TEXAS COMMISSION ON ENVIRONMENTAL QUALITY

Houston 2010 $PM_{2.5}$ Exceptional Events Demonstration

For $PM_{2.5}$ Exceptional Events at the Houston Clinton Monitoring Site

5/22/2013

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Introduction

Exceptional events are unusual or naturally occurring events that affect air quality and are not reasonably controllable or preventable. An event may also be caused by human activity that is unlikely to recur at a particular location. Under Section 319 of the Federal Clean Air Act (FCAA), states are responsible for identifying air quality monitoring data affected by an exceptional event and requesting EPA to exclude the data from consideration when determining whether an area is in attainment or nonattainment of a National Ambient Air Quality Standard (NAAQS). EPA has promulgated an exceptional event rule, 40 Code of Federal Regulations § 50.14, and guidance to implement the requirements of the FCAA regarding exceptional events. States are required to identify air quality monitoring data potentially affected by exceptional events by "flagging" the data submitted into the EPA air quality system (AQS) database for air quality monitoring data. If EPA concurs with this demonstration, the flagged data will not be eligible for consideration when making attainment or nonattainment determinations.

This document discusses the Texas Commission on Environmental Quality's (TCEQ) proposed exceptional event flags for particulate matter of 2.5 micrometers or less in aerodynamic diameter ($PM_{2.5}$) data collected at the Houston Clinton site on June 9, June 10, and July 13, 2010. This document will be posted on the main TCEQ web page beginning on May 22, 2013 for a 30-day public comment period. All comments received will be submitted to EPA for consideration. With this demonstration, TCEQ is providing detailed evidence to support concurrence by the U.S. Environmental Protection Agency (EPA) for the $PM_{2.5}$ exceptional event flags shown in Appendix A. These proposed exceptional event flags for 2010 are for daily measurements from the Federal Reference Method (FRM) $PM_{2.5}$ monitor at the Houston Clinton site. A map identifying the Houston area $PM_{2.5}$ sites, including the Houston Clinton site, is shown in Figure 1.

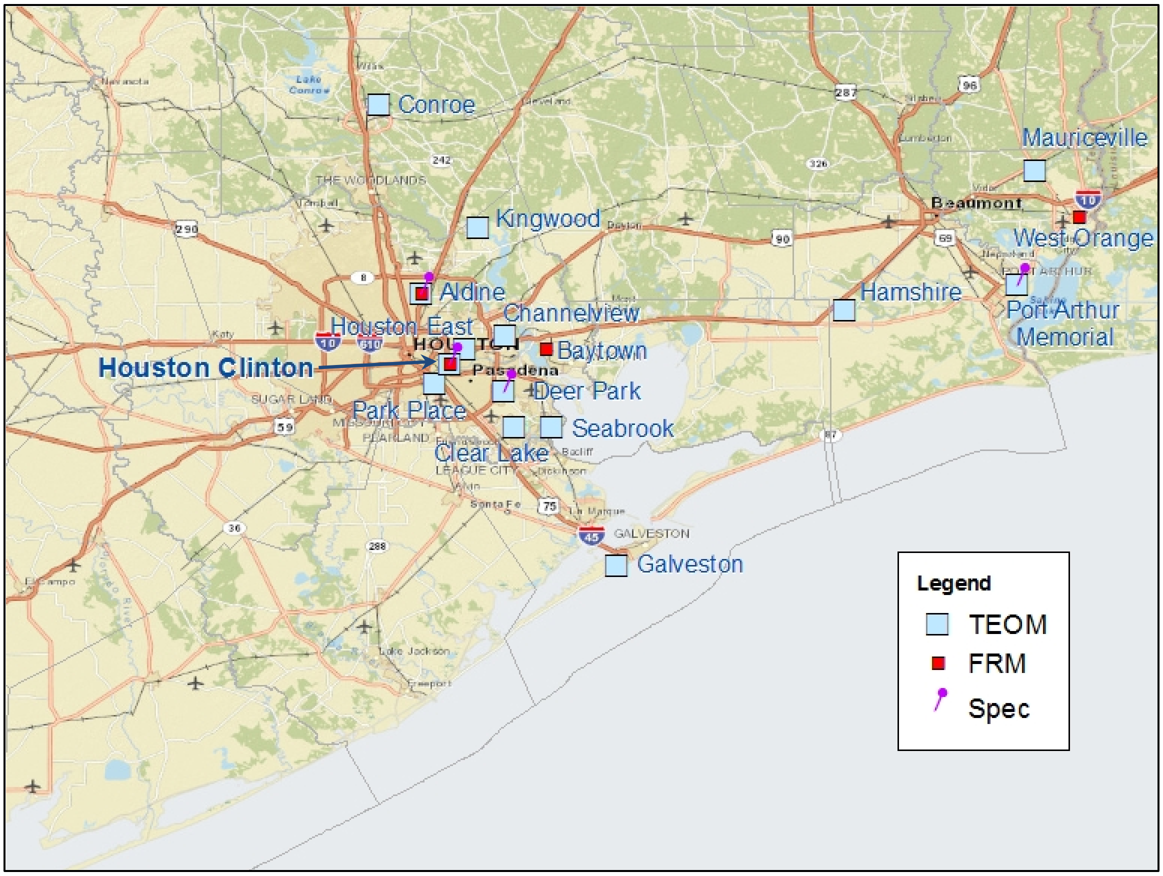

Figure 1. Map of Houston area $PM_{2.5}$ monitoring sites including the Houston Clinton FRM site, as well as other FRM sites, continuous $PM_{2.5}$ sites (TEOM), and speciated $PM_{2.5}$ sites (Spec).

Exceptional Event Definition and Criteria

An exceptional event is defined in Title 40 Code of Federal Regulations (CFR) Part 50.1(j) as "[1] an event that affects air quality, [2] is not reasonably controllable or preventable, [3] is an event caused by human activity that is unlikely to recur at a particular location or a natural event, and [4] is determined by the [EPA] Administrator in accordance with 40 CFR 50.14 to be an exceptional event". Furthermore, 40 CFR 50.14(c)(3)(iv) states that the demonstration to justify data exclusion shall also provide evidence that "[5] there is a clear causal relationship between the measurement under consideration and the event that is claimed to have affected the air quality in the area; [6] the event is associated with a measured concentration in excess of normal historical fluctuations, including background; and [7] there would have been no exceedance or violation but for the event". These seven requirements must all be satisfied for data to be excluded from regulatory decisions as an exceptional event. Requirements 1 through 3 and 5 through 7 will be addressed individually in this demonstration document.

Mitigation of exceptional events is also required by 40 CFR 51.930. "A State requesting to exclude air quality data due to exceptional events must take appropriate and reasonable actions to protect public health from exceedances or violations of the national ambient air quality standards. At a minimum, the State must: (1) Provide for prompt public notification whenever air quality concentrations exceed or are expected to exceed an applicable ambient air quality standard; (2) Provide for public education concerning actions that individuals may take to reduce exposures to unhealthy levels of air quality during and following an exceptional event; and (3) Provide for the implementation of appropriate measures to protect public health from exceedances or violations of ambient air quality standards caused by exceptional events." These requirements will be addressed in the "Mitigation of Exceptional Events" section.

Summary of Approach

The TCEQ used several methods for developing a demonstration that, giving consideration to all required factors, on balance indicates that the high $PM_{2.5}$ measurements in question qualify as exceptional events. The TCEQ identified five different factors that could provide meaningful evidence for evaluation of whether the flagged air monitoring data qualify for exclusion as being influenced by exceptional events. $PM_{2.5}$ concentrations from three Houston FRM monitors were evaluated for a period of over 10 years to adequately establish historical trends in the data. In addition, the TCEQ evaluated $PM_{2.5}$ speciation data from these monitors to identify African dust contributions. Satellite imagery from the National Aeronautic and Space Administration (NASA) (NASA Earth Observatory, 2013) and National Oceanic and Atmospheric Administration (NOAA) (NOAA, 2013) was used to track the African dust across the Atlantic Ocean, Caribbean Sea, and Gulf of Mexico and corroborated with aerosol modeling provided by the Naval Research Laboratory (NRL). Finally, the TCEQ analyzed Houston area $PM_{2.5}$ data to estimate contribution from long-range transport (incoming background levels) and contribution from local sources during the events as well as for the non-event baseline incoming background levels for use in the "but for" analyses.

Summary of Findings

The information provided in this demonstration document supports the conclusion that the high $PM_{2.5}$ measurements at Houston Clinton on June 9, June 10, and July 13, 2010, qualify as exceptional events. The measured $PM_{2.5}$ concentrations on these days were not reasonably preventable, were clearly due to African dust events, were in excess of normal historical fluctuations, and would not have occurred but for the African dust events. The TCEQ requests EPA's concurrence on these exceptional events and to have these days removed from consideration when making attainment or nonattainment determinations for the annual $PM_{2.5}$ National Ambient Air Quality Standard (NAAQS).

Data and Analysis Methods

Data and Imagery Used

A variety of TCEQ monitoring data and processed satellite imagery, along with satellite imagery and air trajectory information from federal sources, were used for the analyses presented in this document. As detailed in Table 1, the TCEQ monitoring data include FRM non-continuous $PM_{2.5}$ daily measurements, non-continuous $PM_{2.5}$ acceptable speciated daily measurements, and continuous $PM_{2.5}$ acceptable hourly and daily measurements (used for daily reporting of the EPA Air Quality Index), as well as hourly and daily wind measurements.

Table 1. $PM_{2.5}$ monitors with data used for analyses.

Site Name	AQS Site Identifier	AQS Parameter Identifier	AQS POC Identifier	$PM_{2.5}$ Monitor Type
Galveston	481671034	88101	1	FRM non-continuous
Galveston	481671034	88502	3	Acceptable continuous
Aldine	482010024	88101	5	FRM non-continuous
Aldine	482010024	88502	5	Acceptable non-continuous speciated
Aldine	482010024	88502	3	Acceptable continuous
Channelview	482010026	88502	3	Acceptable continuous
Baytown	482010058	88101	1	FRM non-continuous
Park Place	482010416	88502	3	Acceptable continuous
Clear Lake	482010572	88502	3	Acceptable continuous
Houston East	482011034	88502	3	Acceptable continuous
Clinton	482011035	88101	1	FRM non-continuous
Clinton	482011035	88101	2	FRM non-continuous
Clinton	482011035	88502	5	Acceptable non-continuous speciated
Clinton	482011035	88502	3	Acceptable continuous
Deer Park	482011039	88502	3	Acceptable continuous
Deer Park	482011039	88502	5	Acceptable non-continuous speciated
Kingwood	482011042	88502	3	Acceptable continuous
Seabrook	482011050	88502	3	Acceptable continuous
Port Arthur	482450021	88502	5	FRM non-continuous
Port Arthur	482450021	88502	5	Acceptable non-continuous speciated
Port Arthur	482450021	88502	3	Acceptable continuous
Hamshire	482450022	88502	3	Acceptable continuous

Site Name	AQS Site Identifier	AQS Parameter Identifier	AQS POC Identifier	$PM_{2.5}$ Monitor Type
Conroe	483390078	88502	3	Acceptable continuous
West Orange	483611001	88101	1	FRM non-continuous
Mauriceville	483611100	88502	3	Acceptable continuous

Note: POC stands for parameter occurrence code.

All of the TCEQ data used in this demonstration document are available in EPA's Air Quality System (AQS) database (EPA1, 2013) and meet EPA quality assurance requirements and guidelines. The satellite imagery used in this document came from NASA and NOAA and the imagery shown in the appendices were received and processed by TCEQ for display on the TCEQ web site (TCEQ, 2013). The air parcel trajectories were produced using the NOAA Applied Research Laboratory (ARL) Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model available on the ARL HYSPLIT web page (http://ready.arl.noaa.gov/hysplit-bin/trajtype.pl?runtype=archive) (NOAA ARL, 2013).

