P 3.9 CHARACTERIZATION OF DUST STORMS SOURCES IN SOUTHWESTERN U.S. AND NORTHWESTERN MEXICO USING REMOTE SENSING IMAGERY

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ABSTRACT

Extreme aerosol events, such as dust storms, can produce large quantities of dust and haze dispersed over regional or global scales. Remote Sensing data (ground-based and satellite) can be used to assess the frequency and magnitude of these dust events for potential impacts on climate, visibility, and health-related air quality issues. We examine different visible and infrared spectral bands from satellite data (NOAA/GOES/GVAR/Imager, NOAA/POES/-AVHRR, and NASA/TERRA/MODIS) to locate the origin of dust plumes in the southwestern United States and northwestern Mexico, a region that currently is not well characterized with respect to dust sources. We superimpose the dust source locations on LANDSAT-7 images to identify the surface features associated with these dust sources. This methodology is applied to several dust events, including specific events associated with long-distance aerosol transport to determine whether these surface features are persistent sources of dust in this region. These findings establish a baseline for continued research in determining potential locations for future dust outbreaks in the southwestern U. S. and northwestern Mexico.

1. INTRODUCTION

Aerosols play a significant role in the Earth's climate system, affecting the radiation budget, atmospheric photochemistry, and cloud processes, among others (Grini et al., 2005). An important factor in present day changes in climate is the increased dust content of the atmosphere due to anthropogenic activities (Kondratyev, et al., 1983). Remote sensing data obtained from satellites have opened up new possibilities for studying atmospheric dust and its effect on climate. Remote sensors like TOMS, AVHRR, Landsat TM, GOES-10, SeaWiFS, and MODIS,

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are some of the platforms that obtain data used to map the sources of dust emissions.

Dust storms can typically spread over hundreds or thousands of kilometers. Dense aerosol plumes are easily observed and visualized through satellite images and surface observations, allowing monitoring of their transport and transformation (Falke, et al., 2001). Sensors are designed and deployed on different satellites to detect and monitor the large events that occur in the atmosphere. Based on the analysis of satellite images, new data have been obtained on enormous dust outbreaks in various regions of the earth, especially in regions where information cannot be obtained easily via ground-based monitoring platforms. Specific locations can be persistent sources of significant dust outbreaks on a continental and global scale.

Dust sources can usually be associated with geomorphic features, like topographical lows, located in arid regions with annual rainfall under 200-250 mm (Prospero et al., 2002). Remote sensing data can be used to monitor such surface features and their changes over time. Dust sources are often seasonal and are extremely sensitive to some environmental conditions including high wind speeds, lack of non-erodible roughness elements, low threshold wind velocity, lack of aggregation or crusting, high particle availability, and low binding energies of the suspended particles in the soil matrix (Gillette, 1999). Many major dust sources have been flooded some time during the last 2 million years and are areas where alluvial dust particles are available for erosion (Prospero et al., 2002).

Dust sources from the southwestern United States and northwestern Mexico are only recently becoming well characterized (see Figure 1). Dust from these regions has been linked to long-range continental transport, especially seasonally. Recent research in the area of West Texas and New Mexico showed that image analysis techniques could improve our understanding of the

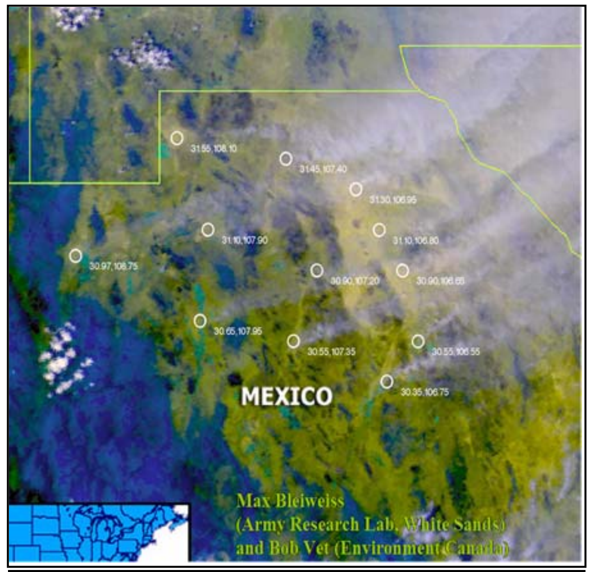

Figure1: Area of ChihuahuaMexico. White circles are the locations of some dust plumes that emanate from this region almost every year. (Image courtesy of Bob Vet (Environment Canada)).

dispersion of the dust storms in the areas mentioned above, especially during the windy seasons (i.e. winter and spring) (Gill, et al. 2000; Prospero et al., 2002). Characterizing dust sources in northwestern Mexico and the southwestern U.S. is critical because these areas have major seasonal dust outbreaks that can have continental impacts, and the land-surface features and meteorological conditions leading to these dust events are largely unstudied. We develop methodology using satellite imagery of atmospheric dust and land surface features that allows us to locate and characterize the dust sources in this area for two specific large dust events in April and December of 2003.

2. DATA AND METHODOLOGY

2.1 Satellite imagery data

Satellite imagery from GOES-10, MODIS, AVHRR (NOAA-12 and NOAA-16), and Landsat is used in this research. GOES (Geostationary Operational Environmental Satellite) satellites circle the earth in a geosynchronous orbit and are part of a network of meteorological satellites. The U. S. operates two of these systems referred as GOES-12 (East) and GOES-10 (West). They have 5 different channels with 3 different spatial resolutions of 1 km, 4 km and 8 km. MODIS (Moderate Resolution Imaging Spectroradiometer) is an instrument on board the Terra and Aqua satellites. Both look at the surface of the earth every 1 to 2 days, acquiring the data in 36 spectral bands. Two bands have a spatial resolution of 250 meters, five bands have 500 meters resolution and twenty-nine bands have 1 km of nominal resolution at Nadir. The NOAA-POES (Polar Orbiting Environmental Satellite) satellites contain the Advanced Very High Resolution Radiometer (AVHRR). It has five spectral channels of 1km spatial resolution. Landsat 7 satellite was launched by NASA to acquire remotely sensed images of the earth surface. It has a panchromatic band with 15 meters of spatial resolution, 6 bands with 30 meters and 1 band with 60 meters of spatial resolution, with a repeat coverage interval of 16 days. Table 1 provides a summary of the satellites used in this study.

