



Numerical
simulation of “An
American Haboob”

A. Vukovic et al.

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Numerical simulation of “An American Haboob”

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Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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**Numerical
simulation of “An
American Haboob”**

A. Vukovic et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Abstract

A dust storm of fearful proportions hit Phoenix in the early evening hours of 5 July 2011. This storm, an American haboob, was predicted hours in advance because numerical, land-atmosphere modeling, computing power and remote sensing of dust events have improved greatly over the past decade. High resolution numerical models are required for accurate simulation of the small-scales of the haboob process, with high velocity surface winds produced by strong convection and severe downbursts. Dust productive areas in this region consist mainly of agricultural fields, with soil surfaces disturbed by plowing and tracks of land in the high Sonoran desert laid barren by ongoing draught.

Model simulation of the 5 July 2011 dust storm uses the coupled atmospheric-dust model NMME-DREAM with 3.5 km horizontal resolution. A mask of the potentially dust productive regions is obtained from the land cover and the Normalized Difference Vegetation Index (NDVI) data from the Moderate Resolution Imaging Spectroradiometer (MODIS). Model results are compared with radar and other satellite-based images and surface meteorological and PM₁₀ observations. The atmospheric model successfully hindcasted the position of the front in space and time, with about 1 h late arrival in Phoenix. The dust model predicted the rapid uptake of dust and high values of dust concentration in the ensuing storm. South of Phoenix, over the closest source regions (~ 25 km), the model PM₁₀ surface dust concentration reached ~ 2500 μg m⁻³, but underestimated the values measured by the PM₁₀ stations within the city. Model results are also validated by the MODIS aerosol optical depth (AOD), employing deep blue (DB) algorithms for aerosol loadings. Model validation included Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO), equipped with the lidar instrument, to disclose the vertical structure of dust aerosols as well as aerosol subtypes. Promising results encourage further research and application of high-resolution modeling and satellite-based remote sensing to warn of approaching severe dust events and reduce risks for safety and health.

Numerical simulation of “An American Haboob”

A. Vukovic et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



1 Introduction

Particular sandstorms, called haboobs (“habb” – to blow), are very frequent events in Sudan (Sutton, 1925). The Sudan haboob appears mostly in the rainy season in the afternoon hours, followed by thunderstorms and wind speeds of 50–70 km h⁻¹, carrying dust to heights over 1000 m and dust wall diameters to 30–40 km. With the development of aviation it was possible to collect more information about these sandstorms. In his following paper, Sutton (1931) presents more data on such events. They are characterized by a sharp fall in temperature and a sudden strong wind often followed by rain. The principal cause for such events appears to be related to a current of relatively cold air undercutting warm air. Similar events have been recognized in India and Iraq. Pilots have reported great instability and convection in the region of such sandstorms. In the following decades, knowledge and theory about haboob formation, processes and characteristics have developed. Freeman (1952) has shown that the haboob can last for more than 6 h with a peak intensity lasting between 30 min to 1 h. Average haboob duration is about 3 h. These and other characteristics reported by Sutton (1931), such as fluctuation in air pressure, fall in air temperature, and rise of relative humidity are also confirmed. A decrease in the air temperature in severe cases can be as great as 15 °C, with the maximum wind speed twice the haboob’s speed of advance (Lawson, 1971). The shape of the leading edge is not one large arc, but consists of several “lobes” (Lawson, 1971). Idso et al. (1972, 1973) noticed dust storms with characteristics similar to those in Sudan appear in the arid southwestern US.

“An American haboob” is the title of a paper by Idso et al. (1972), which, for the first time, recognized a Sudanese sandstorm called haboob over American soil. Haboob is generally caused by downdrafts from thunderstorms that develop over mountain regions in southern Arizona. Thunderstorms that develop southeast of Tucson usually continue to move through the Santa Cruz Valley and arrive in Phoenix in the period 17:00–21:00 LT. Other storms, not as severe, generally arrive between 15:00 and 17:00 LT. Dust storms in most cases are followed by thunder and rain after the dust

ACPD

13, 26175–26215, 2013

Numerical simulation of “An American Haboob”

A. Vukovic et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Numerical simulation of “An American Haboob”

A. Vukovic et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

storm, within approximately 2 h. The severe dust storm appears to take the shape of a squall line, composed of multiple cells that probably contribute with its own downdraft pattern and can intensify on its path through the Valley. The leading edge can be 100 mi (~ 160 km) wide with a wall of dust reaching 8000 ft (~ 2400 m). The authors describe a classic haboob that occurred on 16 July 1971: a massive dust storm hit Phoenix in the evening hours, spawned from thunderstorms that developed over southern Arizona near Tucson. Severe downdrafts dropped near-surface temperature, raised humidity and pressure, and forced high velocity winds over the dry soil of Santa Cruz Valley, picking up dust from the dry, hot soil. Using available measurements and photographs of the event they reconstructed the shape and path of the storm. It was clear that it consisted of merged macro-lobes, which were composed of smaller micro-lobes. This was a good example describing similarities with haboobs in Sudan. Idso et al. (1972) estimated that about half of the major dust storms that occur in the southwest US are haboobs (2–3 in a year). The event that happened decades later, on 5 July 2011, the subject of this paper, had the same general characteristics.

A general lack of observations of the haboob environment prior to its formation, during its life span and after its demise inhibits full understanding of the haboob process. Hales (1975) used satellite and radar data, along with ground measurements from synoptic stations, to produce detailed explanations of a severe southwest US desert thunderstorm case. Gillette et al. (1978) presented measurements from the ground and aircraft measurements aloft, of dust particle size distribution during dust storm events over erodible sites (bare and agricultural) in Texas, Oklahoma, New Mexico and Arizona; they noticed a log-normal distribution with modes around 6 μm diameter. Dust samples collected at 1 m above the ground have a bimodal particle size distribution: 1–30 μm diameter range and 30–100 μm range. Aircraft measurements over and far from erodible areas showed a single mode 1–20 (or 30) μm . These studies found that only a small portion of the dust produced by wind erosion is carried to higher altitudes (2–9 km) over long distances. They also noticed that desert soil erodes at a lesser rate

than agricultural areas. The dust particle size distribution during the dust storm event in Texas is also described in Chen and Fryrear (2002).