Analysis Methods

A variety of methods were used to analyze the data to determine if the specific monitor values of concern qualify as exceptional events. These methods include time series plots to show trends and events, comparison to statistical percentiles to show relevance, examination of satellite imagery for evidence of dust clouds, and review of backward-in-time air trajectories for independent confirmation of transport path of the affected air. Also, daily averages of hourly $PM_{2.5}$ continuous data were compiled for comparison with non-continuous measurements.

The Houston area $PM_{2.5}$ local contribution and transport contribution were estimated for each proposed exceptional event day. The transport contribution was derived using the second lowest area daily measurement. The local contribution was then calculated by subtracting the transport contribution from the Houston Clinton measurement. This approach has previously been presented as a method for estimating the impact of transport on annual $PM_{2.5}$ averages where significant gradients in incoming background concentrations can result in a misrepresentation of the transport contribution (Lambeth, 2010).

Choosing the second lowest area daily measurement rather than the lowest area daily measurement with a sufficient number of samples is more statistically robust, similar to using the 98th percentile rather than the maximum for the 24-hour $PM_{2.5}$ NAAQS. Other researchers have also noted problems in using the lowest area measurement to represent incoming background levels in the Houston area (Nielsen-Gammon & et al, 2005). On days where the incoming background levels are more uniform, the lowest and second lowest measurements will be close. However, significant gradients in the incoming background levels can result in substantial differences between the lowest and second lowest measurements. In these instances, the lowest may not best represent the transport contribution at the site of interest. Given the size of the Houston metropolitan area, significant gradients in the incoming background levels are quite common and result from the passage of incoming smoke plumes, haze, and dust clouds. These gradients are typically seen as horizontal variations in incoming background levels, but vertical gradients in the incoming background levels can also be present. This pattern of greater concentrations aloft is consistent with measurements collected by Baylor University aircraft investigating African dust on the Texas coast on July 2, 1997 as shown in Figure 2. Vertical mixing of the air on sunny summer days, like the three proposed exceptional event days, often reaches 1,500 to 2,000 meters above ground level inland, but is only about 800 meters or less near the coast and offshore (Parrish & et al, 2009). Thus, inland vertical mixing is typically about two to three times higher than along the coast. If incoming background levels have a greater concentration aloft than near the surface, more of the air pollution aloft will mix to the ground inland causing greater incoming background levels than observed near the coast. The second lowest area daily measurement approach can avoid an unrepresentatively low estimate of incoming background levels caused by concentration gradients and/or data quality issues.

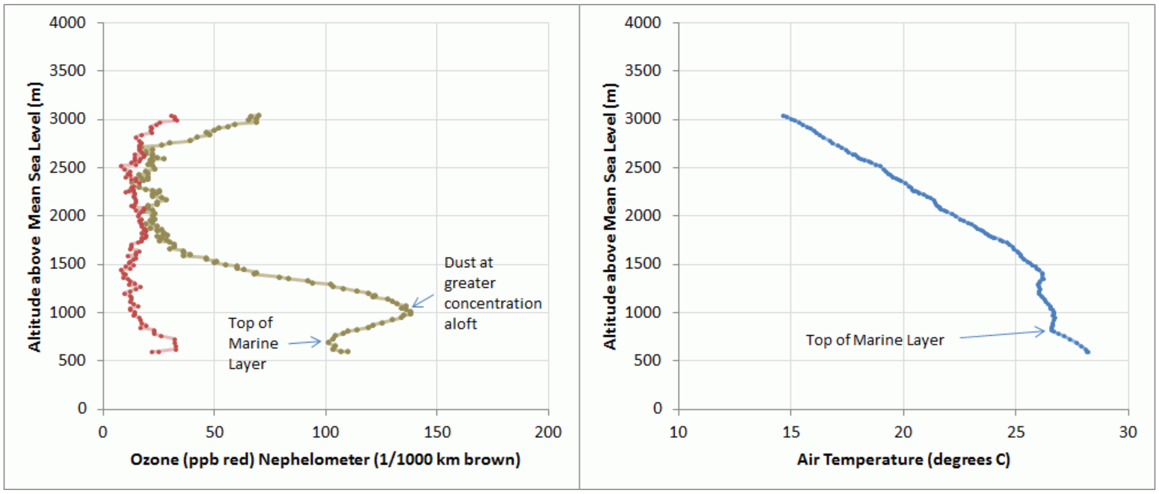

Figure 2. Dust at greater concentration aloft above the top of the marine layer as indicated by Baylor Aircraft nephelometer measurements of an African dust cloud on the Texas coast near Port O'Connor on July 2, 1997.

Houston $PM_{2.5}$ Trends and Sources

PM2.5 Air Quality Trends

With the exception of the Houston Clinton site, $PM_{2.5}$ levels in the Houston area have shown a gradual overall decline since monitoring began in 1999. As shown in Figure 3, the Houston Clinton site measured a pronounced increase in $PM_{2.5}$ concentrations from 2002 to 2007 caused by localized sources in the immediate vicinity of the site. This increase has been followed by a sharp decline resulting from extensive voluntary source remediation efforts (Sullivan & et al, 2013) that are described in the Local Source Contributions section below.

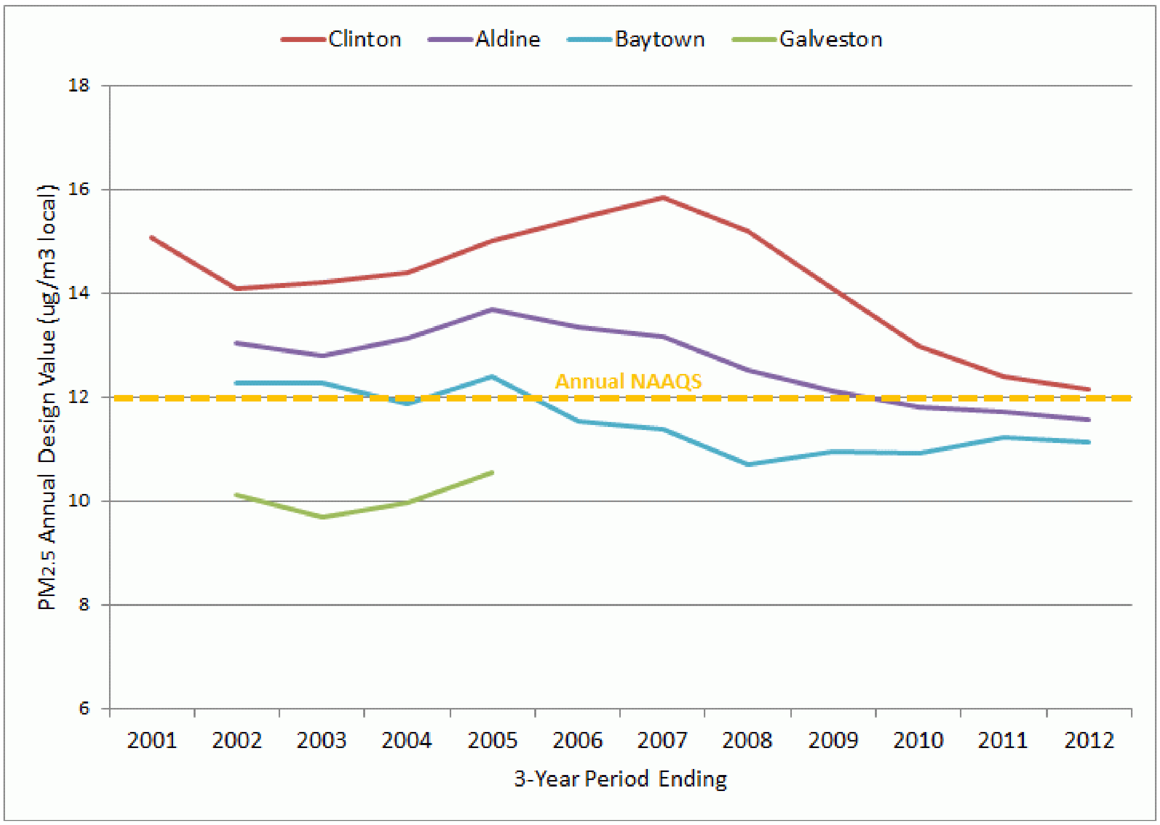

Figure 3. Houston $PM_{2.5}$ annual design value trends for long-term FRM monitoring sites including exceptional event days.

Historically, $PM_{2.5}$ in the Houston area is greatly impacted by long-range transport from natural events outside of the area including wildfires; African dust; dust from large, intense regional dust storms in the West Texas-New Mexico-Northern Mexico area; and smoke from agricultural burning in Mexico and Central America. Long-range transport from other types of events also impact the Houston area, including controlled burns and haze and smoke accumulated from man-made emissions in the U.S. and Canada (also known as continental haze).

African dust impacts the Houston area every year, mainly in the summer, with typically three to six intense episodes that are characterized by high incoming background levels and lasting one to three days or more. Smoke from agricultural burning in Mexico affects the Houston area mainly from April to early June each year when the winds bring in air from eastern Mexico and Central America. Continental haze events are most common from May through October and often include high ozone background levels as well. All of these sources of $PM_{2.5}$ air pollution cannot be controlled locally and prior work indicates that these sources, along with the global background, account for about 75 to 90 percent of the annual $PM_{2.5}$ average at sites in the Houston area (Lambeth, 2010) as shown in Figure 4. A variety of urban and industrial local sources of $PM_{2.5}$ also contribute the remaining 10 to 25 percent of the annual means for 2010-2012.

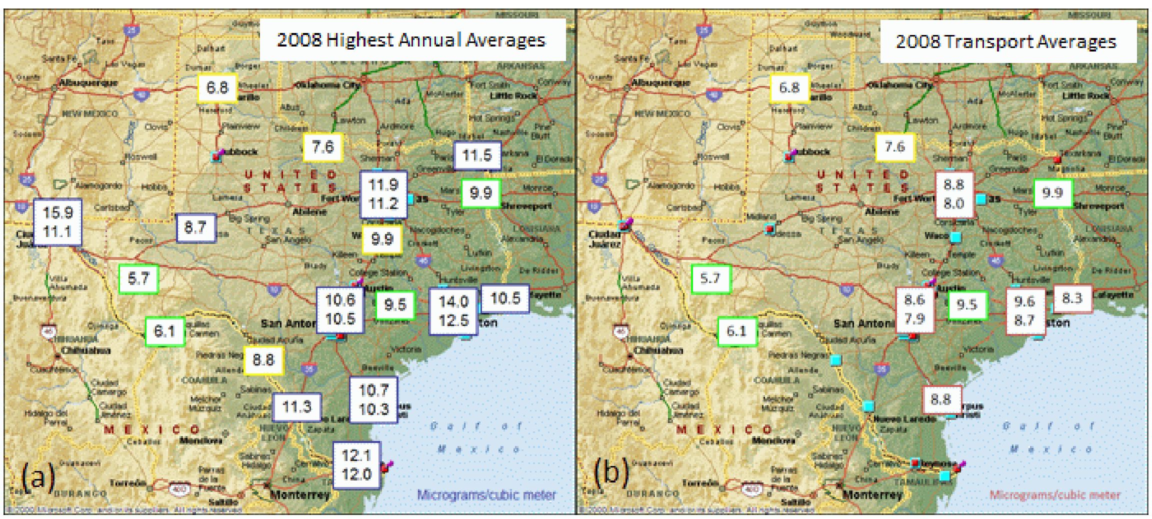

Figure 4. Texas annual average $PM_{2.5}$ concentrations, 2010. (a) Map showing the highest site annual averages by area, with the second highest shown in areas with more than one site. (b) Map showing the estimated annual average contribution from transport by area with the top average based on the second lowest area daily measurements for areas with more than one site (Lambeth, 2010).