The data used in this study are archived at New Mexico State University. The data sets from GOES-10, MODIS and NOAA-POES span from the period of December 2001 to present, mid 1998 to 2004, and July 1997 to present, respectively. We investigate specific events from spring and winter 2003 to develop the methodology for locating dust sources. The software used to process the data is the Environment for Visualizing Images (ENVI 4.1).

2.2 *MM5 Data*

The MM5 (NCAR/Penn State Mesoscale Model) data are used to investigate meteorological conditions. We use two data sets that span the same time period of the dust events investigated in this study. One is from April 15-16, 2003 and the other is from December 14-16, 2003. In particular, we examine wind speed data at the surface during these events.

2.3 Methodology

The methodology used in this research consists of examining difference “split-window” images for far-infrared (far-IR) channels (Gu, et al., 2003) in the various satellite images to highlight the dust plumes. The split-window product is created by differencing the 12 µm IR and 10.7 µm brightness temperatures, which highlights the absorption (and subsequent emission) of thermal radiation by the silicate particles in the dust plume. Dust plumes viewed in this manner can be difficult to separate from clouds; therefore we also incorporate different spectral bands from the various satellite data and create real color images, and false color IR images to better emphasize the dust plumes. We then estimate and obtain the location of the sources of the plumes on the images. These

Satellite	Number of Bands/Channels	Spatial Resolution	Coverage
GOES-10	5	ch1 - 1km	Three-hourly full disk coverage to 15 minute interval coverage
		ch 2, 4, 5 - 4km	
		ch 3 - 8km	
MODIS	36	two bands - 250m	1 to 2 days
		five bands - 500m	
		twenty-nine - 1km	
NOAA-AVHRR	5	1km each	daily
LANDSAT	8	Band 1-5, 7 - 30m	Every 16 days
		Band 6 - 60m	
		Band 8 - 15m	

Table 1: Summary of the satellite data used in this study.

source regions are located on the Landsat images to determine the origin of the plumes and also assess the surface type, (e.g. agriculture, playa, etc.). This methodology benefits from the availability of several platforms of satellite data (and spectral bands); however the agreement of the location from all the satellite images will depend on the differing spatial and temporal resolution of the various satellite overpasses and the temporal evolution of the storms themselves.

3. RESULTS AND DISCUSSION

Earth observation satellites record data in different spectral bands or wavelength intervals. With these spectral bands it is possible to construct different band combinations that accentuate the dust plume features. In the next section we will show different satellite data and the band combinations used to create the images. We focus on two dust events observed in April and December 2003.

3.1 *April 15, 2003 Event*

NOAA-/AVHRR – We have three data files from 18:10 and 20:23 UTC on April 15, and 00:05 UTC on April 16 2003, from the NOAA-17, 16, and 12 satellites, respectively. These data also have 5 different spectral bands. From these bands we create false color images (Figures 2-3) with an RGB (red, green, blue) combination of 1, 2, and 4 of channels 1, 2, and 4, respectively. The dust plumes are shown in a light yellow-brownish color. In the image, the bright yellow parts are clouds. Figure 2 through Figure 4 show the source locations marked with a plus sign of red color. The latitude and longitude locations of the dust sources are reported in Table 2.

Landsat – We obtained different Landsat images from the southwestern part of the U.S. and northwestern Mexico. False color images were created with a RGB combination of channels 7, 4, and 2, respectively. This band combination shows the vegetation in various green shades (band 4 has high reflectance of vegetation) and band 7 detects the hydrous minerals in geologic settings such as clays. In the image, the different green shades can be trees and bushes, crops or wetlands vegetation. The black to dark shades are water. The lavender shades are urban areas and the magenta, lavender or pale pink can be bare soils. White Sands National Monument located in New Mexico, is also present on the landsat image, as the bright aqua blue shade at the top of the image. The dust source locations that we plotted on this image were located in areas that can be classified as agricultural land and bare soil.

MM5 Data - The MM5 data were used to investigate the wind velocity and wind direction during the dust events. Wind speed was calculated from the U and V winds at the surface. These plots (showed in Figure 4) show wind speed data every two hours from the hour 13 UTC until the hour 23 UTC of April 15, 2003. The arrows and different color shades show the wind direction and wind speed, respectively. The size of the arrow represents the magnitude of the wind speed and it points the direction that the wind is blowing. The surface wind speed increased dramatically from approximately 5 m s^{-1} at 13:00 UTC to over 12 m s^{-1} at hour 17:00 UTC in the source location region. As seen in Figure 4, the wind was blowing from the southwest to the northeast during this period of time, similar to the direction of the dust plumes in the NOAA satellite images.

3.2 December 15, 2003 Event

GOES-10 – We obtained 27 data files from the hours of 15:00 to 23:45 UTC from December 15 2003, all of which contain 5 different spectral channels. We selected the file that contains the hour 17:30 because the dust plume first becomes visible at this time. We used channel 1 to identify the dust locations because they were more apparent in the visible spectral channel, and this channel has a higher spatial resolution of 1 km. The source locations of the dust plumes are marked in red in Figure 5. Table 3 reports the exact locations with their latitude and longitudes. It is clear from Figure 5 that the dust is being transported in a southeastern direction, except for the most southern dust plume which is being advected to the northeast.

MODIS – The MODIS data was obtained somewhat later than the GOES data, at 18:25 and 18:30 UTC on December 15, 2003. These data contain the 36 different spectral bands. We created a real color image with an RGB (red, green, blue) combination of channels 1, 4, and 3 respectively (Figure 6). We also performed a square root enhancement to enhance the appearance of the dust plumes. As seen in Figure 6, the dust plumes source locations are marked in light blue and the plumes have a white-beige color. The exact locations of those plumes are listed in Table 3. Similar features are noticeable in these data as compared to the GOES image, except now the most southern plumes appear to be advected due east.