Wilkerson (1991) highlighted that haboobs received considerable attention in the previous 10 yr due to several aircraft crashes related to microbursts (Fujita, 1986), a common feature generating haboobs. Because of the small scale of a microburst it is difficult to forecast. A mesoscale high-pressure area and strong winds are created from cool sinking air and heavy rain under a thunderstorm. It is common that most or all of the rain evaporates before reaching the ground because the surrounding area is very dry, cooling the air further and accelerating the downdraft. Upon meeting the ground, strong downdrafts become high-velocity horizontal wind, pushing out from the cloud downdraft region. These horizontal winds continue through the desert, picking up dust. Small solenoidal circulations are formed at the leading edge. An horizontal vortex forms within the cool air at the nose of the frontal area that faces warm air, which then contributes greatly to uptake of large amounts of dust (Fujita, 1986). The dust cloud may reach 10–14 000 ft (3000–4300 m) (Idso, 1976). Visibility falls rapidly inside the haboob (Lawson, 1971). Most dust particles within these storms are 10–50 μm (Lawson, 1971), but larger particles (several mm) are carried along also (Foster, 1969), although settling rapidly. The haboob travels fast and the air clears quickly as dust is advected out of the area.

Characteristics of the density currents, which generate dust propagation, are summarized in Solomos et al. (2012). They showed that the area of the maximum dust productivity is related to the increased turbulence (reverse flow) near the surface behind the leading edge. More information on density currents can be found in Knippertz et al. (2007), Emmel et al. (2010), Knippertz and Todd (2012).

Pauley et al. (1995) described a dust storm on 29 November 1991 that caused a pileup on Interstate 5 in California, US, involving 164 vehicles. They reported that dust uptake came from surrounding agricultural areas that were left unplanted after being plowed, before the rainy season began. Disturbing a soil surface makes it more susceptible to dust generation (Gillete et al., 1980). Pauley et al. (1995) also noted that

Numerical simulation of “An American Haboob”

A. Vukovic et al.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



in these agricultural regions dust is present often enough that the US Environmental Protection Agency (EPA) is proposing sanctions for San Joaquin Valley growers for not attending the standard for PM₁₀ (particulate matter of 10 micrometers or less). It should also be noted that drought conditions had prevailed in that area for 6 yr.

5 Numerical models for simulation/forecast of the dust cycle are generally inter- compared over the large geographic domains (Todd et al., 2008; Uno et al., 2006). These studies showed a large variability in model performance, up to one order of mag- nitude. Typical resolutions of regional dust models are several tens of kilometers, and
10 global model resolutions are ~ 100 km or coarser. It is not general practice to use dust models with higher resolutions. However, Sundram et al. (2004) describes simulations of dust storm events over central and eastern Washington using a CALMET/CALGRID model and a new dust emission module EMIT-PM, driven by MM5, on 4 km resolu- tion. Considering the complexity of the events, these experiments produced excellent results. The model performed best for large, strong dust storms, but did not simulate
15 smaller storms or dust plumes. They noted that in order to simulate individual dust events it is necessary to use high resolution dust models and to introduce agricultural areas as dust productive sources. Extensive studies over Sahara region also highlight the relevance in use of high resolution numerical models for simulation of such events (e.g. Knippertz et al., 2009; Marsham et al., 2011; Solomos et al., 2012).

20 On 5 July 2011, a dust storm having all the characteristics of an haboob formed in the area around Tucson, Arizona, and moved north toward Phoenix through the Santa Cruz Valley. High wind gusts picked up dust particles along the way, creating a high (> 5000 ft), wide (1 mile) and dense (visibility zero) wall of dust that hit Phoenix in the early evening hours. Available ground and radar measurements, National Weather
25 Service Forecast Office and news media reports, amateur photos and videos of the storm, showed that this event was much like the one described by Idso et al. (1972). All this information indicated that for successful numerical simulation of the event, the model must represent convective activity and active dust sources very well. This dust storm was created by the high surface winds generated from strong downbursts of

Numerical simulation of “An American Haboob”

A. Vukovic et al.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Numerical
simulation of “An
American Haboob”**A. Vukovic et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

cold air. High wind velocity over the bare and dry land created favorable conditions for intense dust uptake and transport. In our numerical simulation of this event we would expect to face several significant problems: definition of dust sources; ability of the model to simulate location, timing and strength of the downburst and high velocity winds; and ability of the model to produce high dust concentrations in a very short time. We used the atmospheric model NMME (Non-hydrostatic Mesoscale Model on E grid, Janjic et al., 2001) coupled with the dust model DREAM (Dust REgional Atmospheric Model, Nickovic et al., 2001; Perez et al., 2006). Model resolution was 3.5 km. The model is informed of the potential dust-productive area from the NDVI data closest to the date of the haboob under study obtained from MODIS. In forecast operations, the dust sources are refreshed for model ingestion every 16 days.

2 Phoenix dust storm on 5 July 2011

The North American Monsoon is a climatological feature over a large part of North America and of the American southwest in particular (Douglas et al., 1993; Adams and Comrie, 1997). Spring and summer warming of Mexico and the southwest US, followed by shifts of wind and atmospheric pressure patterns during summer, bring moisture into the hot dry environment from, primarily, the Gulf of California and eastern Pacific at low altitude, and upper level moisture transported by easterly winds from the Gulf of Mexico. Additional moisture may invade the arid southwest from the southern planes of the US that are usually wet and green during early summer months. Much of western North America is affected by a quickly developing, distinct rainy season due to this combination of wind pattern and moisture inflow. Dual rainfall patterns are present in the US southwest. The first one occurs from December through March; the second pattern from July through September. The summer monsoon brings surges of wet tropical air and frequent but localized violent thunderstorms, arriving in the southwest US in early July. The largest portion of the July and August precipitation over the southwestern US averages over 50 and 70 mm respectively (Hu and Feng, 2002). However, in

2011 much of the southern plains had been under long term drought and the pattern of the monsoon set up early, although inflow of deep moisture from Mexico was lacking. It became a summer of extreme heat, drought and dust storms. Records show 33 days with temperatures higher than 110°F (43°C) in Phoenix, well above the normal of 18 days (source news media reports, Vukovic et al., 2011).