<u>African Dust Events</u>

In 2010, the greatest incoming background levels were associated with African dust events and the worst three African dust days are being recommended as exceptional events for the Houston Clinton FRM $PM_{2.5}$ measurements as seen in Figure 5.

Silicon, aluminum, iron, and calcium are the most abundant soil components in African dust events (Goudie & et al, 2001) (Formenti & et al, 2011). Silicon, aluminum, and iron show very clear high peaks in association with African dust events at Houston Clinton in the summer and much lower levels the remainder of the year, whereas calcium is dominated by contributions from local sources and does not show this trend. The implication is that silicon, aluminum, and iron from local sources are relatively low, as indicated by fall, winter, and spring measurements, as compared to levels during African dust events. There is no evidence that would support the ability for local sources to contribute much higher concentrations of silicon, aluminum, and iron during very discrete time periods in the summer and not at any other time of year.

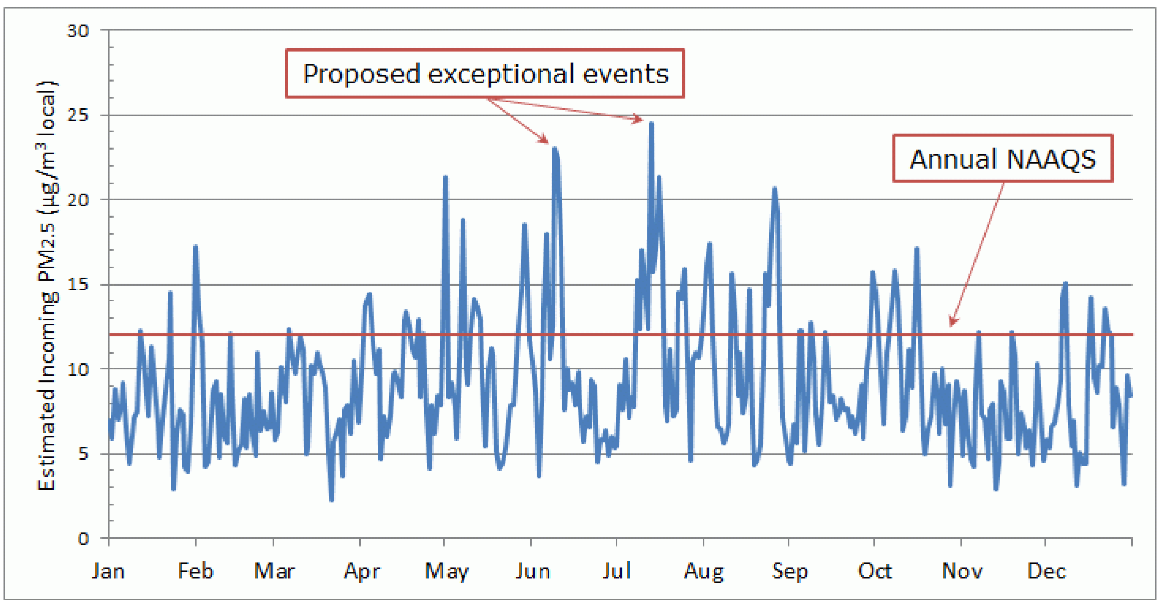

Figure 5. Houston area 2010 estimated incoming $PM_{2.5}$ background level based on area second lowest daily measurement.

Figure 6 shows a seasonal pattern consistent with summer impacts from African dust for the silicon, aluminum, and iron portion (SAF) of the soil reconstruction formula used by the Interagency Monitoring of Protected Visual Environments (IMPROVE) $PM_{2.5}$ speciation monitoring program (Eldred, 2003). The individual speciated silicon measurements show the same seasonal pattern in Figure 7 and likewise for aluminum in Figure 8. The aluminum measurements show evidence of small local contributions that were highest in 2006 when the average aluminum concentration was 0.13 micrograms per cubic meter (µg/m^3) on 27 routine sample days and excluding four African dust routine sample days with aluminum averaging 1.38 µg/m^3. The aluminum levels decreased in 2007 and 2008, and were lowest in 2009 and 2010, outside of the much higher summer African dust events. In 2010, the average aluminum concentration was 0.07 µg/m^3 on 58 routine samples days and excluding three African dust routine sample days with an aluminum average of 0.89 µg/m^3. The aluminum data also gauge the intensity and frequency of the African dust events each year and show considerable variability of both from year to year.

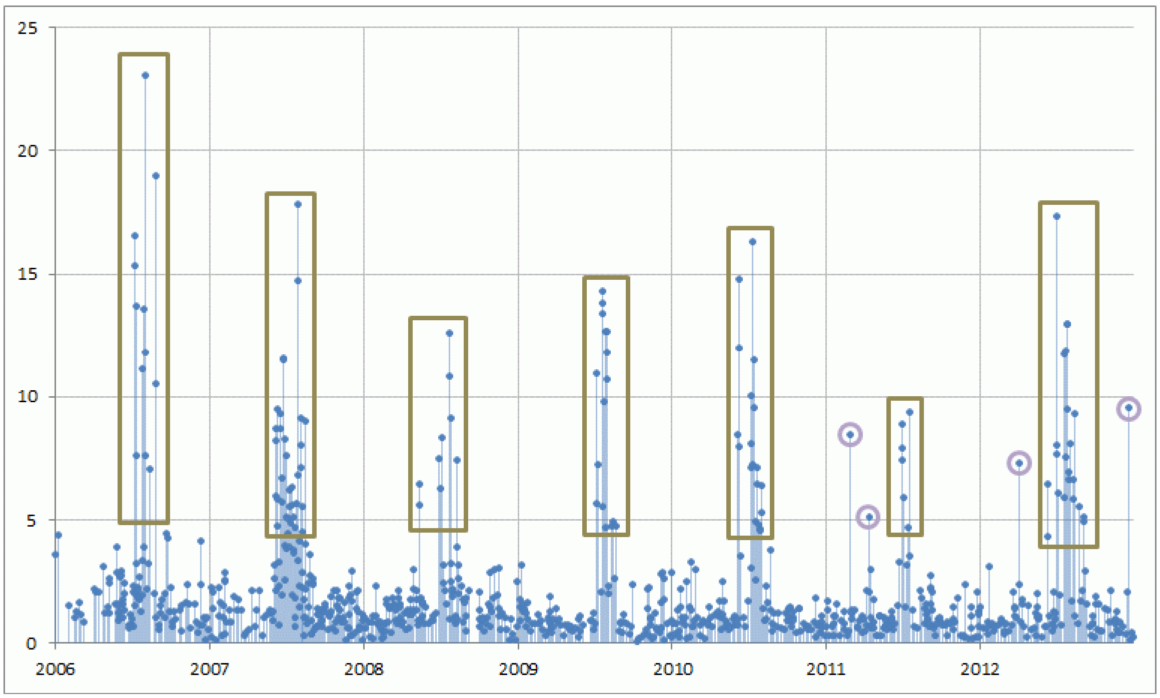

Figure 6. Speciated $PM_{2.5}$ soil component silicon plus aluminum plus iron (SI+AL+FE=SAF) measurements using the IMPROVE soil reconstruction formula. These components of the reconstructed soil concentration show much higher levels during African dust events each summer. African dust events are shown in boxes and four transported dust events from West Texas dust storms in 2011 and 2012 are circled.

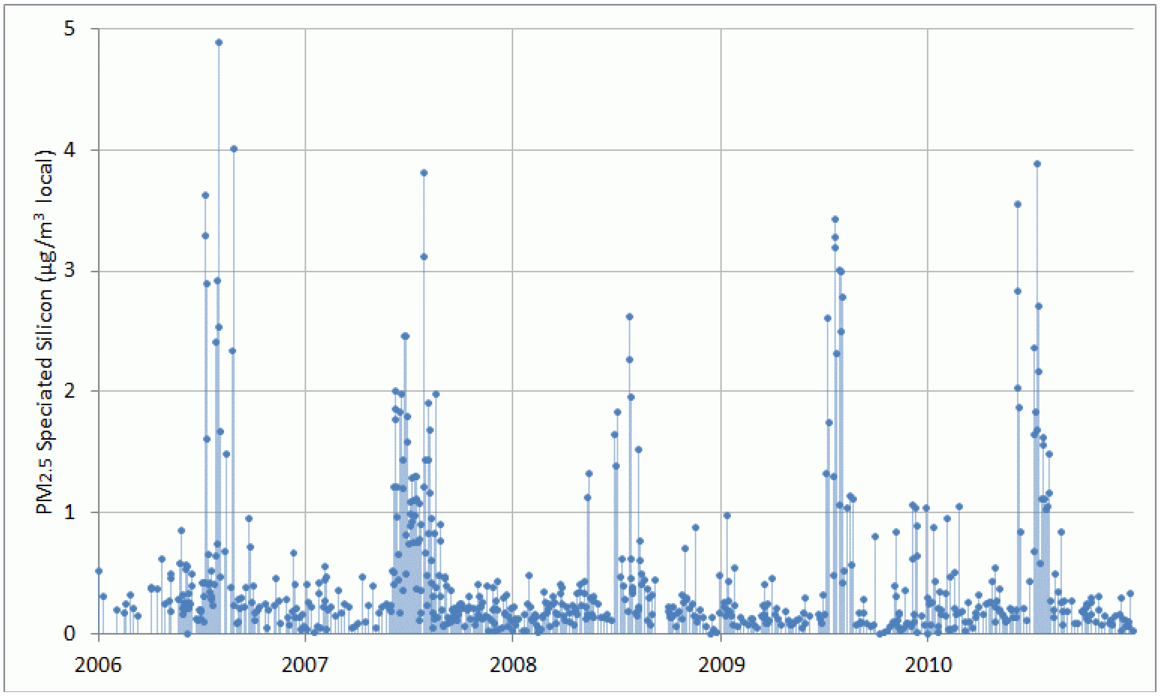

Figure 7. Speciated $PM_{2.5}$ silicon measurements showing much higher levels during African dust events each summer from 2006 through 2010.

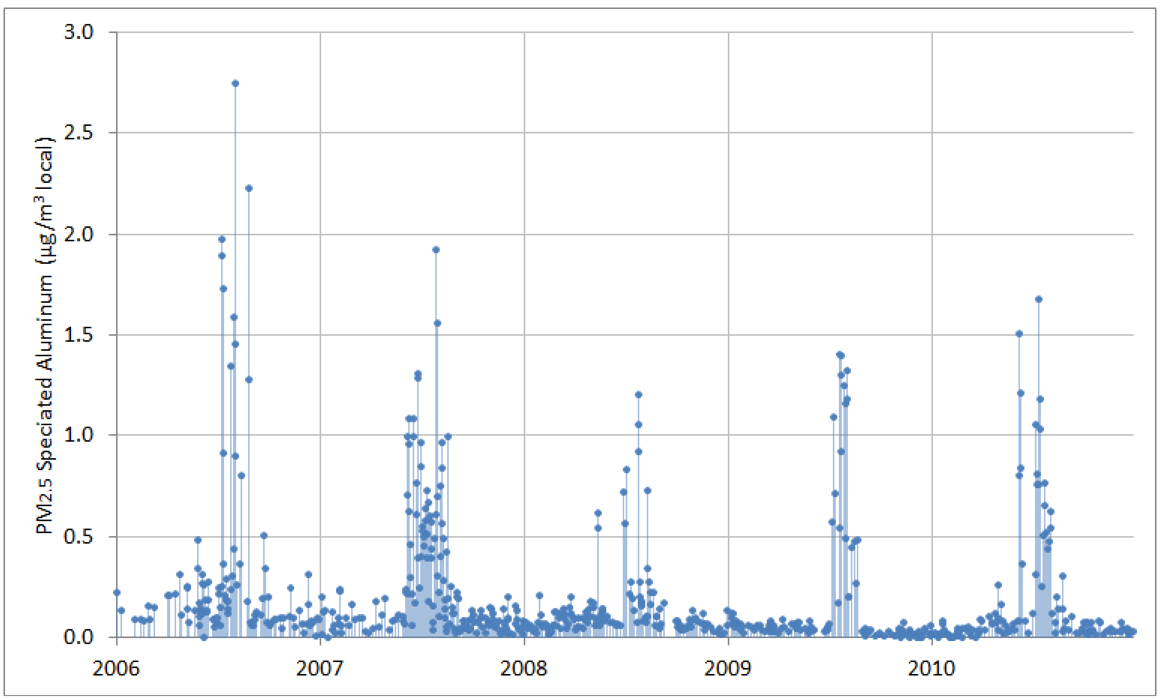

Figure 8. Speciated $PM_{2.5}$ aluminum measurements showing much higher levels during African dust events each summer from 2006 through 2010.