NOAA-16/AVHRR – We have two AVHRR data files from 19:51 and 21:31 UTC, December 15 2003. Both files have 5 different spectral bands. From these bands we create a false color image (Figure 7) with an RGB combination of channels 1, 2, and 4 respectively, to better enhance the appearance of the dust plumes. The dust plumes are shown in a yellow-brownish color. In the image, the bright yellow parts are clouds. Figure 7 shows the source locations marked in white. Table 4 shows the latitude and longitude locations of the dust sources.

LANDSAT – We used the same Landsat image that was explained above, but in that image now we plotted the dust source locations of the December 15, 2003 event. The different colors in the image represent the same surface features that were explained previously; green shades can be trees, black areas are water, etc. In this image with the dust source locations of December we observed that the sources were located more northerly in the border region than the ones from the April event. We determined that the dust sources for that event are located in an area that can be classified as bare soil.

MM5 Plots - Surface wind speed data from the December dust event are presented in Figure 8 (every 2 hours from hour 15 UTC to hour 23 UTC). It is clear from these figures that the wind speed increased from approximately 5 m s^{-1} at 15:00 UTC on December 15 in the source region; to over 12 m s^{-1} when the dust event was first detected in the GOES satellite images (~17:00 UTC). These high surface wind speeds continued through 23:00 UTC on December 15, 2003. The wind direction during these times is consistent with the direction of the plumes in the satellite imagery.

4. SUMMARY AND FUTURE WORK

4.1 *Summary*

We successfully developed a technique to identify the source locations of specific dust storm events using remote sensing imagery. This method located dust plumes sources that were consistent from a variety of satellite platforms. After plotting the source locations of both 2003 events together, we observed that the April event occurred further south than the December event. This difference leads to the question, what features can change over a short period of time that cause changes in dust emissions? We know that the overall geology is not a factor to be considered in this case because it is not going to change in a short period of time. The differences in the locations may have to do with meteorological factors (e.g. position and development of storm or weather systems during the different seasons). Variations in surface features (e.g. vegetation type or soil moisture) during different seasons could also be a factor. For example in the spring, there may be vegetation on the surface in some places, which protects the soil from wind erosion, but perhaps in December the bare sediment is exposed to the wind and is available for lofting. Other factors may also play a role and will be the focus of future investigations.

By examining the source locations plotted on a Landsat image, we identified some surface features that were consistent with typical dust source types (e.g. bare soil, agricultural areas). The source locations of the April event on the Landsat image are located in pale pink areas and others near green areas, where the sources areas are catalogued as bare soil or areas near crops. The December event locations also on the Landsat image are located in the pale pink area also catalogued as bare soil. Results from this study suggest that the source regions in the April and December events are of similar surface type, however, further investigations into the surface features defined in the Landsat images are ongoing.

We know that dust storms are environmental hazards that cause air quality and visibility problems across the southwestern part of the United States. Defining the position of these dust sources is very important because it provides our colleagues with the precise locations at which they can take samples of the soil to study the dust composition, characteristics and emissions in this relatively unstudied region. With that information we can better track the dust transport out of the source region. Also, investigating the meteorological conditions and land surface types associated with these seasonal and annual events provides information that can further our understanding of extreme dust events around the world.

The method developed here to locate the dust sources does have some uncertainties. Differences in temporal and spatial resolution of the satellite imagery used to pinpoint the source locations can cause some discrepancy in the locations, as shown in Figures 9 and 10. The inclusion of as many satellite images (and spectral bands) from different platforms as available will help to narrow down the locations. For example, we see much better agreement in source location for the December event (with the added MODIS and GOES imagery) compared to the April event. Another uncertainty with this method is that clouds may be misidentied as dust plumes, however, the persistence of dust plumes over several hours during a dust storm (as shown in this work) mitigates this problem. Smoke plumes may also be misidentified as dust plumes; however using the split-window technique reduces this possibility since smoke plumes do not appear in them.

4.2 *Future Work*

We will apply this methodology to other dust events to determine the persistence of the sources in this region. We will then characterize the dust composition by using ground-based data from the IMPROVE network (Malm et al., 1994) and dust optical properties from ground-based remote sensing networks such as AERONET (Holben et al., 2001) and the UVB network (Goering et al., 2005). The environmental and meteorological conditions that lead to the initiation of these dust events will be examined using meteorological data and MM5 analyses. The long-range transport of the dust across the U. S. will also be investigated.

5. ACKNOWLEDGEMENTS

N. Rivera wishes to thank the SOARS Program Staff and Protégés for their assistance while in residence as a SOARS Protégé. This project is supported in part by the US Environmental Protection Agency through grants provided by the Southwest Center for Environmental Research and Policy (SCERP).

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NOAA-12/AVHRR April 16 05:00 UTC		NOAA-16/AVHRR April 15 20:23 UTC		NOAA-17/AVHRR April 15 18:10 UTC	
Latitude (deg. N)	Longitude (deg. W)	Latitude (deg. N)	Longitude (deg. W)	Latitude (deg. N)	Longitude (deg. W)
31.5582	-107.6562	30.3420	-106.7850	29.3348	-106.8108
31.4541	-107.3923	30.5108	-107.3672	30.3542	-106.7323
32.7840	-106.1515	30.6450	-107.8420	30.2787	-107.2867
30.9539	-107.3179	30.8894	-108.2063	30.5294	-107.2903
32.2692	-107.5226	30.9619	-108.6596	30.4045	-107.7224
		31.5762	-107.8936	30.7389	-107.7494
		32.1089	-107.4960	31.0299	-107.9242
		32.7679	-106.2304	31.1930	-107.9936
				31.4421	-107.9856

Table 2: Dust storm source locations (latitude, longitudes) from the NOAA-12, 16, and 17 satellites images April 15-16, 2003.