The National Weather Service (NWS) Forecast Office in its report on the 5 July dust storm (<http://www.wrh.noaa.gov/psr/pns/2011/July/DustStorm.php>) provides an explanation and description of this event. The southwest US was affected badly by on-going drought. This area received less than 50% normal precipitation since the end of the previous summer, leaving the ground dry. The US Drought Monitor placed the area between Tucson and Phoenix in “moderate” to “extreme” drought category. During the North American Monsoon, dust storms are a common phenomenon across the Sonoran Desert. According to NCDC (National Climatic Data Center) Storm Data, in the past 10 yr over 100 significant dust storm events were reported across Arizona; the Phoenix area averages one to three large dust storms per year (Raman and Arellano, 2013). During the 2011 summer there were six in this region. The most severe of these occurred on 5 July. The NWS Forecast office estimated the dust reached a peak height of at least 5000 to 6000 ft (1500 to 1800 m), with an areal coverage on the leading edge stretching nearly 100 miles (160 km). The main dust cloud traveled at least 150 miles (240 km). Blowing dust reduced visibility in Phoenix to zero. At about 7 p.m. MST (02:00 UTC) the dust wall hit the far southeast part of Phoenix and moved through the city during the next two hours. The cause for this event was development of severe thunderstorms in southern Arizona that produced downburst winds, enhanced along the storm path between Tucson and Phoenix because of topography, a drop in elevation of 460 m. Strong outflow winds continued north, crossing over very dry areas. This dust storm halted traffic on roads and highways. Air traffic into and out of Phoenix Sky Harbor International Airport was stopped for 45 min. This storm is classified as an haboob. NWS/Phoenix reported the formation of the cold pool atmospheric circula-

Numerical simulation of “An American Haboob”

A. Vukovic et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Numerical simulation of “An American Haboob”

A. Vukovic et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



mass/heat/momentum exchanges over surfaces such as ocean with that of mobilized dust particle over desert surfaces (Chamberlain, 1983; Segal, 1990). This parameterizes the turbulent transfer of dust into the lowest model layer accounting for different turbulent regimes (laminar, transient and turbulent mixing), using the simulated surface dust concentration as the lower boundary. Parameterization of the wet removal is done with a parameterization method for wet deposition involving rainfall rate and washout ratio (Nickovic et al., 2001). DREAM has demonstrated its capabilities in a number of validation studies (e.g. Perez et al., 2006; Balis et al., 2006; Jiménez-Guerrero et al., 2008; Todd et al., 2008) using data from observation networks such as the European Lidar Network EARLINET and the AERONET/PHOTONS sun photometer network. The model has been validated and tested against measurements at source regions for SAMUM-I (Haustein et al., 2009) and BODEX research field campaigns (Todd et al., 2008).

DREAM provides operational dust forecasts in the SEEVCCC/RHMSS (South East European Virtual Climate Change Center, Republic Hydrometeorological Service of Serbia) as part of the World Meteorological Organization Sand and Dust Storm Warning Advisory and Assessment System (WMO SDS-WAS), and is validated on a daily basis. It and predecessor versions have been applied to the US southwest (Yin et al., 2005; Morain et al., 2007; Sprigg et al., 2008; Morain et al., 2009; Estes et al., 2009; Yin and Sprigg, 2010; Sprigg et al., 2012). Herein we report on the NMME-DREAM numerical simulation of the haboob on 5 July 2011 in Phoenix, Arizona. Model resolution was 3.5 km. Forecast start time was 12:00 UTC 5 July 2011, and forecast is done for 24 h, with output data on 1 h interval. Model has cold start, with no dust in the initial field. Initial and boundary conditions are downscaled from the ECMWF forecast data.

Specification of dust sources implies mapping of the areas that are dust productive under favorable weather conditions. The simplest approach is the application of only the land cover data (Nickovic et al., 2001; Walker et al., 2009), selecting the land cover types that are barren and arid. Another approach is to assume that dust productive regions are the ones that have long-term average of precipitation lower than

July 2011 haboob, also highlighted the importance of defining the dust sources: even simulations with the WRF-Chem on 1.8 km resolution underestimated dust concentration, because their erodibility mask at 1° resolution is too coarse to describe sources properly over this region.

Simulation of the dust storm on 5 July 2011 on high resolution using the approach from the ENPHASYS project showed that real dust sources had not all been taken into account (Vukovic et al., 2011). Land cover types that could be dust productive are presented in Fig. 1, on the left panel. Open shrubland covers most of the region and it was necessary to correct the mask with introduction of these areas. According to Tegen et al. (2002) if NDVI is less or equal to 0.1 it can be considered as barren, and that open shrubland is 30–70 % covered with vegetation. We assumed that points classified as open shrubland with NDVI 0.1 or less are 100 % dust source. Areas with NDVI values increasing from 0.11 to 0.13 decreased linearly from 70–30 % as a dust source. The MODIS NDVI values assigned to 4 July 2011 are presented in Fig. 1, middle panel. The final mask in the model simulation combined the barren land cover type as 100 % dust productive, cropland as dust productive if NDVI was less then 0.25, and open shrubland as explained above. The mask specification, obtained using MODIS data with 500 m resolution, is considered as the mask of potential dust sources, since the dust uptake further depends on the soil texture, soil moisture and near-surface atmospheric conditions. This version of the mask is used in the NMME-DREAM for the numerical simulation of the 5 July 2011 dust storm, and it is presented in Fig. 1 (right panel) after being interpolated into the model resolution. Information about the soil texture used by the model is from STATSGO-FAO soil map (US Department of Agriculture, 1994), available in 30 s resolution for USDA 12 soil texture classes. Following Tegen et al. (2002) and Shirazi (2001), clay and silt content is determined in each soil texture class in order to evaluate the amount of each particle mode in the model bins for the dust emission (Perez et al., 2006).

Numerical simulation of “An American Haboob”

A. Vukovic et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



4 Model results and discussion

Haboob dust storms are characterized in the model with the dust transport within the first 1–2 km of the lower atmosphere, implying the importance of the model surface dust concentration to describe the process. In Fig. 2 we present the NMME-DREAM PM₁₀ surface dust concentration and 10 m wind for the selected period of model simulation, i.e. 00:00–08:00 UTC 6 July 2011, over the entire model domain. The strong downdraft outburst near the southern border of Arizona, first visible at 00:00 UTC, produced strong surface wind that propagates north and west, lifting dust along the way. The downburst of cold air generated an almost radial diverging pattern in the 10 m horizontal wind. During the time period 02:00–05:00 UTC, the event reached and passed over Phoenix. On its way north-northeast, the wind lost its strength and, by the end of the model simulation, dust concentrations decreased over the Phoenix area. To discuss the dust model performance further, we must first evaluate the atmospheric model forecast.