Although calcium is considered a part of African dust (Formenti & et al, 2011), it is overwhelmed by contributions from local Houston area sources such that African dust events are difficult to distinguish in the speciated calcium measurements shown in Figure 9. Even though calcium measurements show a sharp decline in recent years due to voluntary remediation measures, local calcium is still largely obscuring calcium from 2010 African dust event in the figure. The large difference in the pattern and trends seen in the calcium measurements versus the silicon, aluminum, and iron measurements offers further evidence that the high summer peaks in the data for silicon, aluminum, and iron are mostly from African dust and not local sources. The primary local source of the calcium is calcium sulfate (gypsum) used to cover roadways and parking areas frequented by large trucks in the port area (Sullivan & et al, 2013).

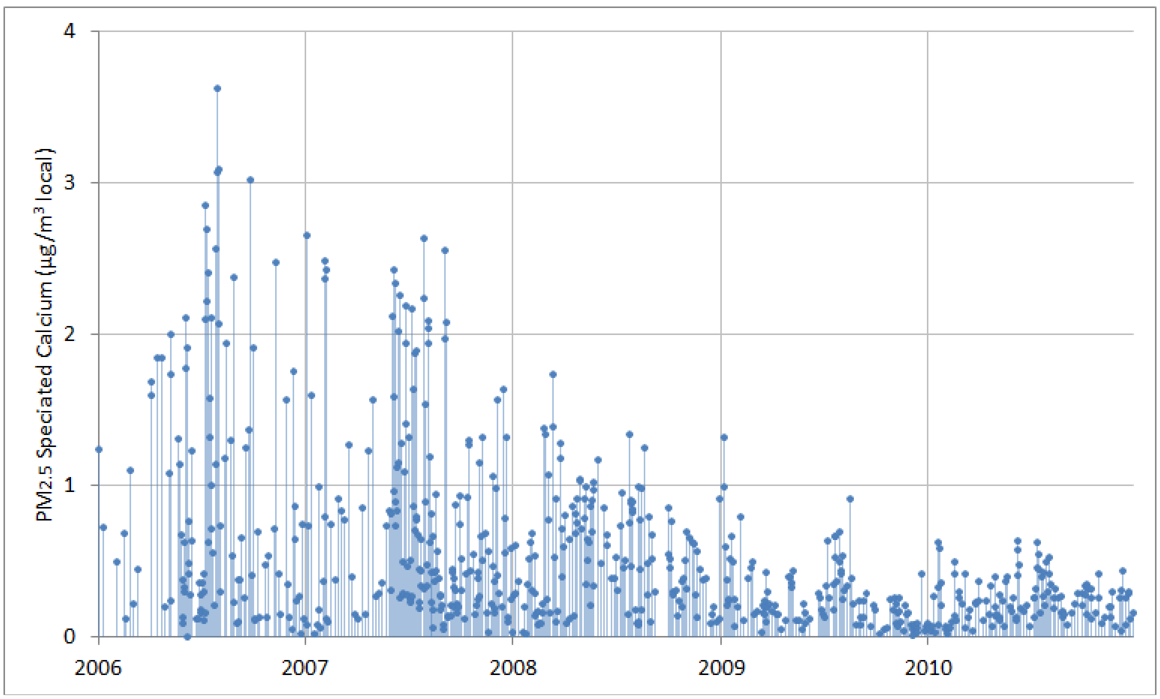

Figure 9. Speciated $PM_{2.5}$ calcium measurements showing dominance of local contributions and a decreasing trend from 2006 through 2010.

<u>Local Source Contributions</u>

The Houston Clinton monitoring site, located near the west end of the Houston Ship Channel, was originally sited to measure impacts from industrial air pollution sources along the channel. When $PM_{2.5}$ concentrations began rising to near the level of the annual NAAQS in 2005 and 2006, voluntary control measures were pursued by the TCEQ and the City of Houston. Implemented control strategies included improving traffic flow through traffic barriers on the shoulder of Clinton Drive and traffic lights, adding vegetation along Clinton Drive, reducing locomotive emissions at the nearby port, removal of calcium sulfate from port roadways and work yards and replacement with fresh compacted soil topped by emulsified asphalt, paving of some parking areas, and dust control measures at a nearby fluorspar unloading and storage facility. As a result of these activities, the estimated annual contribution from local $PM_{2.5}$ sources at Houston Clinton declined approximately 50 percent from approximately 6 µg/m^3 in 2006 to approximately 3 µg/m^3 in 2010 as shown in Figure 10. Figure 10 also shows the estimated incoming background level contribution to the annual average declined by about 1 µg/m^3 from 2007 to 2012. Analysis of the speciated $PM_{2.5}$ data at Houston Clinton indicated a 2 µg/m^3 decline in the soil component from 2006 to 2011 (Sullivan & et al, 2013).

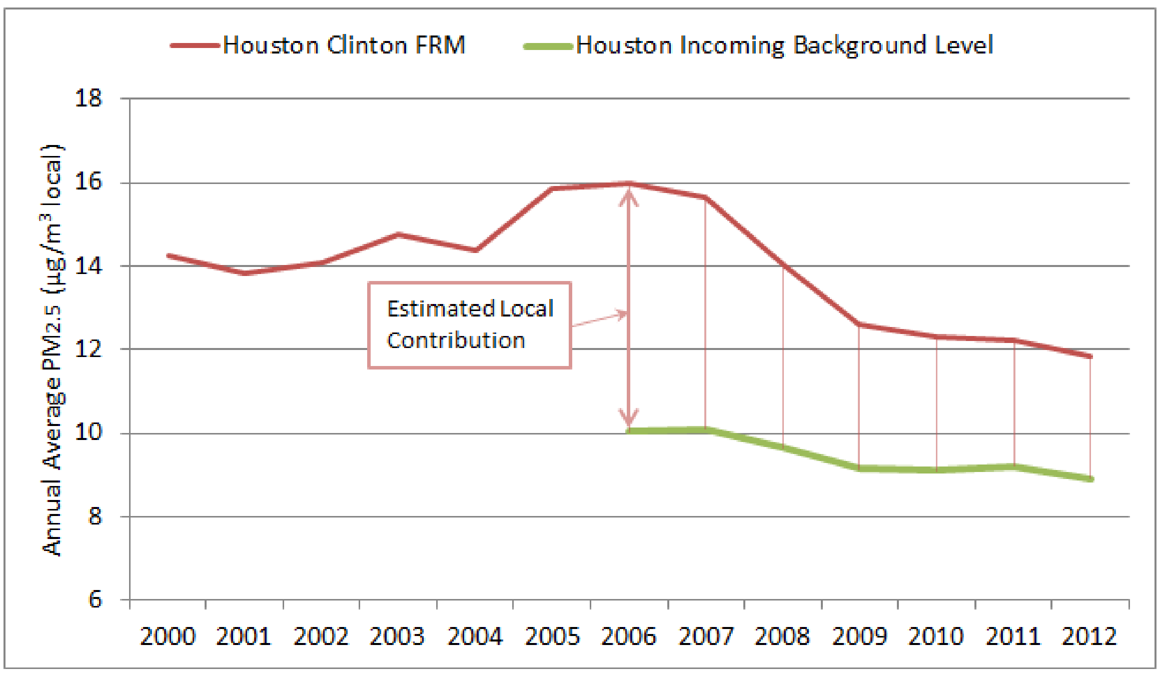

Figure 10. Houston Clinton FRM annual $PM_{2.5}$ concentrations, estimated Houston area incoming background level (transport contribution) based on the daily second lowest measurements, and estimated local contribution to $PM_{2.5}$ levels from 2000 – 2012 (for all days including proposed exceptional events).

Event Summaries

June 9 and 10, 2010

A large African dust cloud moved through the Houston area with the highest $PM_{2.5}$ concentrations on June 9th and 10th of 2010. The impact of the African dust cloud was primarily seen in the greatly increased soil component of the speciated $PM_{2.5}$ data, for which silicon is the strongest marker. Daily $PM_{2.5}$ Air Quality Index (AQI) ratings across the U.S. are illustrated in Figures 11 and 12. These maps show a large regional event with "Moderate" AQI levels in association with the African dust covering South and Southeast Texas on June 9th (Figure 11) and most of Texas on June 10th (Figure 12).

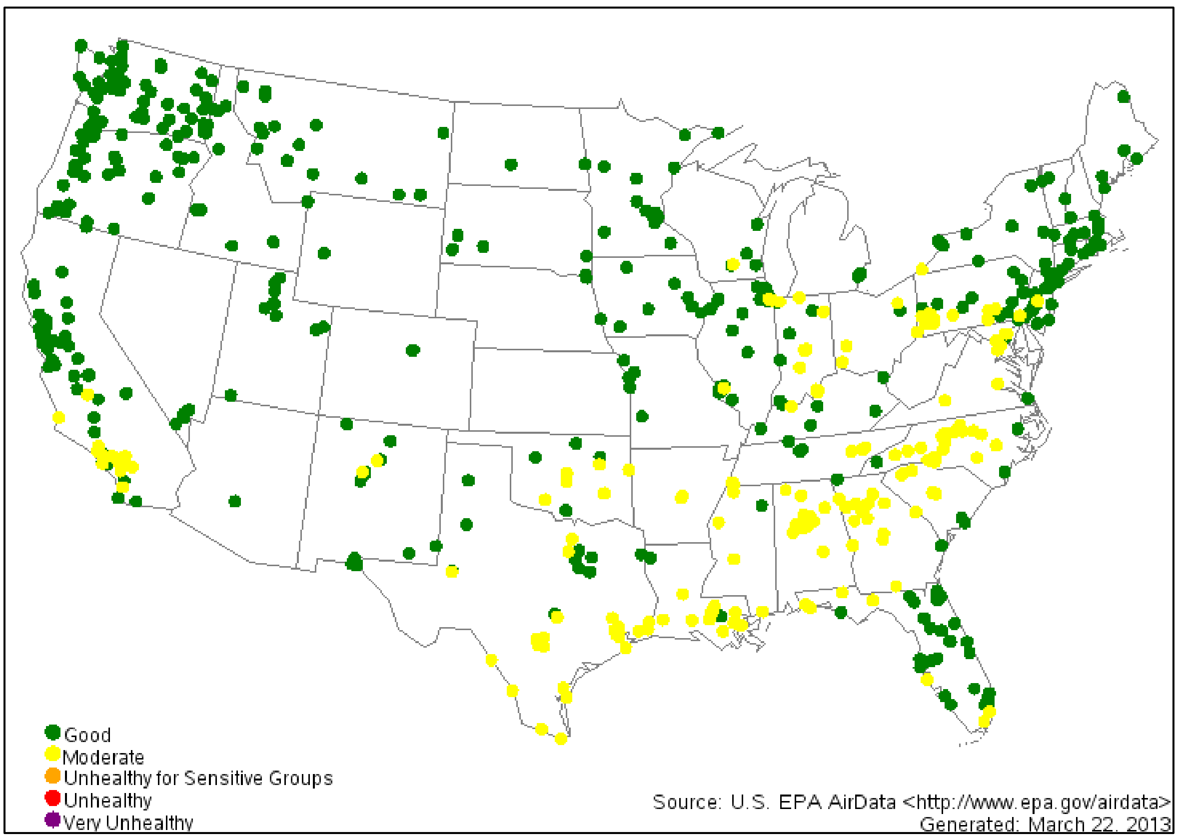

Figure 11. $PM_{2.5}$ AQI levels by site on June 9, 2010.