GOES-10 December 15 17:30 UTC		MODIS December 15 18:25 UTC		MODIS December 15 18:30 UTC	
Latitude (deg. N)	Longitude (deg. W)	Latitude (deg. N)	Longitude (deg. W)	Latitude (deg. N)	Longitude (deg. W)
32.787	-106.212	32.986	-106.148	32.897	-106.152
31.871	-107.527	32.905	-106.160	32.854	-106.159
31.759	-107.605	32.757	-106.228	32.731	-106.225
31.618	-107.465	31.963	-106.637	31.565	-107.583
31.541	-107.581	31.977	-107.492	31.643	-107.451
29.424	-107.905	31.872	-107.582	31.709	-107.432
31.470	-105.010	31.743	-107.584	31.801	-107.388
		31.562	-107.616	31.745	-107.253
		31.555	-107.634	29.386	-107.774
		31.392	-107.430	31.893	-105.024
		29.361	-107.803	31.824	-104.968

Table 3: Dust storm source locations (latitude, longitudes) from the GOES-10 and MODIS images December 15, 2003.

NOAA-16/AVHRR December 15 19:51 UTC		**NOAA-16/AVHRR December 15 21: 31 UTC**	
Latitude (deg. N)	Longitude (deg. W)	Latitude (deg. N)	Longitude (deg. W)
32.778	-106.357	32.770	-106.185
31.900	-105.226	31.977	-106.019
31.898	-105.105	32.167	-107.133
31.978	-107.535	32.036	-107.357
31.738	-107.572	31.998	-107.439
31.568	-107.721	31.901	-107.421
		31.702	-107.351
		31.542	-107.513
		31.572	-107.261
		29.372	-106.436

Table 4: Dust storm source locations (latitude, longitudes) from the NOAA-16 satellite image December 15-16, 2003.

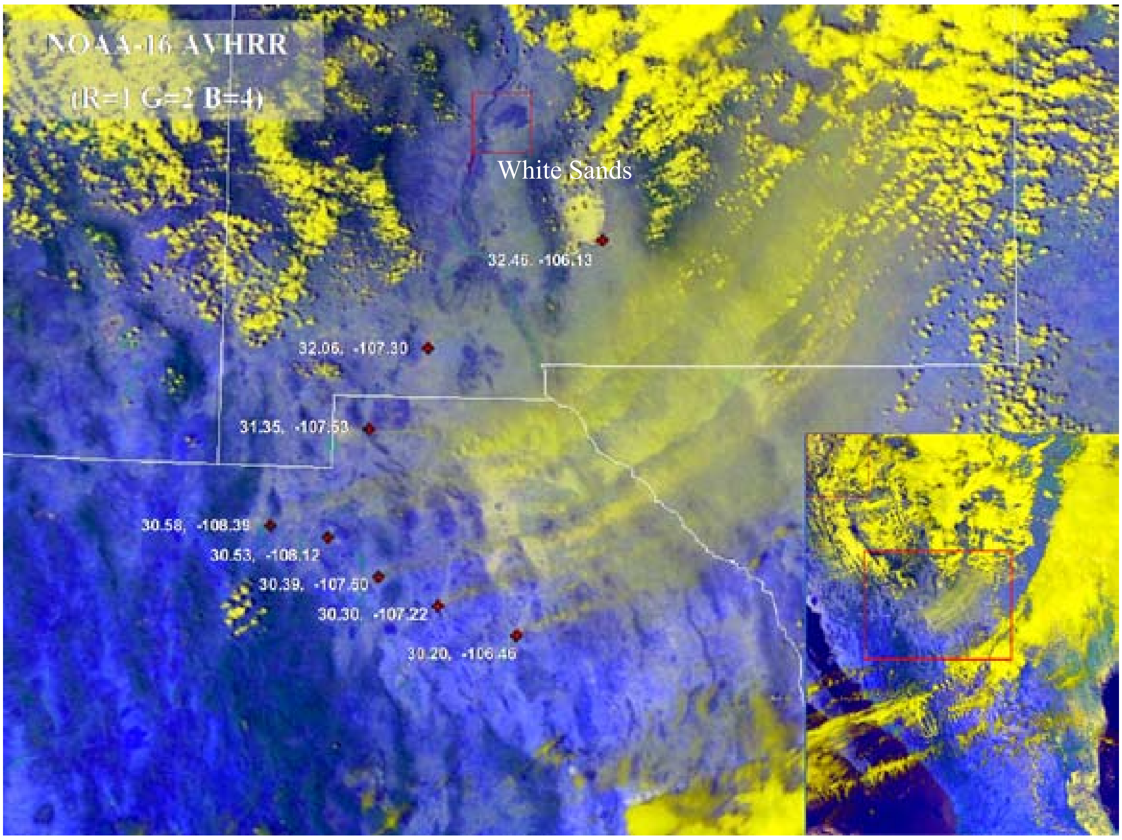

Figure 2: NOAA-16/AVHRR image on 20:23 UTC April 16, 2003. RGB combination of channels 1, 2, and 4 respectively. Dust source locations marked in red.