Routine meteorological observations available for this event were widely scattered over the model domain and are insufficient to obtain shape, path and timing of the storm since they do not cover most of the area of interest. To evaluate the atmospheric model performance we use images obtained from the KIWA Phoenix radar. The focus of further discussion will be on the selected region inside the model domain that is captured by the radar (32.1–34.7° N, 110–113.5° W). KIWA operated in volume coverage pattern 11 (VCP 11), which includes 14 constant-elevation angle sweeps from 0.58 through 19.58°. The KIWA radar completes a scan in 5 min, and the range gate resolution is 1 km for reflectivity. Figure 3 presents several variables obtained from the radar, where the border of the dust storm, direction of movement and velocity are visible. The radar reflectivity factor, Z_{hh} , (Fig. 3, upper panels) shows the incoming front from the south-southeast, moving north-northwest. At 01:50 UTC, the storm front is south of Phoenix and approximately 30 km distant from the radar. At 02:45 UTC the front line is inside Phoenix, already past the radar location. Reflectivity strongly depends on par-

Numerical simulation of “An American Haboob”

A. Vukovic et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Numerical simulation of “An American Haboob”

A. Vukovic et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



ticle size and concentration. Employing Z_{hh} alone (as is done with single-polarization radars) limits microphysical interpretation because of the inherent ambiguity associated with its measurement. For instance, two radar-sampling volumes, one containing large concentration of small particles and the other a smaller concentration of large particles, can yield similar Z_{hh} values. However, polarization diversity allows this distinction to be made. This study considers co-polar correlation coefficient, ρ_{hv} , as one of polarimetric variables, observed in the Phoenix dust storm. It is not known yet whether this is a signature of all dust storms or just of the intense ones, as this is the first dust storm to be sampled by a radar with dual polarization capabilities. The co-polar correlation coefficient is a measure of the correlation between the backscattered horizontal and vertical polarized signals from each scatterer within a sampling volume. It depends on particle orientations and shapes, as well as phase compositions within the radar sampling volume. For spherical particles of any size $\rho_{hv} \equiv 1$. In pure rain at S band, ρ_{hv} does not differ significantly from unity. Observations of slight decreases in ρ_{hv} in pure rain (no lower than ~ 0.98 at S band) are attributed to randomness in orientations and oblateness diversity of raindrops. Furthermore, ρ_{hv} can decrease significantly for irregular scatterers such as hailstones with large protuberances (Balakrishnan and Zrnica, 1990), chaff (Zrnica and Ryzhkov, 2004), and debris (Ryzhkov et al., 2005); ρ_{hv} values below 0.8 indicate non-meteorological targets. Figure 3, middle panels, shows the correlation coefficient of about 0.5, which confirms the presence of dust, since only non-meteorological particles can cause such low values of ρ_{hv} . The front line that approaches from the south-southeast is moving approximately toward the radar, so the Doppler radar velocity can be considered as valid (Fig. 3, lower panels). While approaching, velocity is negative. After the storm passes the radar point velocities are positive. Radar data are used to verify position of the front, direction of the movement and velocity.

The simulated wind at the height of about 500 m is chosen to compare with the radar images because it is the approximate height the radar depicts at the selected times and locations of the front. Figure 4 displays the divergence, the magnitude and direction of

**Numerical
simulation of “An
American Haboob”**A. Vukovic et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

the wind at 02:00, 03:00 and 04:00 UTC 6 July 2011. The divergence field marks the front position. Where it is negative, there is convergence and strong upward movement. Comparing the radar (Fig. 3) and the model (Fig. 4) images, we can confirm that position and the direction of the front line is approximately good, but the model is about 1 h late. Model wind velocity is over 20 m s^{-1} , which is also visible in the radar data. The model front may be late because of blocking by the approaching cold air from the north that met the front line earlier than in reality. This would have slowed frontal movement. It may also be that the center of the haboob is shifted west in the model, and the wind energy is not strong enough to push toward the north, as it actually happened. The cause cannot be explained with certainty because of the lack of observations. Despite these differences, the model results about the front line position, direction of the movement and the velocity are considered very similar to the radar data. The atmospheric component of NMME-DREAM produced a downburst and wind energy strong enough to generate the haboob.

Performance of the atmospheric model near the surface is presented in Fig. 5. Available observations of the temperature at 2 m, dew point, surface pressure, and 10 m wind are presented on the same image at meteorological station locations. The front line is clearly visible from the model temperature field and is in good agreement with observed values. A rise in the surface pressure follows a decrease in temperature. Observed surface wind is obtained as the average value of the 10 min data. The model value is shown exactly at full hour marks. Because of large surface wind variability, and the fact that this was the time with wind gusts that are not likely to coincide in time with model calculations, it is more difficult to obtain a credible conclusion about the wind field using anemometer data than when validating against radar data. The 1 h later arrival of the front line is also visible in the surface wind. In order to simplify comparison of the model and observed data, we selected the Phoenix/Sky Harbor observation station with measurements on the every hour during the entire event. In Fig. 6 observed values are presented for the 2 m temperature, relative humidity (calculated from the 2 m temperature and dew point) and surface pressure against the model data. It is obvious

Numerical simulation of “An American Haboob”

A. Vukovic et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



that temperature in the model initial field at this location is 5 °C colder than observed values, which led to the large difference in the values of relative humidity. Despite this difference at the initial moment of the model simulation, the model corrected these values after several hours. Change in surface variables, large decrease in temperature (over 10 °C during one hour), increase in the humidity and change in the surface pressure, are well represented by the model during the event. After the storm, temperature stopped decreasing, but the model-simulated temperatures were lower than observed. This may be the influence of concrete urban areas that accumulated heat during the day, or it may be due to the difference between model and reality in the position of the cold air from the north when it meets the frontal line.

Atmospheric model evaluation showed that weather conditions that drive the dust storm are simulated very well. We can assume that meteorology in the coupled atmospheric-dust model is correct, but should expect about 1 h later arrival of the dust in the Phoenix. This means that, in further discussion about model performance, and accounting for later dust arrival in the model, we can exclude atmospheric model quality and analyze the data as the product of the dust model alone.

Vertical distribution of the dust, simulated by the model, is presented in Fig. 7. Selected cross section is along 112.2° W, where high dust concentration at near-surface levels, vertical mixing, and the front line with upward movement are noticeable. During the period 02:00–04:00 UTC formation of the dust storm and its movement toward Phoenix is visible. Height of the dust storm approximately coincides to the height evaluated by the NWS Forecast Office. Small solenoidal circulations – horizontal vortex within cool air in the frontal area (behind the front line), which is characteristic for the haboob, are also visible.

Figure 8, left panel, depicts variability of PM₁₀, and the real intensity of the dust storm. Presented here are measured values of PM₁₀ every five minutes, maximum, minimum and mean value obtained from the 11 sites in Maricopa County, but mainly located in the Phoenix metropolitan area. Highest concentrations are measured in the period 03:00–04:00 UTC, with a maximum reaching 9000 µg m⁻³. Variability in the con-

of convective dust mixing schemes (Perez et al., 2011) or different emission schemes (Sundram et al., 2004). Another source of uncertainty: the observations themselves. PM_{10} observations include particles of different origin that are not simulated in this setup of DREAM.