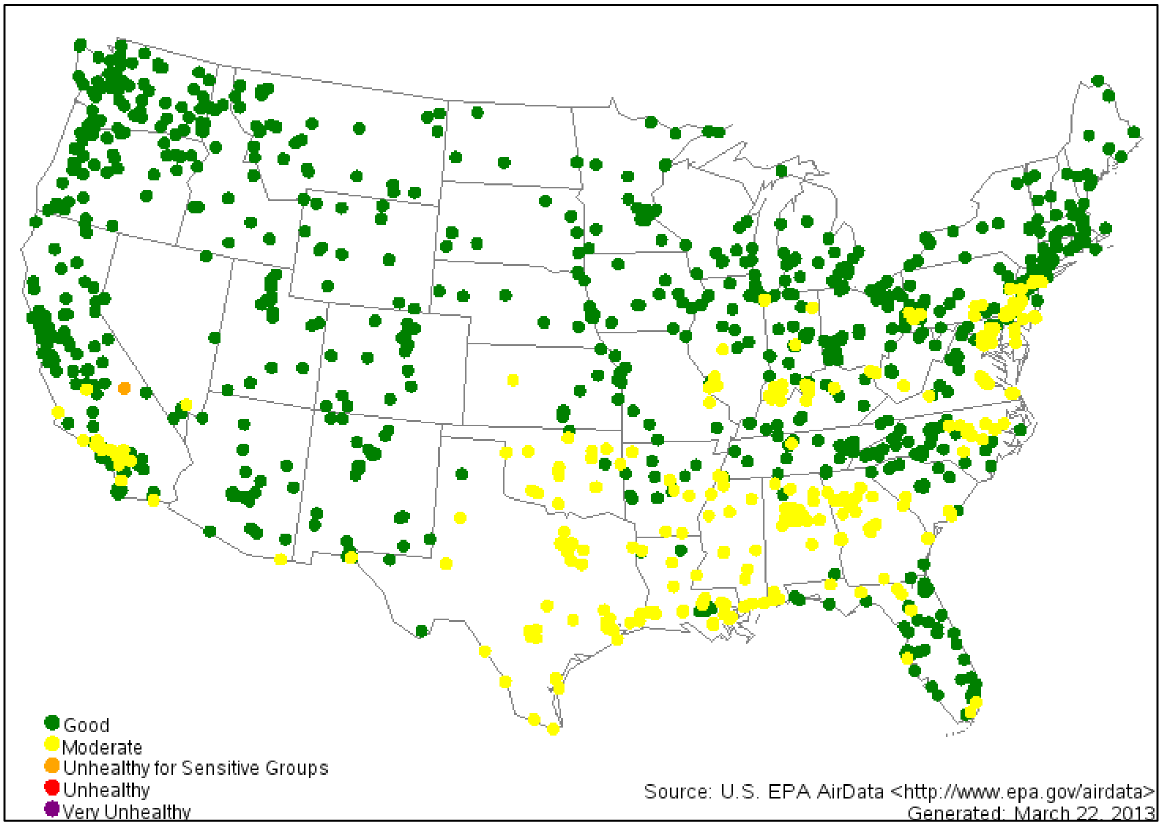

Figure 12. $PM_{2.5}$ AQI levels by site on June 10, 2010.

As illustrated in Figures 13 and 14, widespread elevated $PM_{2.5}$ measurements along with moderate southerly winds across Southeast Texas on June 9th and 10th support the influence of increased incoming background concentrations. While concentrations measured at Galveston were substantially lower than at sites further inland, this difference can be attributed to greater dust concentrations aloft being mixed to the ground due to increasing mixing heights further inland. Because of moderate wind speeds over 10 miles per hour on these days, local contributions at inland sites would have been minimized by strong dilution effects. These meteorological conditions paired with increased $PM_{2.5}$ concentrations inland are consistent with increased vertical concentration gradients representative of higher vertical mixing. This mixing is further illustrated by $PM_{2.5}$ concentrations at the Hamshire site, which is mid-way between Beaumont and Galveston and has no significant $PM_{2.5}$ sources upwind to the south. On June 9th Hamshire measured 25.4 $\mu g/m^3$ when Galveston measured 20.2 $\mu g/m^3$ and on June 10th Hamshire measured 24.2 $\mu g/m^3$ when Galveston measured 18.6 $\mu g/m^3$. This data indicates that incoming background levels were about 20 to 30 percent greater in concentration inland than along the immediate coast.

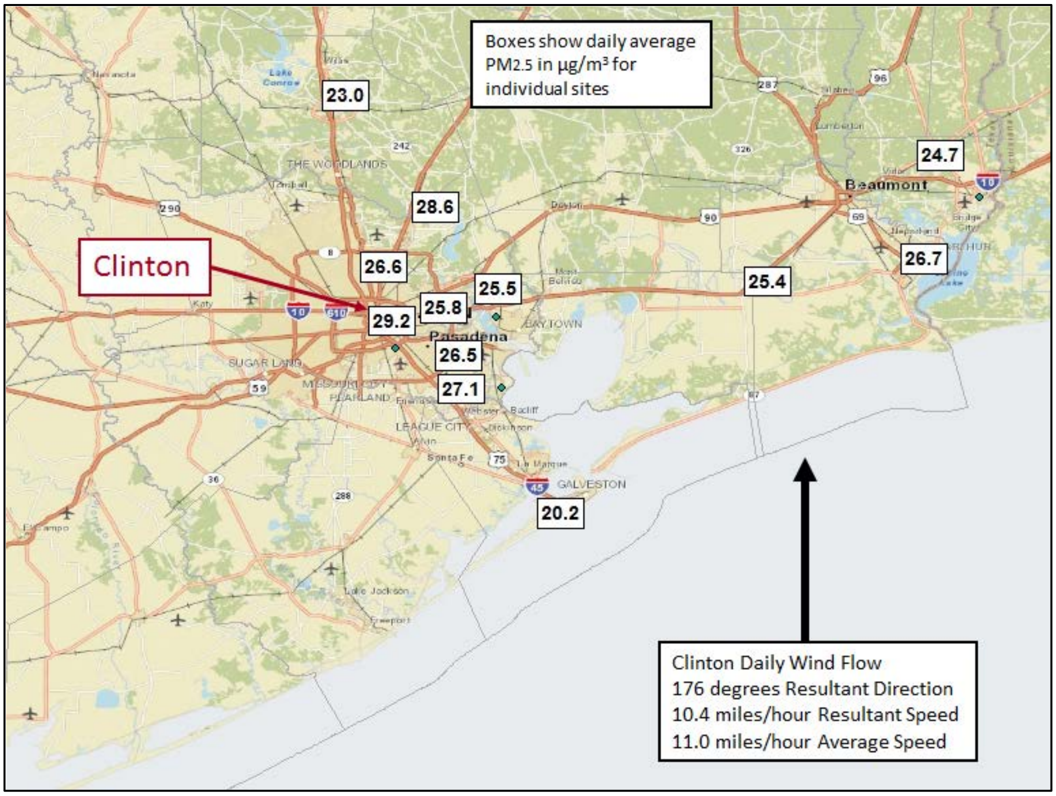

Figure 13. Map of $PM_{2.5}$ ($\mu g/m^3$) and wind measurements on June 9, 2010.

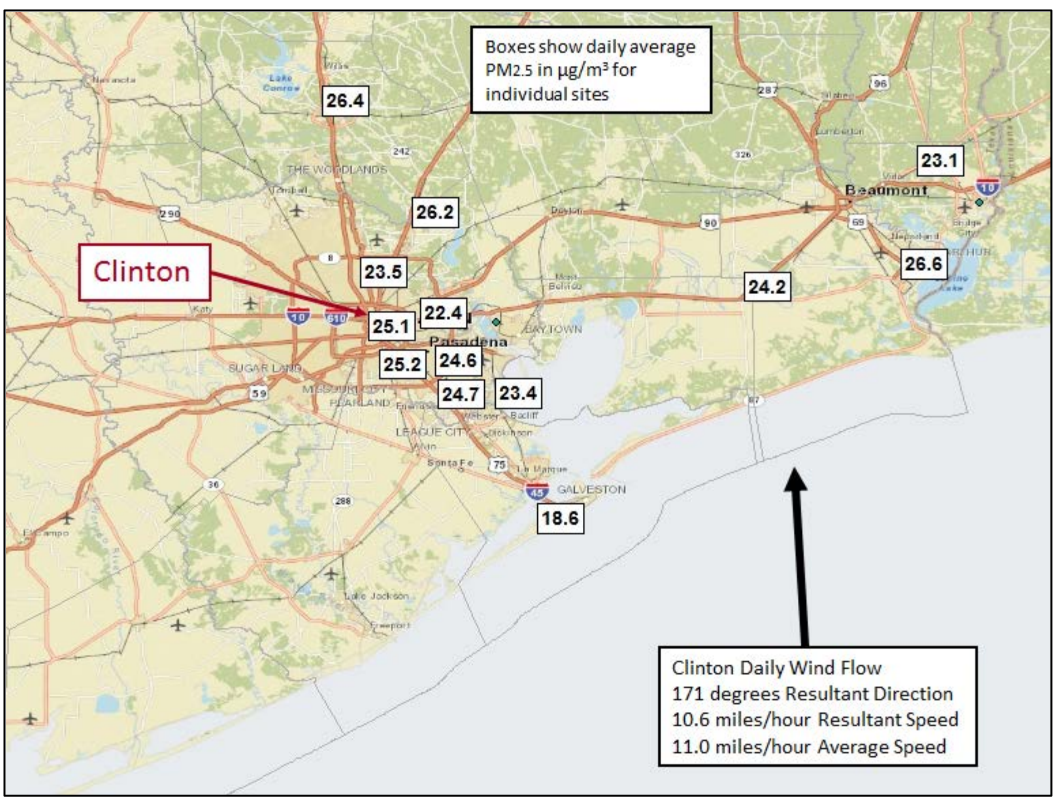

Figure 14. Map of $PM_{2.5}$ ($\mu g/m^3$) and wind measurements on June 10, 2010.

Wind directions and speeds for June 9th and 10th are depicted in Figures 15 and 16 using wind roses for selected monitoring locations in the region. The length of the bars on each wind rose indicates the frequency of winds occurring in the direction of the bar. The wind flow is along the bar toward the site. The wind roses show that winds were persistently from the south to southeast at all sites on both days.