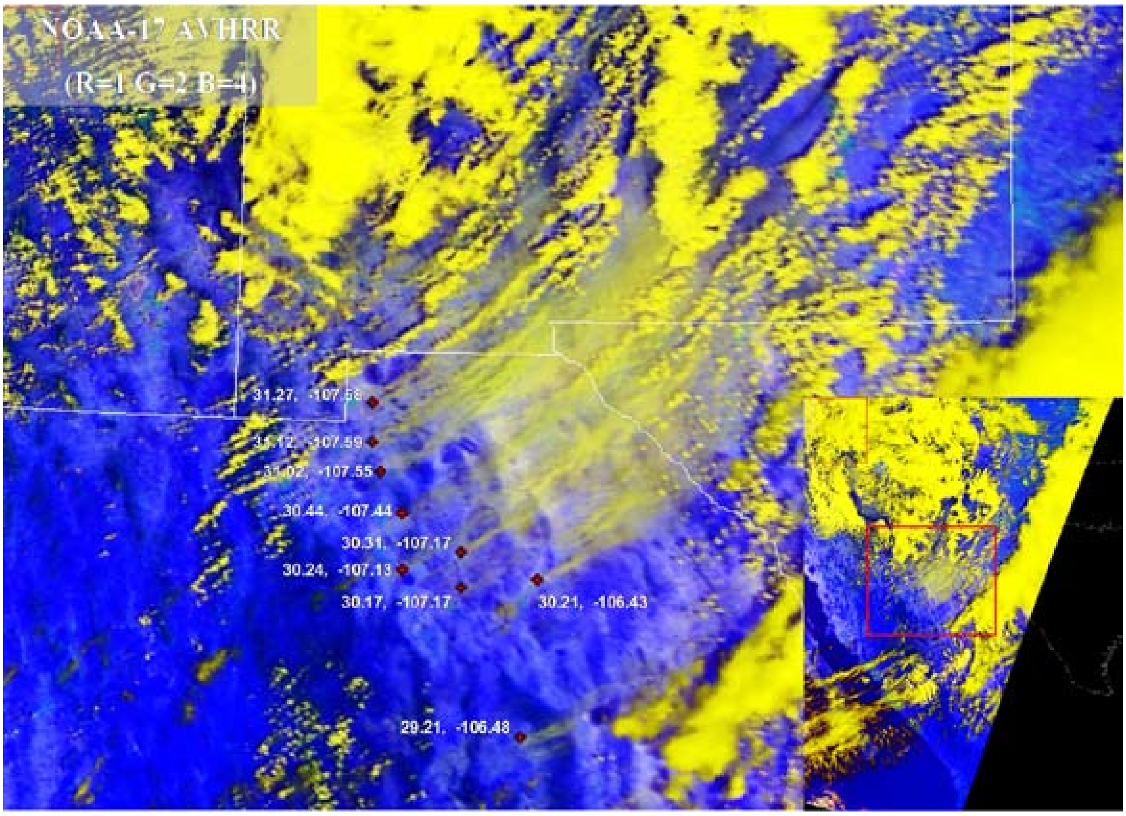

Figure 3: NOAA-17/AVHRR image on 18:10 UTC April 16, 2003. RGB combination for channels 1, 2, and 4 respectively. Dust source locations marked in red.

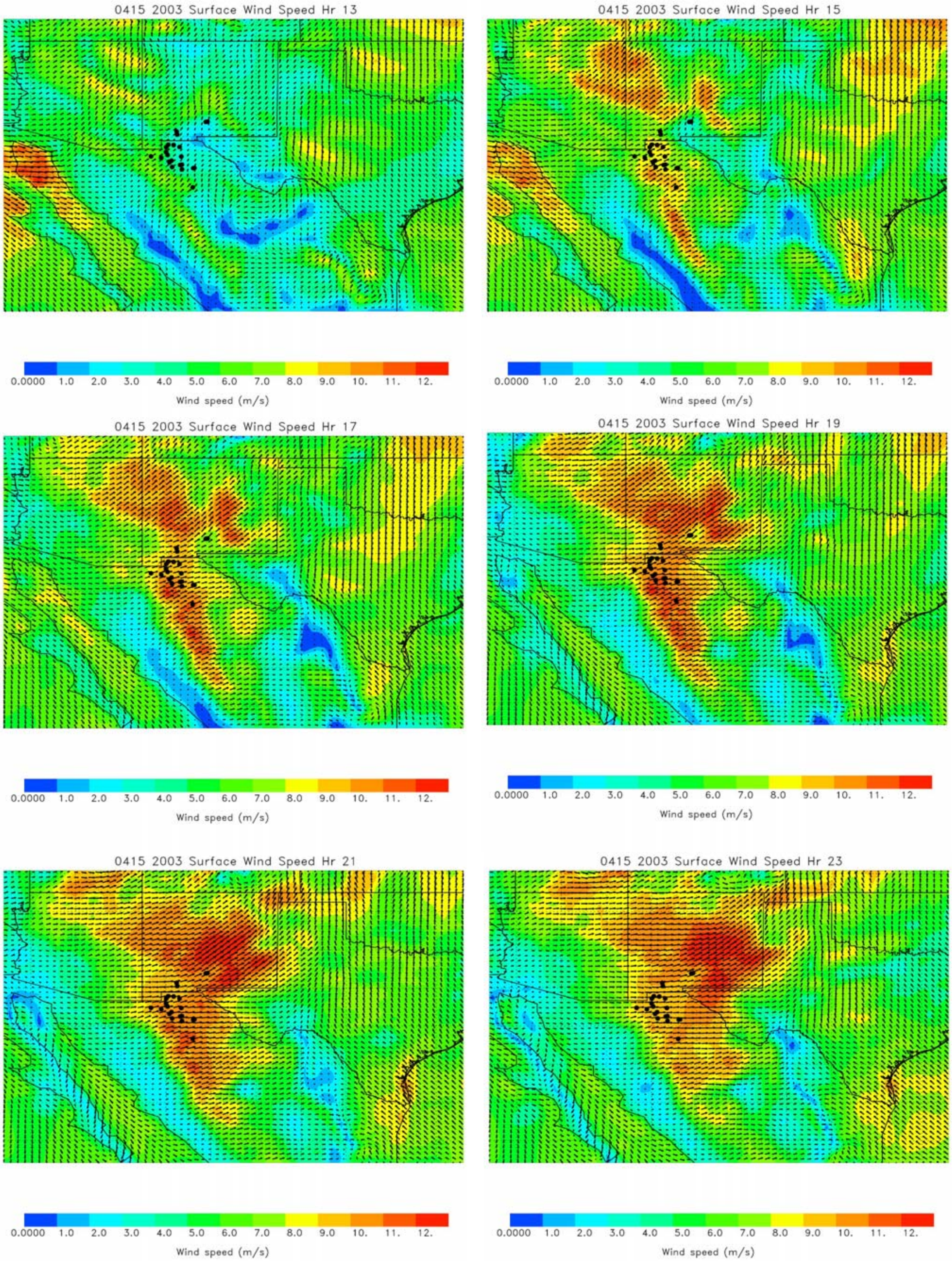

Figure 4: MM5 surface winds (m/s) over southwestern United States and northern Mexico from April 15, 2003. Black dots represent the dust source locations.