Another uncertainty is the definition of the mask of potentially dust productive areas. To demonstrate the sensitivity of the dust model on the definition of the dust mask, in Fig. 10 shows the model PM_{10} surface dust concentration for the model point located in Phoenix (33.4° N, 112.1° W), obtained with three different masks. The meteorology is the same in all three cases, so the timing of peaks is the same, but intensity is different. The blue line (week) is obtained from the model simulation with the mask that includes only barren and cropland land cover types. The black line (selected) is from the model simulation discussed in this paper: open shrubland area with NDVI up to 0.13 is added in the mask. The red line (strong) is obtained from the model simulation with the mask that includes open shrubland area with NDVI up to 0.15. PM_{10} increased over $200 \mu\text{g m}^{-3}$ when open shrubland was included and approximately the same amount with the strong mask. The model dust concentration in Phoenix can be increased to the level of the observed values in this way, but this can cause dust up-take over too large an area of the model domain. Dust concentration observations are needed from the source regions south of Phoenix (Pinal county), where much of this dust originates, in order to see if this is the right solution. Better calibration of the mask was not possible in this case. In the simulations, the mask selected had reproduced the shape of the dust storm. Overall, it compared well with the observational knowledge on the event. Unfortunately, the sum of observational evidence was more descriptive than quantitative.

5 Model validation using satellite observations

Based on the previous analysis, it is quite clear that the haboob event is well detected and its dynamical and physical features are examined in detail using dynamic numerical

Numerical simulation of “An American Haboob”

A. Vukovic et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Numerical
simulation of “An
American Haboob”**

A. Vukovic et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



modeling. Our research has benefitted from Earth-viewing satellite sensors and an integrative approach to dust storm simulations and forecasts. Here we present satellite evidence for the occurrence and development of the event under investigation. Satellite remote sensing is expedient in monitoring various aspects of dust storms in both space and time (e.g., King et al., 1999; El-Askary et al., 2003, 2004, 2006; Shao and Dong, 2006; Li et al., 2007; Xu et al., 2011). During this haboob, synergistic methods are applied to detect and monitor the event for model validation using multi-temporal and/or multi-sensor approaches. These approaches have been applied to detect and monitor sand and dust storms in various regions including the Nile delta (El-Askary et al., 2003, 2009; Prasad et al., 2010; Marey et al., 2010, 2011) and the Indo-Gangetic basin (El-Askary et al., 2006; Prasad et al., 2006; Prasad and Singh, 2007). In this work we used the Aerosol Optical Depth (AOD), which is a measure of the opaqueness of air, using the retrieval algorithm known as Deep Blue (DB). It is applied over bright surfaces such as deserts and other arid land surfaces by incorporating two blue channels (0.412 and 0.470 μm), with uncertainties reported to be around 25–30% (Hsu et al., 2004, 2006). High values indicate poor visibility. Ginoux et al. (2010) were able to identify anthropogenic and natural dust sources using the MODIS DB algorithm along with land use data. Figure 11e shows high agreement with the PM_{10} model simulation (Fig. 2).

We also used CALIPSO, which is a Franco-American mission that supplies a unique dataset of atmospheric vertical profiles measured by CALIOP on-board the satellite with a 30 m vertical resolution to measure aerosol and cloud properties (Winker et al., 2004). The profiles range from the surface to 40 km with a resolution of 30–60 m in the vertical and 333 m in the horizontal. CALIPSO can detect optical depths of 0.01 or less, so it can observe weak aerosol layers and thin clouds (McGill et al., 2007).

In this study, the CALIOP Level 1B data were employed, which contain calibrated and geolocated single-shot (highest resolution) lidar profiles. Nighttime CALIOP profiles are generally better as they depict dust storms more accurately compared to daytime overpass data that are noisier (Labonne et al., 2007). In Fig. 11, the vertical profiles of the atmosphere up to 30 km, represented by total attenuated backscatter at 532 nm, are

Numerical simulation of “An American Haboob”

A. Vukovic et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

depending on precipitation during the previous months. The mask used in this case is obtained from latest NASA MODIS land cover and NDVI data. Verification of results showed that the atmospheric part of the model performed very well, with the front arrival at Phoenix being one hour late. Analysis of the dust model showed that the model produced a peak in dust concentration of $\sim 2500 \mu\text{g m}^{-3}$, over the closest source regions south of Phoenix. Over Phoenix, the model underestimated concentration values compared to PM_{10} measurements. The reason for this discrepancy is unclear: is it model parameterization of the dust cycle or is it the definition of the mask of potentially dust productive areas? Further analysis and possible improvements of the dust model and the sources require more measurements not yet available to the community. Better understanding of the model performance and improvement, and general conclusion on model quality require longer period of simulation, which will be focus of the future work.

Results encourage further development and use of dust models as tools for warning and for risk mitigation policy. Windblown dust and particularly haboobs can have disastrous consequences for traffic and health. Over the southwest US where dust sources are very close to populated areas and major airway and highway traffic, they significantly affect air quality and visibility.

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Numerical simulation of “An American Haboob”

A. Vukovic et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Numerical
simulation of “An
American Haboob”**

A. Vukovic et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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**Numerical
simulation of “An
American Haboob”**

A. Vukovic et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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Numerical simulation of “An American Haboob”

A. Vukovic et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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Numerical simulation of “An American Haboob”

A. Vukovic et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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Numerical simulation of “An American Haboob”

A. Vukovic et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

- Ryzhkov, A. V., Schuur, R. J., Burgess, D. W., Heinselman, P. L., Giangrande, S. E., and Zrnic, D. S.: The Joint Polarization Experiment: polarimetric rainfall measurements and hydrometeor classification, *B. Am. Meteorol. Soc.*, 86, 809–824, 2005.
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Numerical simulation of “An American Haboob”

A. Vukovic et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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Numerical simulation of “An American Haboob”

A. Vukovic et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Numerical
simulation of “An
American Haboob”

A. Vukovic et al.

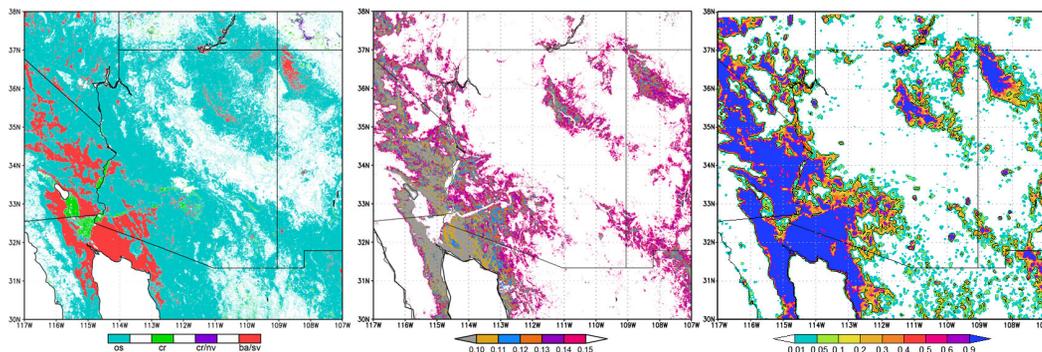


Fig. 1. MODIS land cover types (open shrubland – os, cropland – cr, cropland/native vegetation – cr/nv, barren/sparsely vegetated – ba/sv; left), NDVI (middle), mask of potentially dust productive areas on model resolution (right).