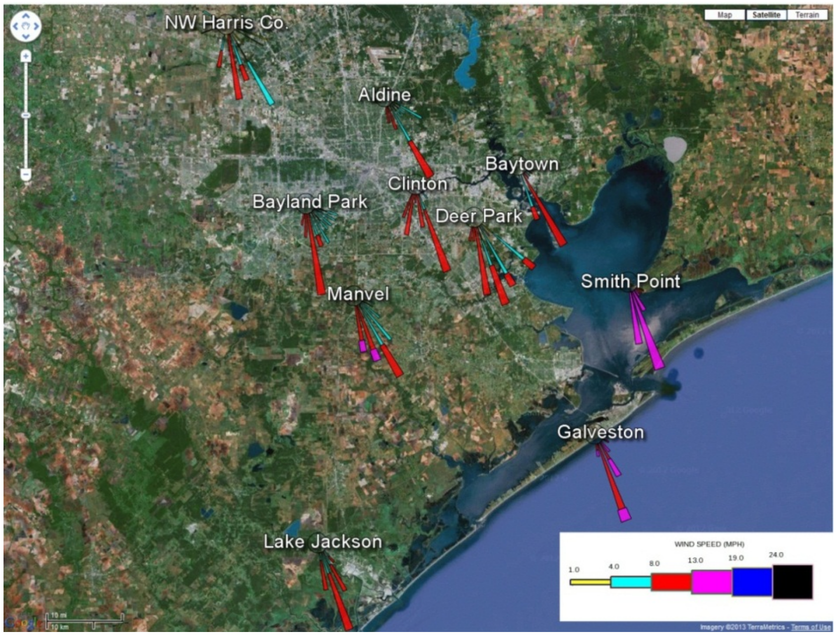

Figure 15. Wind rose plots for June 9, 2010.

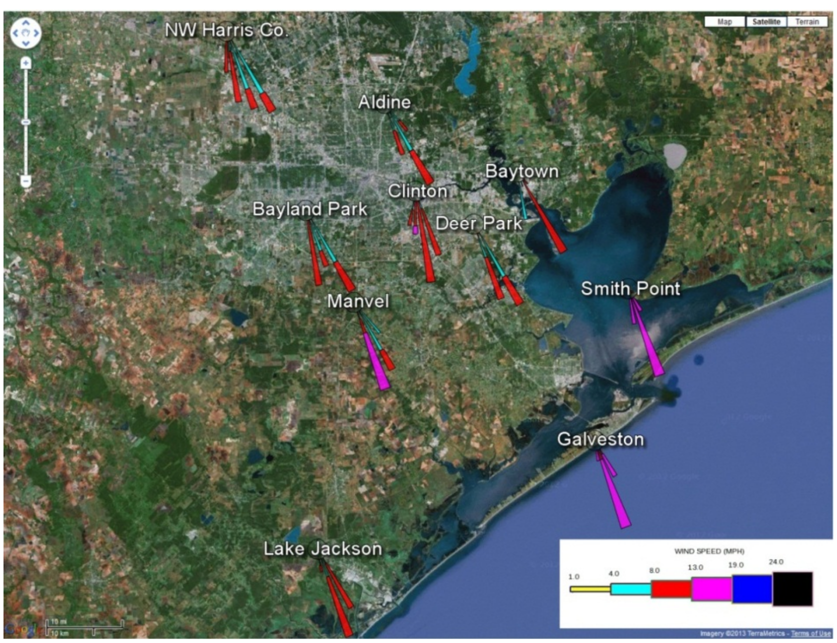

Figure 16. Wind rose plots for June 10, 2010.

$PM_{2.5}$ measurements at sites across the Houston area showed an increase in concentrations from June 8th through 11th. These measurements along with a predominant south to southeast wind flow indicate that $PM_{2.5}$ levels coming onshore from the Gulf of Mexico were very high, as illustrated in Figure 17 by the increase in $PM_{2.5}$ measurements across the area beginning around June 8th. Continuous hourly $PM_{2.5}$ measurements from all Houston sites during the time period of the event show a tight clustering of measurements as concentrations increase and decrease, providing strong evidence of a regional transport event affecting all sites, as illustrated in Figures 17 and 18. In these graphs, measurements from the Houston Clinton site are plotted with a thicker line. Variations among the sites can be caused by gradients in the incoming background levels, impacts from local sources, and/or measurement uncertainties, all of which vary over time. Figure 18 provides a more detailed view of the hourly $PM_{2.5}$ measurements during the African dust event that began late on June 8th and ended early on June 12th.

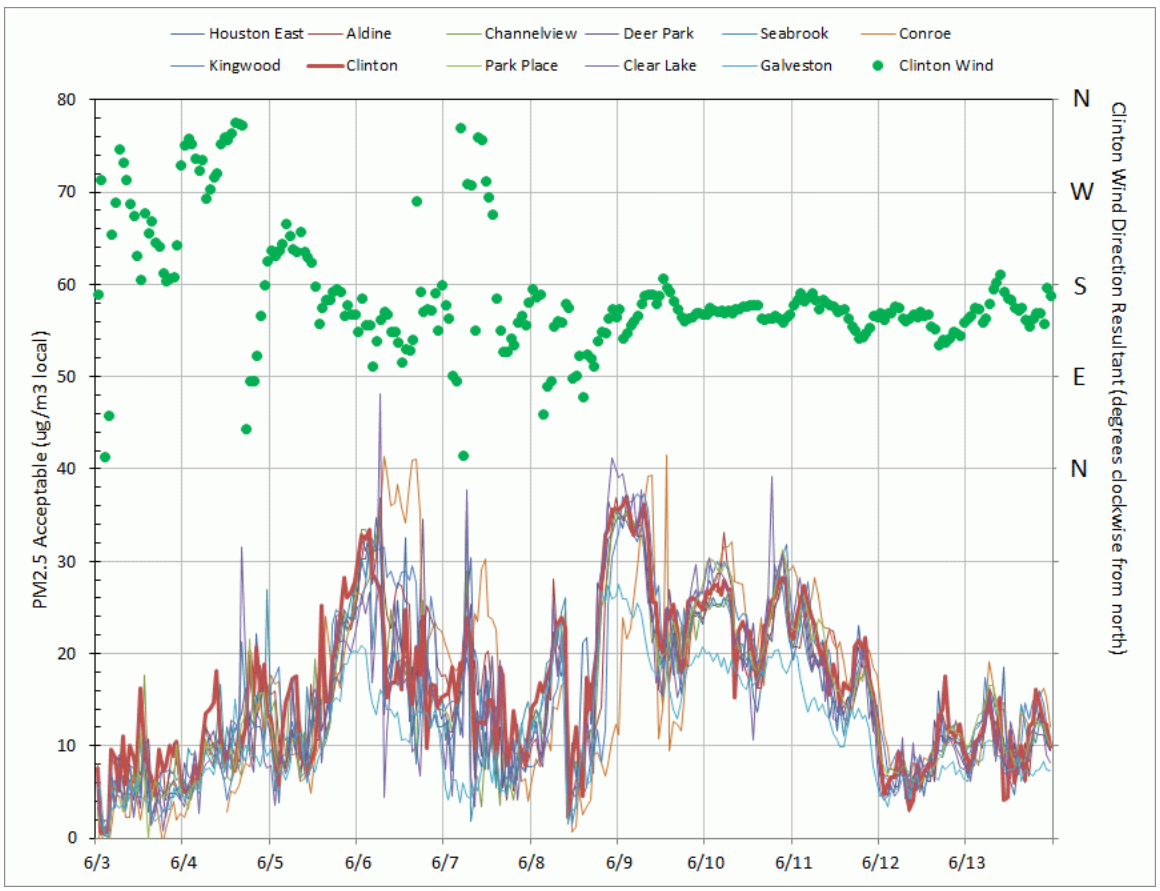

Figure 17. Houston hourly $PM_{2.5}$ concentrations by site for June 3-13, 2010 with hourly wind direction at Houston Clinton.

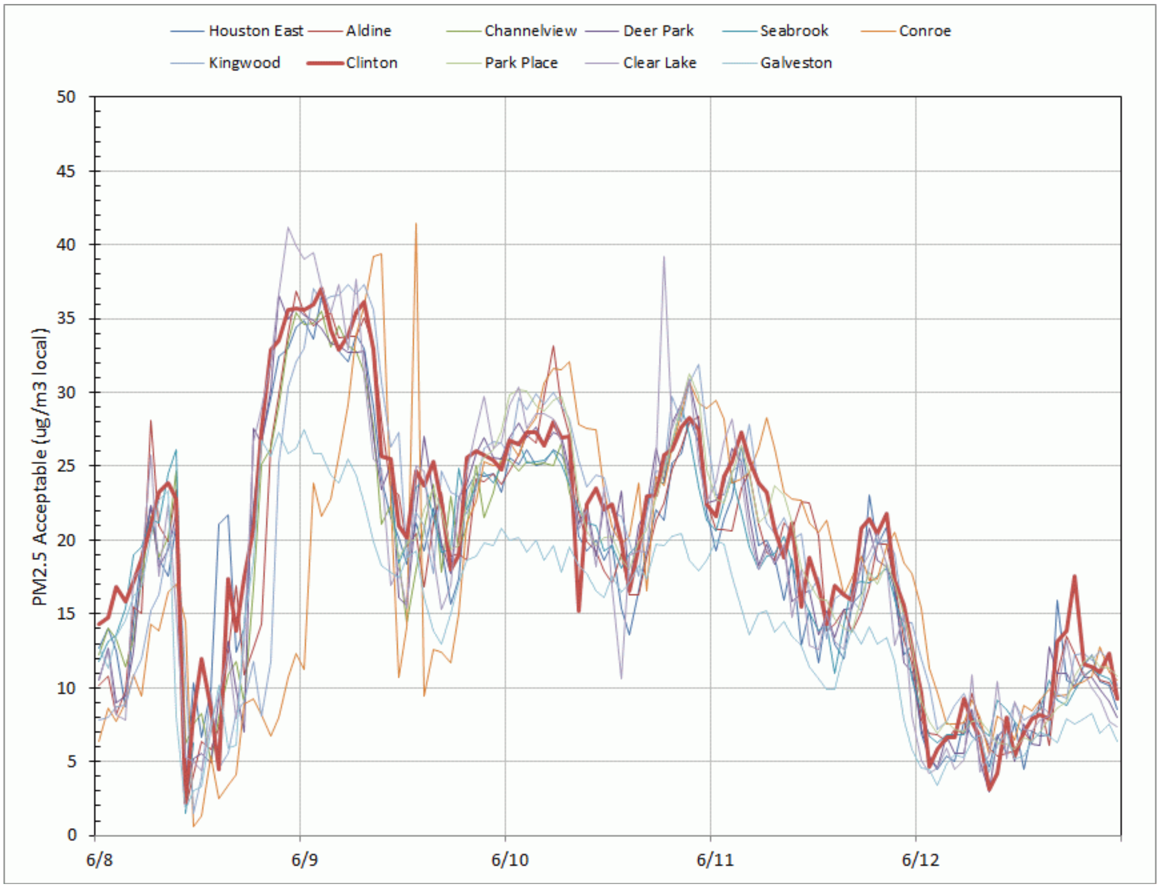

Figure 18. Houston hourly $PM_{2.5}$ concentrations by site for June 8-12, 2010.

Table 2. Houston daily average $PM_{2.5}$ ($\mu g/m^3$) by site June 3-12, 2010.

Site Name	Type	06/03/10	06/04/10	06/05/10	06/06/10	06/07/10	06/08/10	06/09/10	06/10/10	06/11/10	06/12/10
Galveston	AC	3.7	8.1	11.3	*14.1*	6.8	*15.1*	*20.2*	*18.6*	*13.3*	6.2
Seabrook	AC	5.1	11.9	*15.5*	*19.5*	11.7			*23.4*	*17.3*	8.5
Clear Lake	AC	4.5	10.0	*13.7*	*18.0*	11.4	*17.8*	*27.1*	*24.7*	*17.8*	7.7
Deer Park	AS		9.8			11.6			*22.7*		
Deer Park	AC	5.3	11.1	*14.4*	*22.1*	*12.5*	*16.8*	*26.5*	*24.6*	*18.0*	7.6
Baytown	FRM					10.8					
Channelview	AC	5.4	9.1	*14.5*	*22.3*	10.6	*16.7*	*25.5*			
Houston East	AC	5.7	11.0	*14.4*	*22.1*	*12.6*	*18.3*	*25.8*	*22.4*	*17.6*	7.8
Clinton	FRM	6.9	10.2	*15.4*	*22.9*	*13.4*	*18.7*	***29.2***	***25.1***	*19.9*	9.0
Clinton	AC	7.6	11.8	*16.2*	*21.1*	*14.1*	*19.1*	*27.8*	*24.2*	*19.8*	8.7
Park Place	AC	4.8	10.1						*25.2*	*19.0*	8.3
Aldine	FRM					*14.9*					
Aldine	AC	6.1	10.2	*14.1*	*25.5*	*13.7*	*15.9*	*26.6*	*23.5*	*18.6*	8.3
Kingwood	AC	5.2	8.3	*15.1*	*25.8*	*12.4*	*12.5*	*28.6*	*26.2*	*19.5*	9.3
Conroe	AC	2.8	7.9	*14.3*	*31.3*	*17.3*	8.7	*23.0*	*26.4*	*21.9*	9.4

Note: *Emphasis* indicates that a measurement is above the level of the annual $PM_{2.5}$ NAAQS.