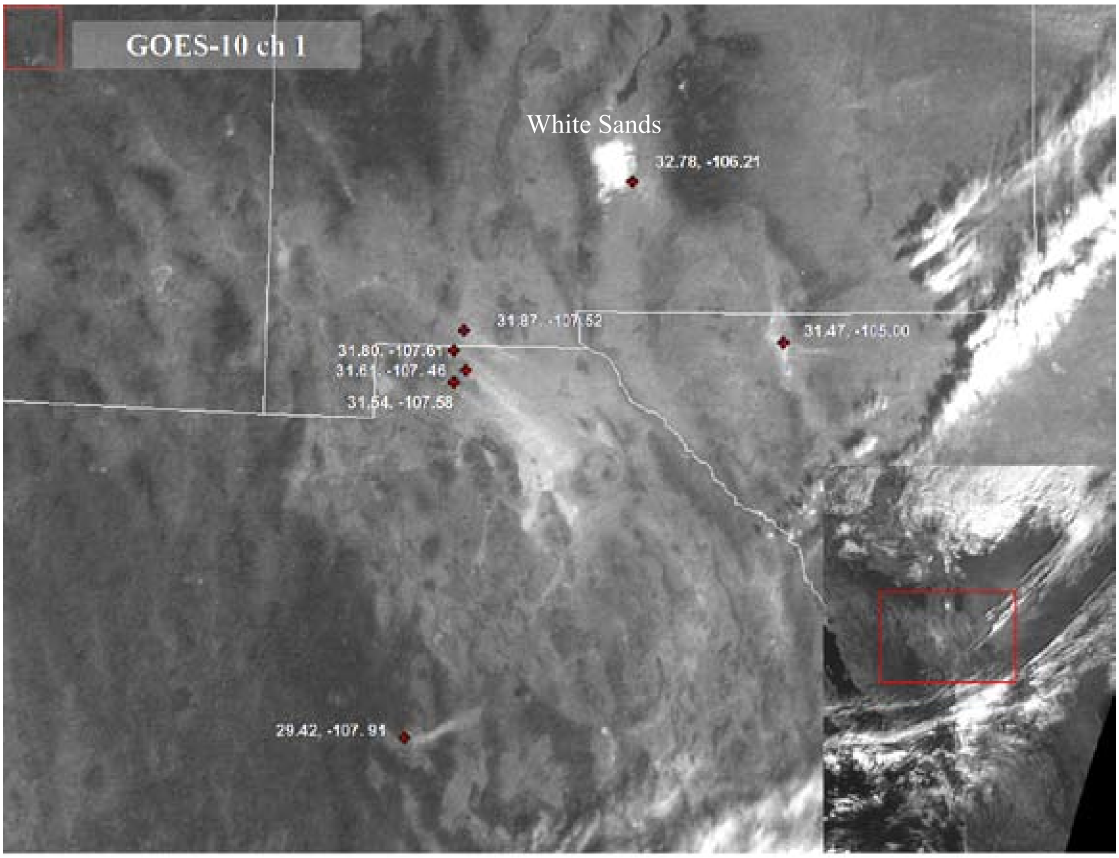

Figure 5: GOES-10, Channel 1 image, 17:30 UTC December 15, 2003. Dust source locations are marked in red.