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Numerical
simulation of “An
American Haboob”

A. Vukovic et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

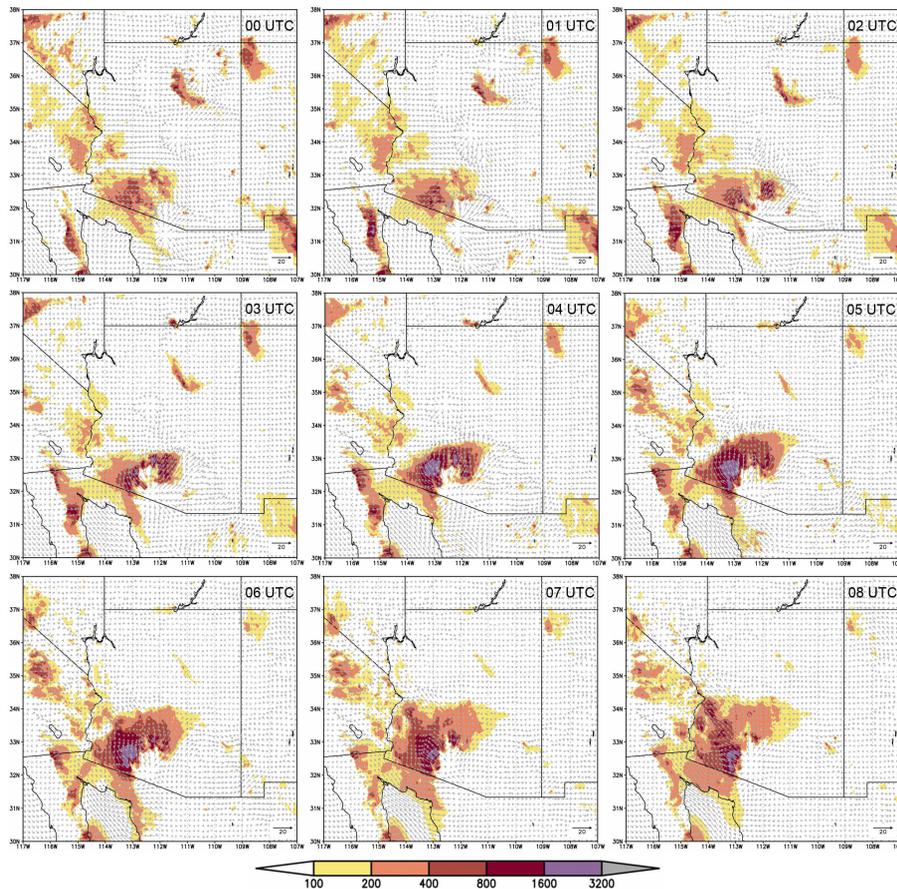


Fig. 2. NMME-DREAM PM_{10} surface dust concentration ($\mu\text{g m}^{-3}$) and wind on 10 m height (m s^{-1}), on every hour for the period 00:00–08:00 UTC 6 July 2011.

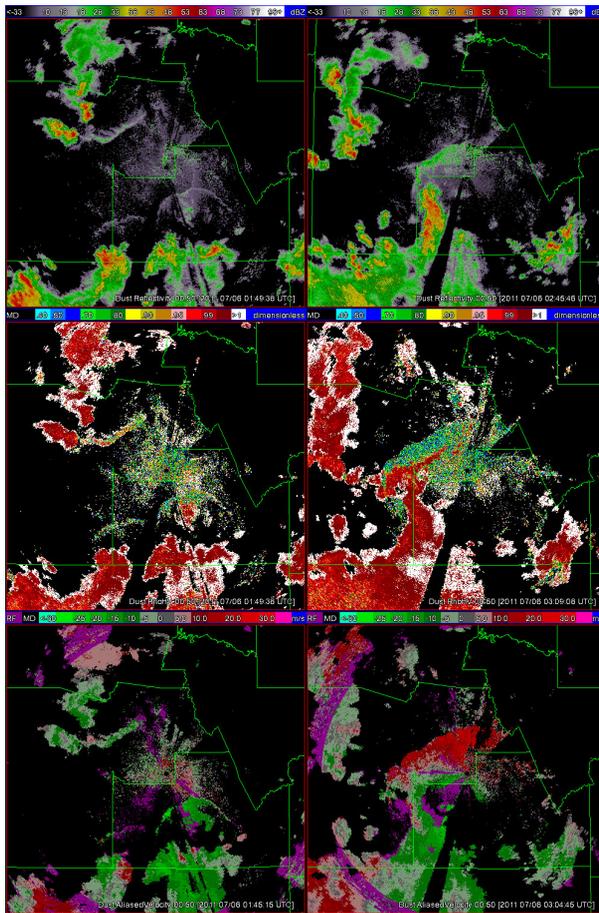


Fig. 3. Radar Z_{hh} at 01:50 UTC (upper left) and 02:46 UTC (upper right), ρ_{hv} at 01:50 UTC (middle left) and 03:09 UTC (middle right), and velocity at 01:45 UTC (lower left) and 03:05 UTC (lower right).