Abbreviations:

AC Acceptable continuous

AS Acceptable speciated non-continuous

FRM Federal Reference Method

To bracket the beginning and end of the African dust event, hourly and daily $PM_{2.5}$ measurements from sites across the Houston area were evaluated. Data shown in Table 2 above indicates that from June 4th through June 12th $PM_{2.5}$ concentrations in the Houston area were influenced by regional transport events. $PM_{2.5}$ was elevated at all sites from June 4th through 7th in association with smoke from agricultural burning in Mexico and Central America. Consequently, June 3rd was used to indicate the initial event-free incoming background level before the African dust event (and also before the smoke event) and June 12th was used to indicate the event-free incoming background level at the end of the event. Figure 19 illustrates the hourly $PM_{2.5}$

concentrations before, during, and after the events and indicates the event-free background levels. The daily measurements from June 3rd and 12th were averaged to estimate the incoming non-event baseline levels for June 9th and 10th.

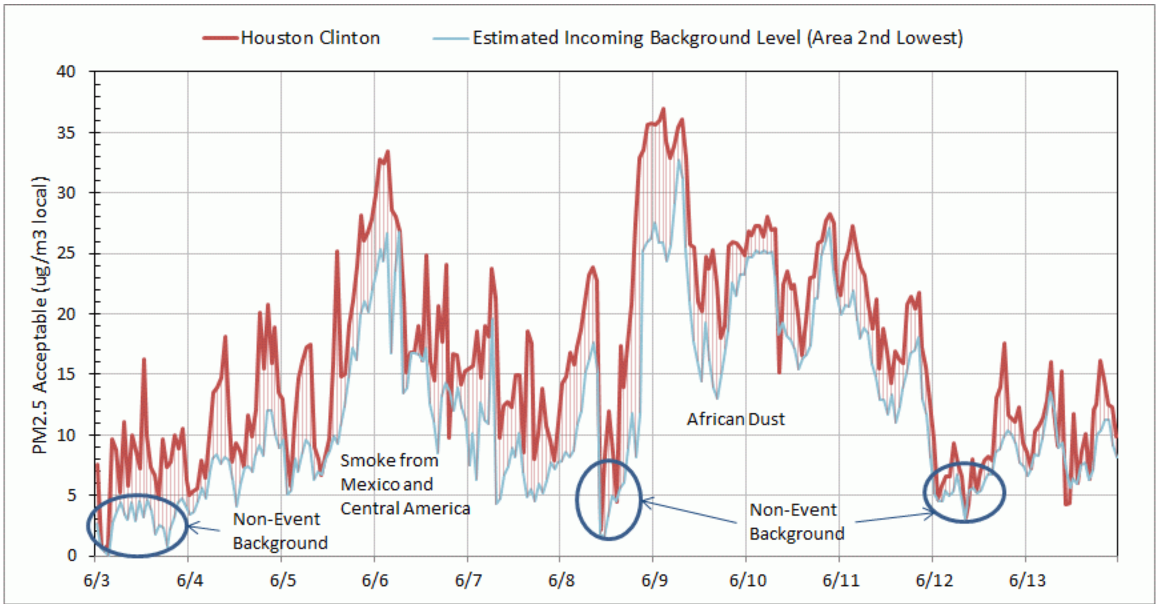

Figure 19. Houston Clinton hourly $PM_{2.5}$ concentrations for Houston Clinton and estimated incoming background, June 3-13, 2010.

In addition to increases in daily concentrations across the region, speciated measurements indicate a large increase in the IMPROVE method estimated soil levels on June 8th, indicating the arrival of African dust, and the soil levels remained high through June 11th. As mentioned previously, high silicon levels have been identified as an excellent marker for the presence of significant amounts of African dust (Goudie & et al, 2001). Figure 20 illustrates the increase in measured silicon concentrations from June 8th through 11th, with the highest silicon levels detected on the proposed exceptional event days of June 9th and 10th. Table 3 shows a summary of Houston area daily $PM_{2.5}$ measurements for June 3rd through 12th, and Table 4 shows the Houston Clinton daily $PM_{2.5}$ and speciation measurements for June 3rd through 12th.

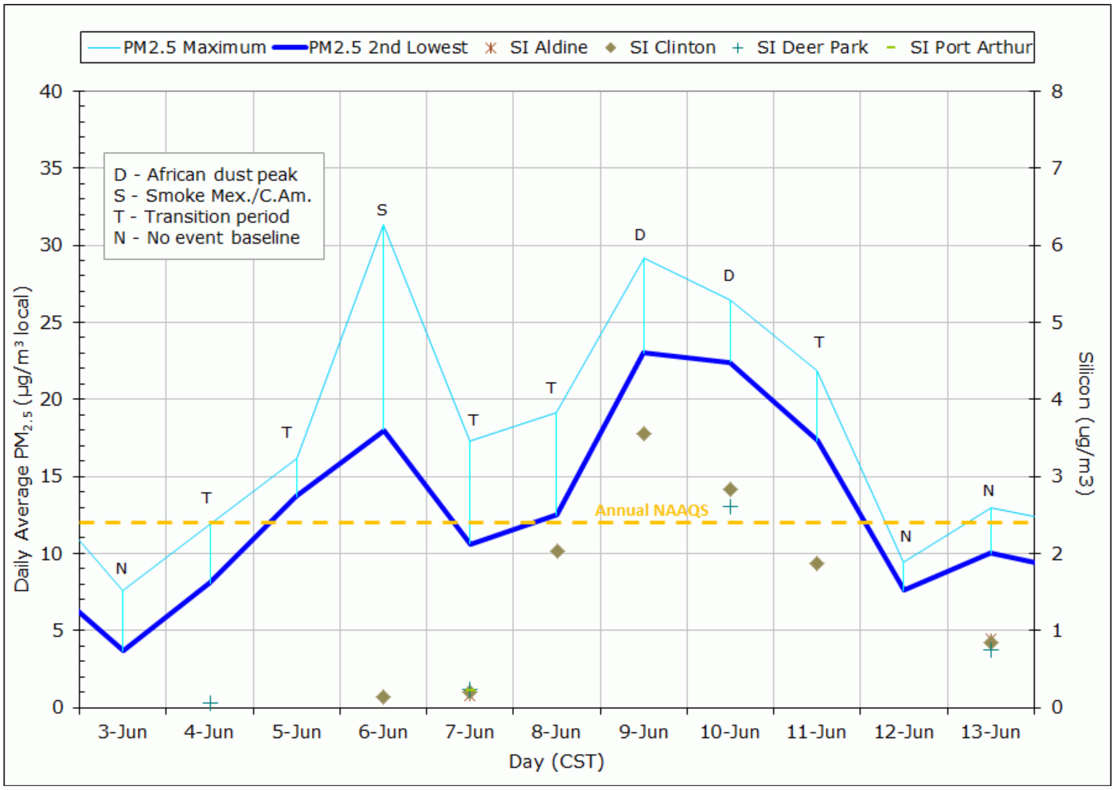

Figure 20. Houston daily average $PM_{2.5}$ and silicon (SI) concentrations at four speciation sites, June 3 through 13, 2010.

Table 3. Summary of Houston area daily $PM_{2.5}$ measurements for June 3rd through 12th (µg/m^3).

Houston Area Daily $PM_{2.5}$ Measurements	06/03/10	06/04/10	06/05/10	06/06/10	06/07/10	06/08/10	06/09/10	06/10/10	06/11/10	06/12/10
Maximum	7.6	11.9	*16.2*	*31.3*	*17.3*	*19.1*	*29.2*	*26.4*	*21.9*	9.4
Second Lowest	3.7	8.1	*13.7*	*18.0*	10.6	*12.5*	*23.0*	*22.4*	*17.3*	7.6
Lowest	2.8	7.9	11.3	14.1	6.8	8.7	*20.2*	*18.6*	*13.3*	6.2

Note: *Emphasis* indicates that a measurement is above the level of the annual $PM_{2.5}$ NAAQS.

Table 4. Houston Clinton daily $PM_{2.5}$ and speciation measurements for June 3rd through 12th ($\mu g/m^3$).

Speciation Measurements	06/03/10	06/04/10	06/05/10	06/06/10	06/07/10	06/08/10	06/09/10	06/10/10	06/11/10	06/12/10
$PM_{2.5}$	6.9	10.2	*15.4*	*22.9*	*13.4*	*18.7*	*29.2*	*25.1*	*19.9*	9.0
Soil				1.0	1.2	9.3	*16.1*	*13.1*	8.8	
OC				3.5	1.8	0.1	1.0			
AS				14.9	7.2	3.3	6.7	7.2	5.5	
Silicon				0.1	0.2	2.0	3.6	2.8	1.9	
Aluminum				0.1	0.1	0.8	1.5	1.2	0.8	
Iron				0.1	0.1	0.7	1.1	0.9	0.6	

Note: *Emphasis* indicates that a measurement is above the level of the annual $PM_{2.5}$ NAAQS.

Abbreviations:

$PM_{2.5}$ Clinton FRM $PM_{2.5}$ measurement

Soil IMPROVE estimate of soil component of speciation data

OC IMPROVE estimate of organic carbon component of speciation data

AS IMPROVE estimate of ammonium sulfate component of speciation data

Evaluation of the Clinton $PM_{2.5}$ concentrations but for the event requires calculation of both the non-event incoming background and local contributions. The baseline non-event incoming background level was estimated using an average of the second lowest Houston area measurement from the non-event days before and after the event, on June 3rd and June 12th. As shown in Figures 21 and 22, the Houston area second lowest $PM_{2.5}$ values indicate that incoming regional background levels were more than three times higher on June 9th and 10th than during non-event days before and after the African dust event. In addition, these figures show graphically the increase in soil SAF at the Clinton site corresponding with the increase in measured $PM_{2.5}$ during the proposed African dust event.