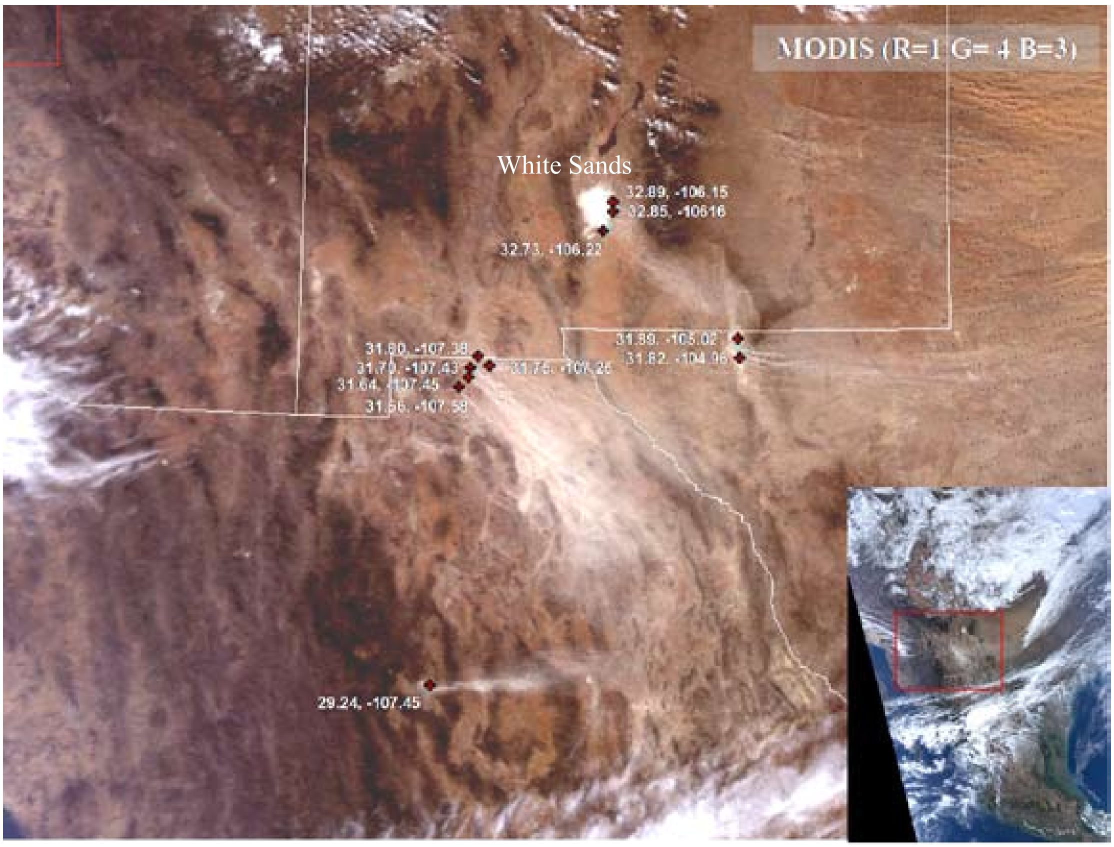

Figure 6: Real color MODIS image from the 18:25 UTC December 15, 2003. The source locations of the plumes are marked in red.

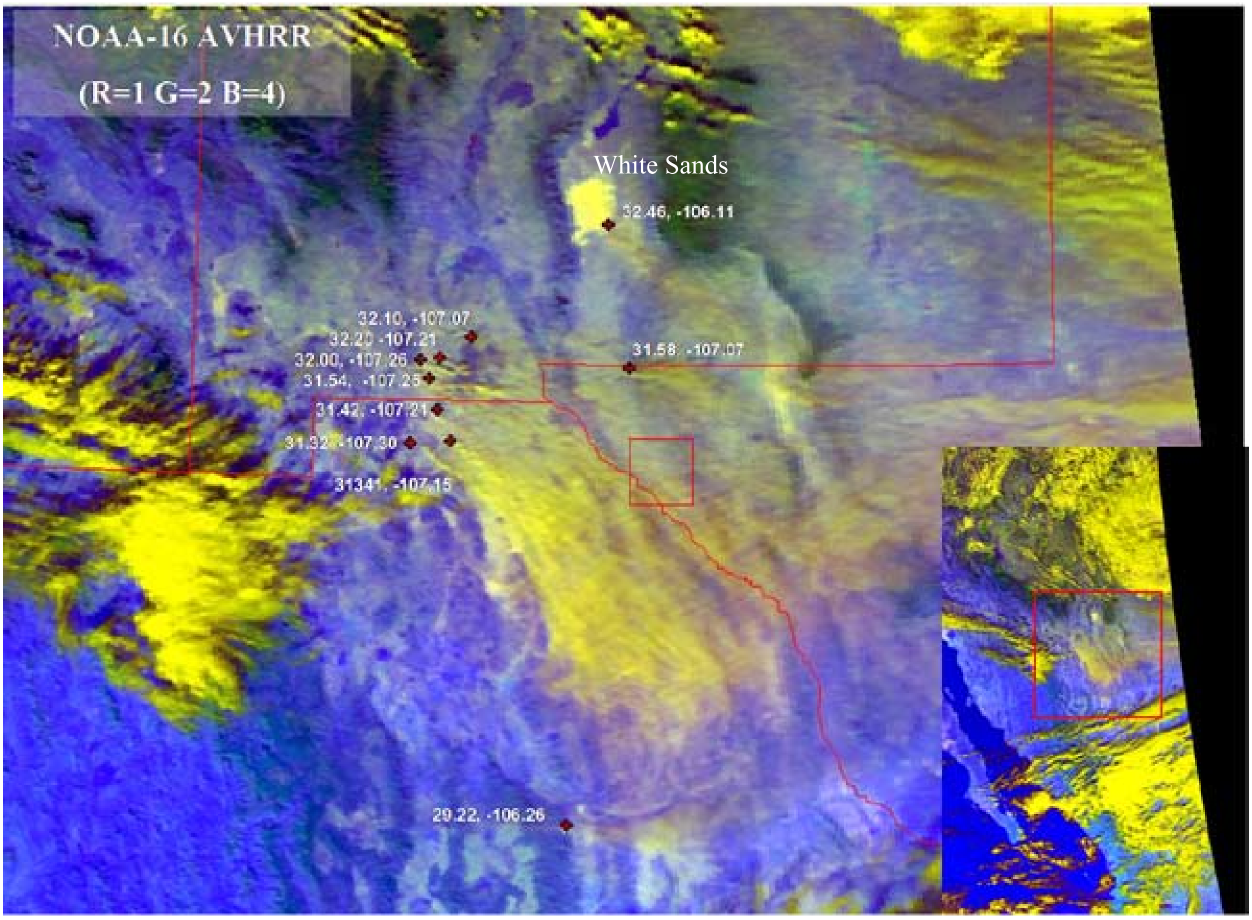

Figure 7: NOAA-16/AVHRR image on 21:34 UTC December 15, 2003. RGB combination of channels 1, 2, and 4, respectively. Dust source locations marked in red.