Numerical simulation of “An American Haboob”

A. Vukovic et al.

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
◀	▶
◀	▶
Back	Close
Full Screen / Esc	
Printer-friendly Version	
Interactive Discussion	



Numerical
simulation of “An
American Haboob”

A. Vukovic et al.

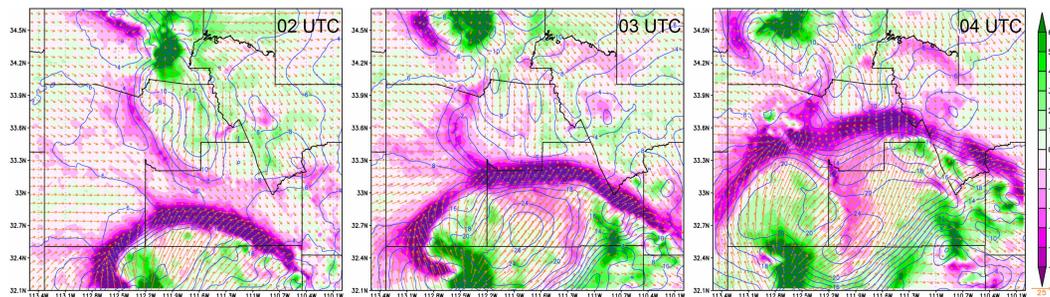


Fig. 4. NMME-DREAM wind at 11th model level (~ 500 m), divergence in 10^{-4} s^{-1} (green to purple), magnitude in m s^{-1} (blue lines), and direction (arrows) at 02:00 UTC (left), 03:00 UTC (middle), and 04:00 UTC (right) 6 July 2011.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Numerical
simulation of “An
American Haboob”

A. Vukovic et al.

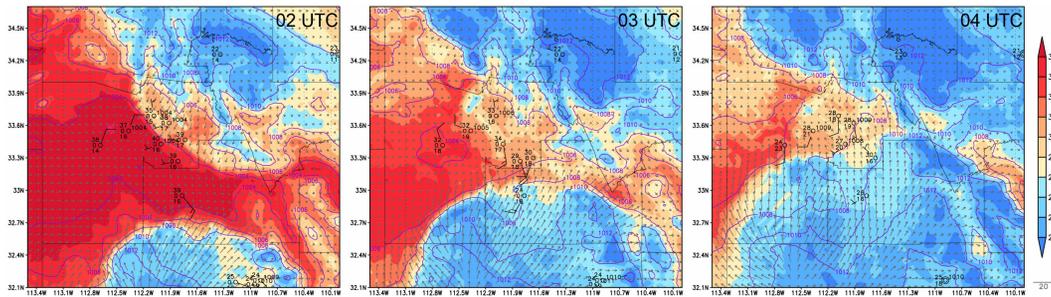


Fig. 5. NMME-DREAM 2 m temperature (blue to red), surface pressure (purple lines) and 10 m wind (arrows), and observed values at stations (2 m temperature, dew point, surface pressure and 10 m wind) at at 02:00 UTC (left), 03:00 UTC (middle), and 04:00 UTC (right) 6 July 2011.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Numerical
simulation of “An
American Haboob”

A. Vukovic et al.

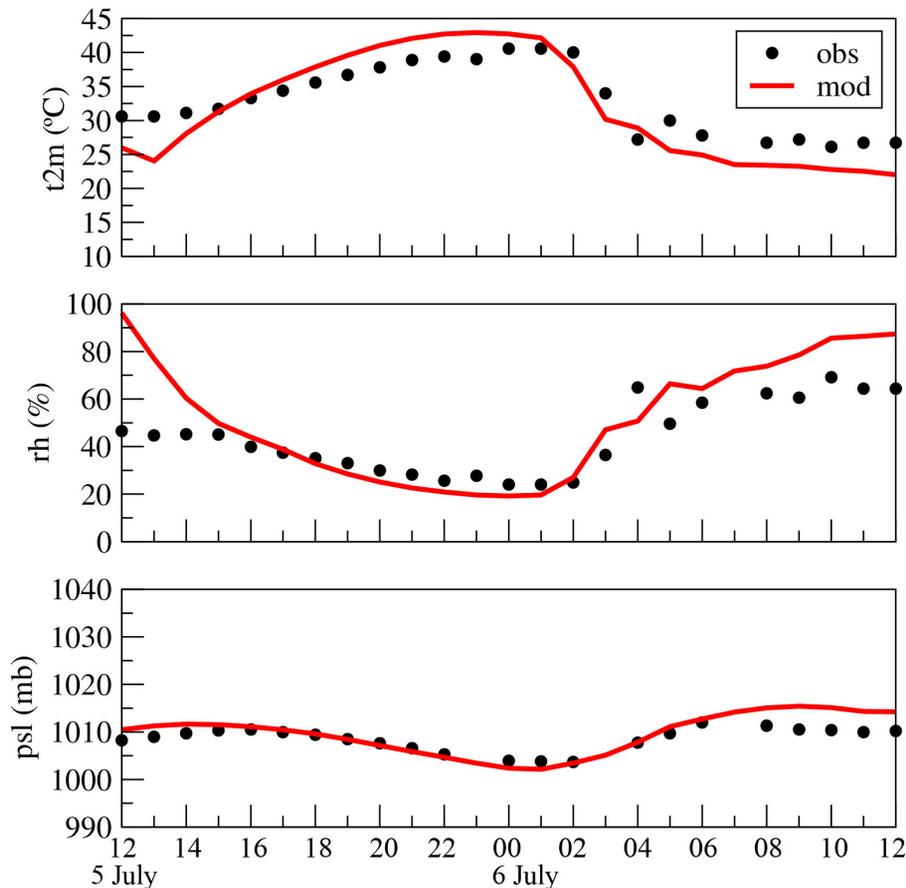


Fig. 6. NMME-DREAM and observed values at Phoenix/Sky Harbor station, 2 m temperature (upper), relative humidity (middle), and surface pressure (lower).

Numerical
simulation of “An
American Haboob”

A. Vukovic et al.

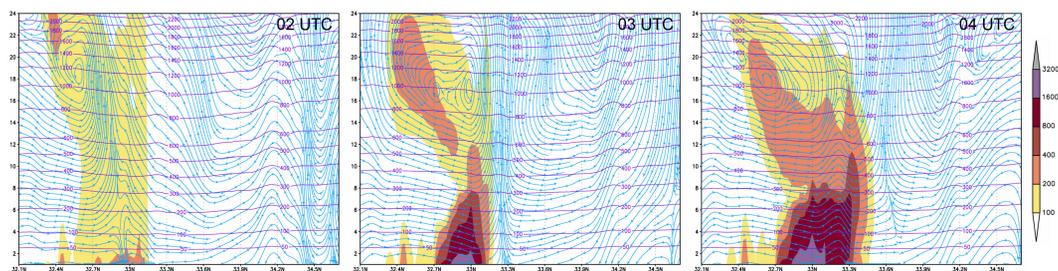


Fig. 7. NMME-DREAM vertical cross section along 112.2° W, PM_{10} dust concentration, streamlines (blue), and height of model levels (purple lines) at 02:00 UTC (left), 03:00 UTC (middle), and 04:00 UTC (right) 6 July 2011.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Numerical simulation of “An American Haboob”

