of the model. If these processes are occurring too rapidly within the model, accurate depiction of the transport of suspended dust away from source regions will not be possible.

It is also recommended that a study be conducted to examine the impact of initial dust concentrations on the evolution of dust plumes. Model runs from cold starts (no dust present) could be compared to those of warm starts (initialized with previous dust concentration forecasts from 12 to 48 hours). If the same meteorological fields are used for all runs, plumes from different initializations should result in different forecasts. However, if all model runs converge to similar forecasts, then it becomes apparent that initial conditions matter little as the model will produce its own dust concentration patterns quickly. Also, this could further verify if the dust model has difficulty with the transport of suspended dust.

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