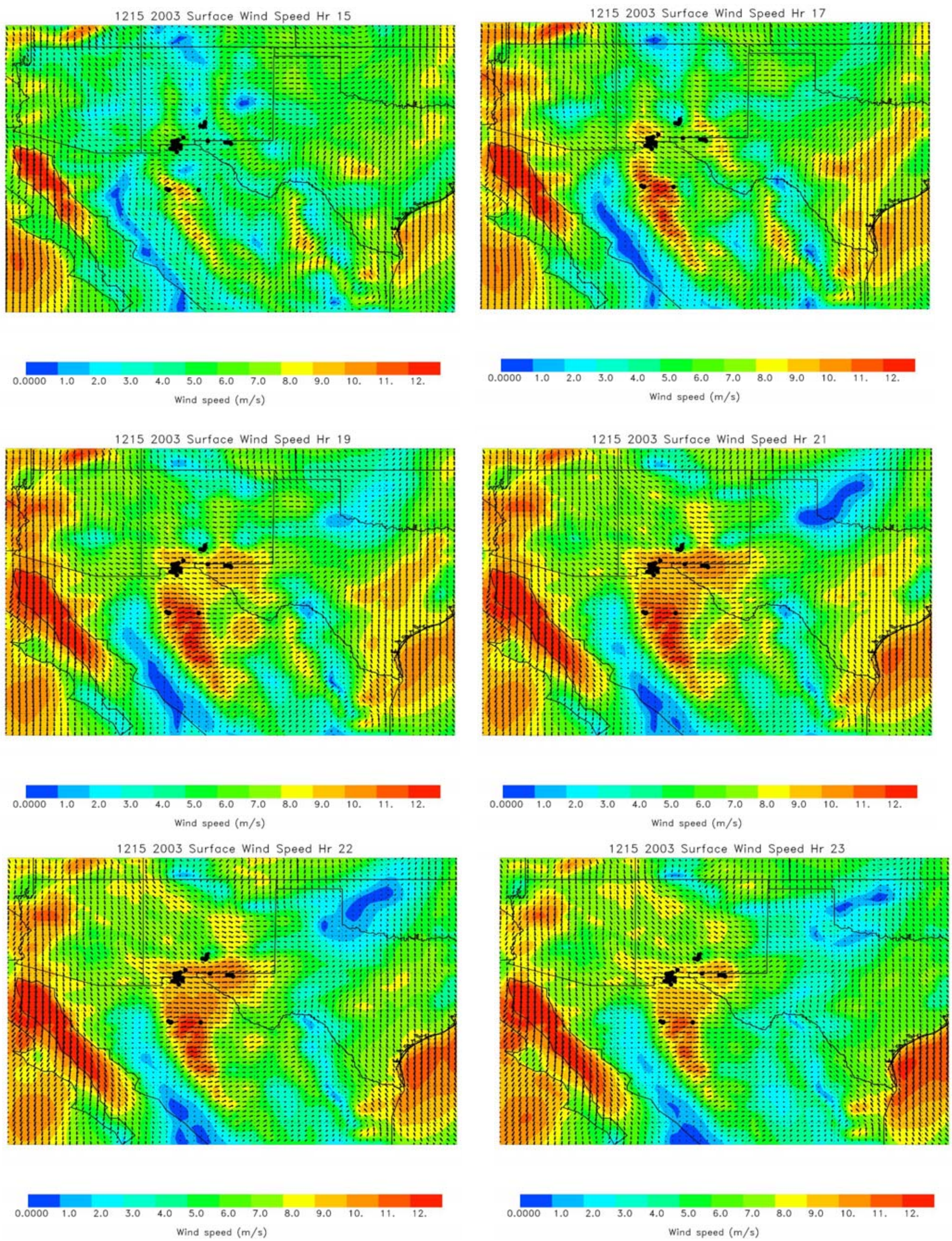

Figure 8: MM5 surface winds (m/s) over southwestern United States and northern Mexico from December 15, 2003. Black dots represent the dust source locations.

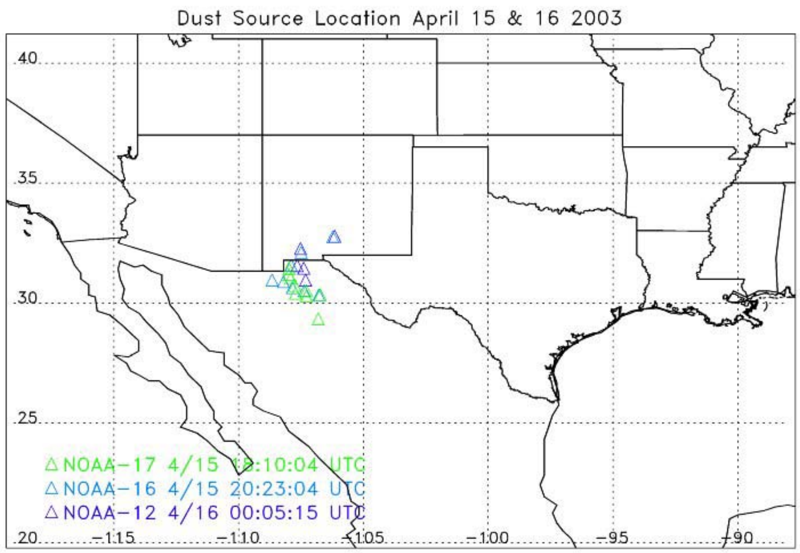

Figure 9: Source locations from the different satellites on April 15-16, 2003

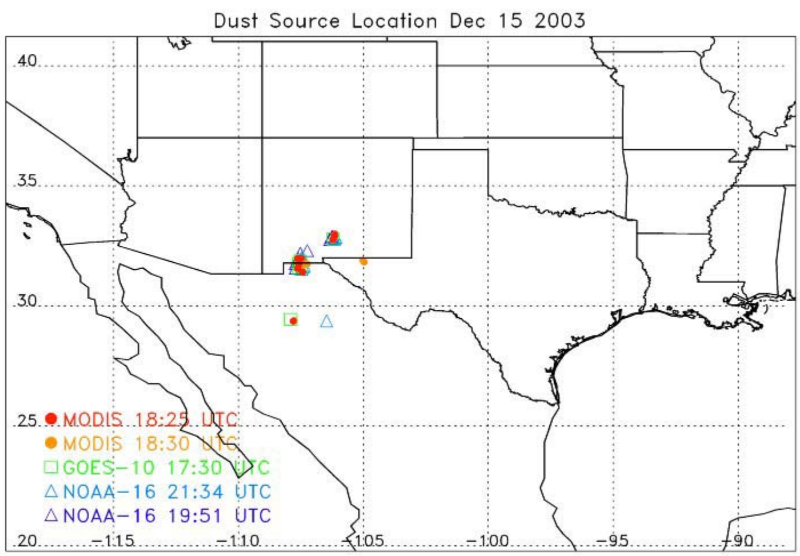

Figure 10: Source locations from the different satellites on December15, 2003