A. Vukovic et al.

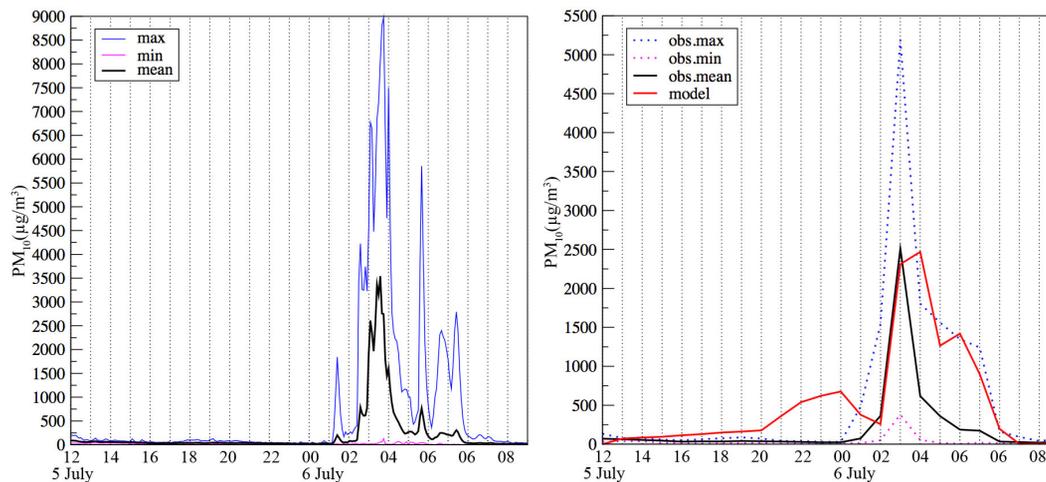


Fig. 8. Observed values of PM₁₀ on 5 min in all 11 stations in Maricopa (left), and values at full hour with model PM₁₀ surface dust concentration at selected point.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



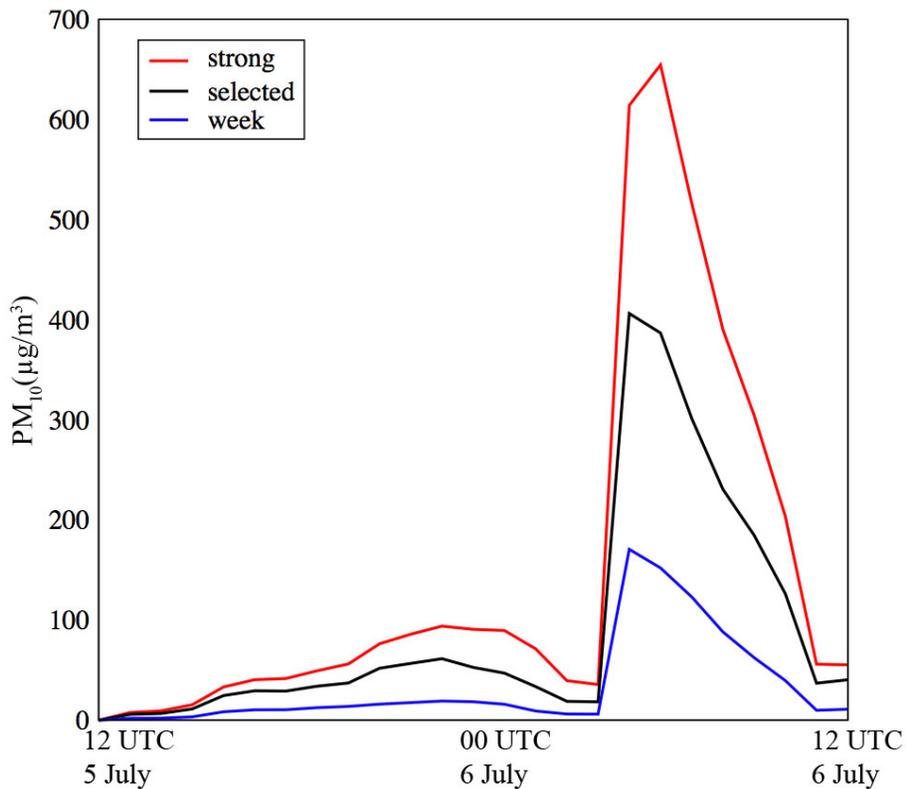


Fig. 10. NMME-DREAM PM₁₀ surface dust concentration in Phoenix for different masks of potential dust sources.

Numerical simulation of “An American Haboob”

A. Vukovic et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Numerical
simulation of “An
American Haboob”

A. Vukovic et al.

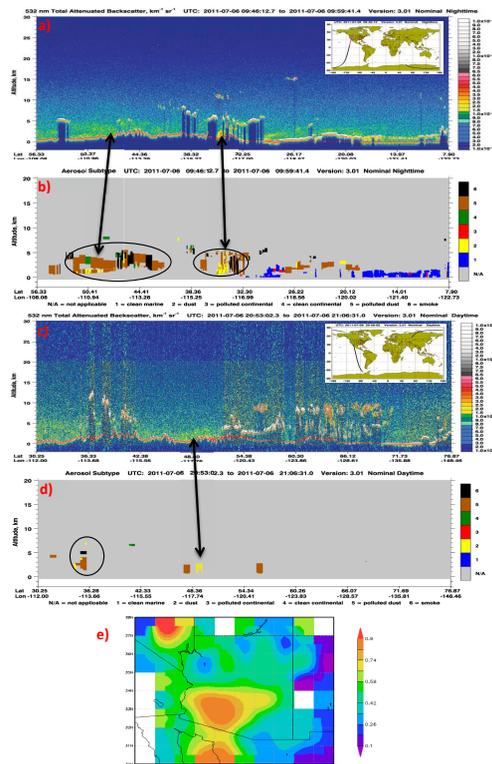


Fig. 11. Satellite observations of Haboob event 6 July 2011 showing total attenuated backscatter at 532 nm of a dust event as measured by (a) the night-time CALIPSO overpass (at 09:46 to 09:59 UTC) and (c) the day-time CALIPSO overpass (at 20:53 to 21:06 UTC) and CALIPSO Aerosol Subtype at (b) nighttime and (d) daytime. The inset map shows the path of CALIPSO overpass over the globe (black line) and the study region (magenta “night” and green “day” lines), as well as (e) Aqua MODIS aerosol optical depth (AOD) based on deep blue (DB) algorithm.