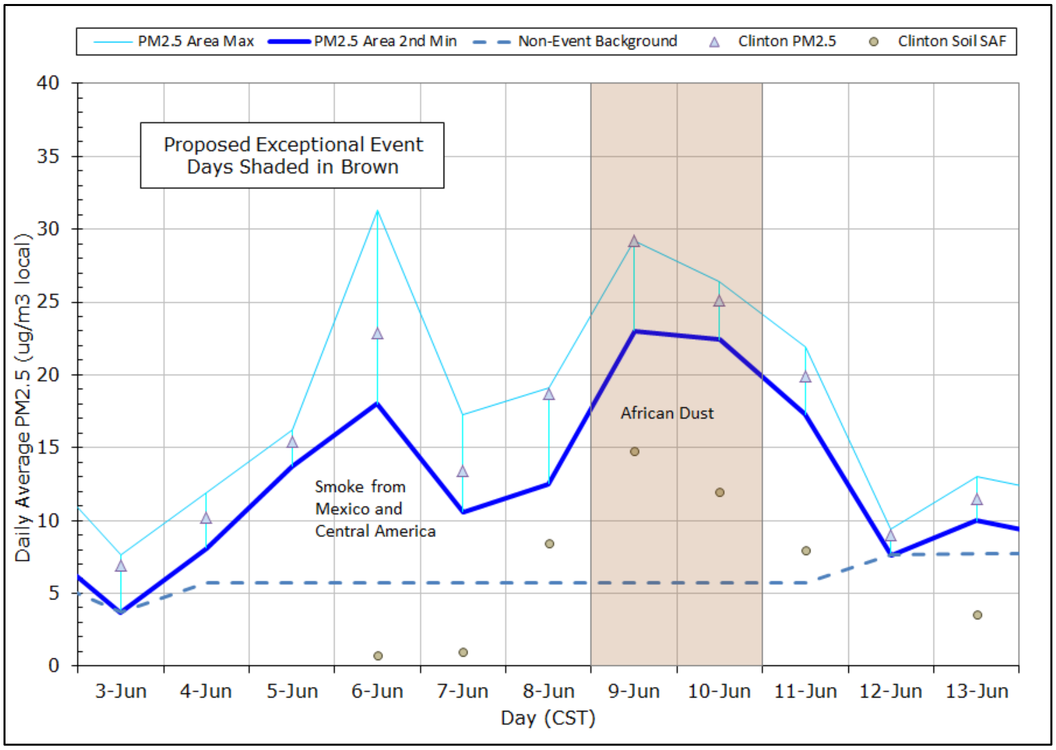

Figure 21. Houston area maximum and 2nd lowest 24-hour $PM_{2.5}$ concentrations with Clinton Soil SAF, June 3-13, 2010.

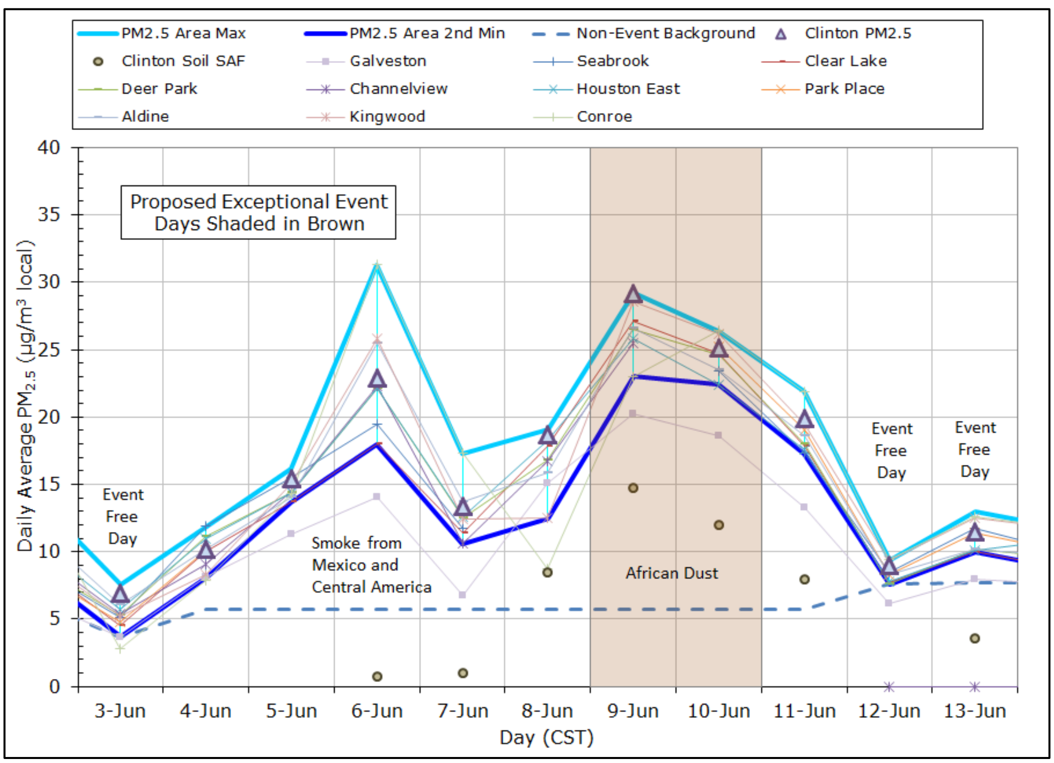

Figure 22. Houston area $PM_{2.5}$ concentrations and Clinton Soil SAF, June 3-13, 2010.

The second half of the "but for" calculation is estimating local contributions at the Clinton site. The local contribution for each day during this time period was calculated by subtracting the Houston area second lowest measurement from the Clinton $PM_{2.5}$ measurement for that day. The calculated local contributions were then added to the baseline non-event incoming background estimates for each day of the event, representing the Clinton "but for" $PM_{2.5}$ values. The Clinton "but for" $PM_{2.5}$ values were below the annual standard on all days of the event. Table 5 shows a summary of Houston daily $PM_{2.5}$ measurements for June 3rd through 12th, and Table 6 shows the Houston Clinton "but for" calculations for June 3rd through 12th. This analysis indicates that Clinton $PM_{2.5}$ concentrations would not have exceeded the annual standard on the proposed exceptional event days of June 9th and 10th without the occurrence of this African dust event.

Table 5. Summary of Houston daily $PM_{2.5}$ measurements for June 3rd through 12th (µg/m^3).

Houston Area Daily Average $PM_{2.5}$ Concentrations	06/03/10	06/04/10	06/05/10	06/06/10	06/07/10	06/08/10	06/09/10	06/10/10	06/11/10	06/12/10
Maximum	7.6	11.9	*16.2*	*31.3*	*17.3*	*19.1*	*29.2*	*26.4*	*21.9*	9.4
Second Lowest	3.7	8.1	*13.7*	*18.0*	10.6	*12.5*	*23.0*	*22.4*	*17.3*	7.6
Incoming Background Non-Event (BNE2)	3.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	7.6

Notes:

BNE2 is the average of the second lowest concentration before and after an event.

Emphasis indicates that a measurement is above the level of the annual $PM_{2.5}$ NAAQS.

Table 6. Houston Clinton "but for" calculations for June 3rd through 12th ($\mu g/m^3$).

Clinton "But For" Calculations	06/03/10	06/04/10	06/05/10	06/06/10	06/07/10	06/08/10	06/09/10	06/10/10	06/11/10	06/12/10
Clinton FRM $PM_{2.5}$ measurement	6.9	10.2	*15.4*	*22.9*	*13.4*	*18.7*	***29.2***	***25.1***	*19.9*	9.0
Difference between Clinton $PM_{2.5}$ measurement and Houston's second lowest concentration (DIF2)	3.2	2.1	1.7	4.9	2.8	6.2	6.2	2.7	2.6	1.4
But for Clinton concentration (BFE2)	6.9	7.8	7.4	10.6	8.5	11.9	11.9	8.4	8.3	9.0

Notes:

DIF2 is the estimate of the local contribution.

BFE2 is the sum of BNE2 from Table 5 and DIF2 from Table 6.

Emphasis indicates that a measurement is above the level of the annual $PM_{2.5}$ NAAQS.

July 13, 2010

A series of three large African dust clouds moved through the Houston area from July 8th through 17th of 2010 with the highest $PM_{2.5}$ concentrations on the proposed exceptional event day of July 13th. The impact of the African dust clouds was primarily seen in greatly increased soil component of the speciated $PM_{2.5}$ data, for which silicon is the strongest marker. Daily $PM_{2.5}$ AQI ratings across the U.S. are shown in Figure 23. This map shows a large regional event with "Moderate" levels (colored yellow) in association with the African dust covering the entire eastern half of Texas on July 13th.

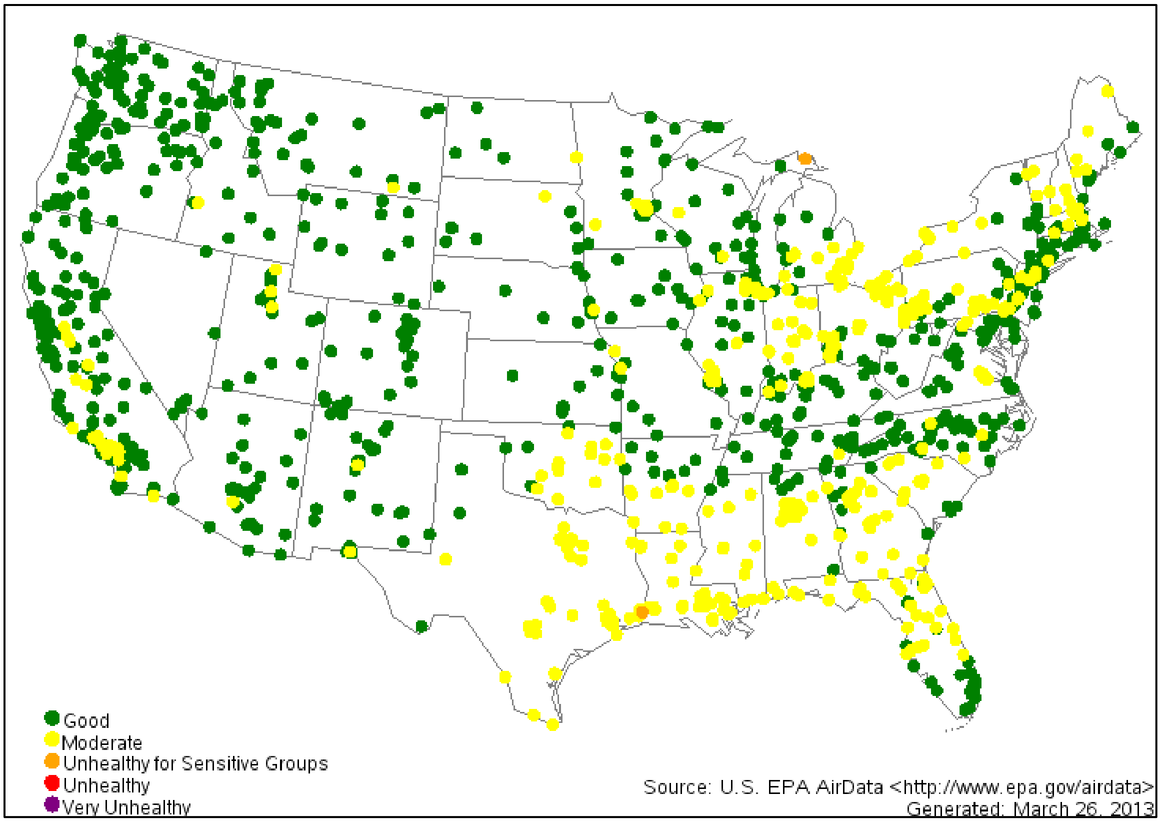

Figure 23. $PM_{2.5}$ AQI levels by site on July 13, 2010.

Elevated $PM_{2.5}$ measurements across Southeast Texas coupled with moderate southerly winds strongly suggest the influence of increased incoming background concentrations. Figure 24 shows a map of the $PM_{2.5}$ measurements in Southeast Texas for July 13th along with the daily wind statistics from the Houston Clinton site. While concentrations measured at Galveston were substantially lower than at inland sites, this difference can be attributed to greater dust concentrations aloft mixed to the ground because of increasing mixing heights inland. Due to moderate wind speeds over 10 miles per hour on this day local contributions at inland sites would have been minimized by strong dilution effects. These meteorological conditions paired with increased $PM_{2.5}$ concentrations inland are consistent with increased vertical concentration gradients representative of higher vertical mixing. This mixing is further illustrated by $PM_{2.5}$ concentrations at the Hamshire site mid-way between Beaumont and Galveston, which has no significant $PM_{2.5}$ sources upwind to the south. On July 13th Hamshire measured 22.3 µg/m^3 when Galveston measured 16.9 µg/m^3, indicating that incoming background levels were about 30 percent greater in concentration inland than along the immediate coast.

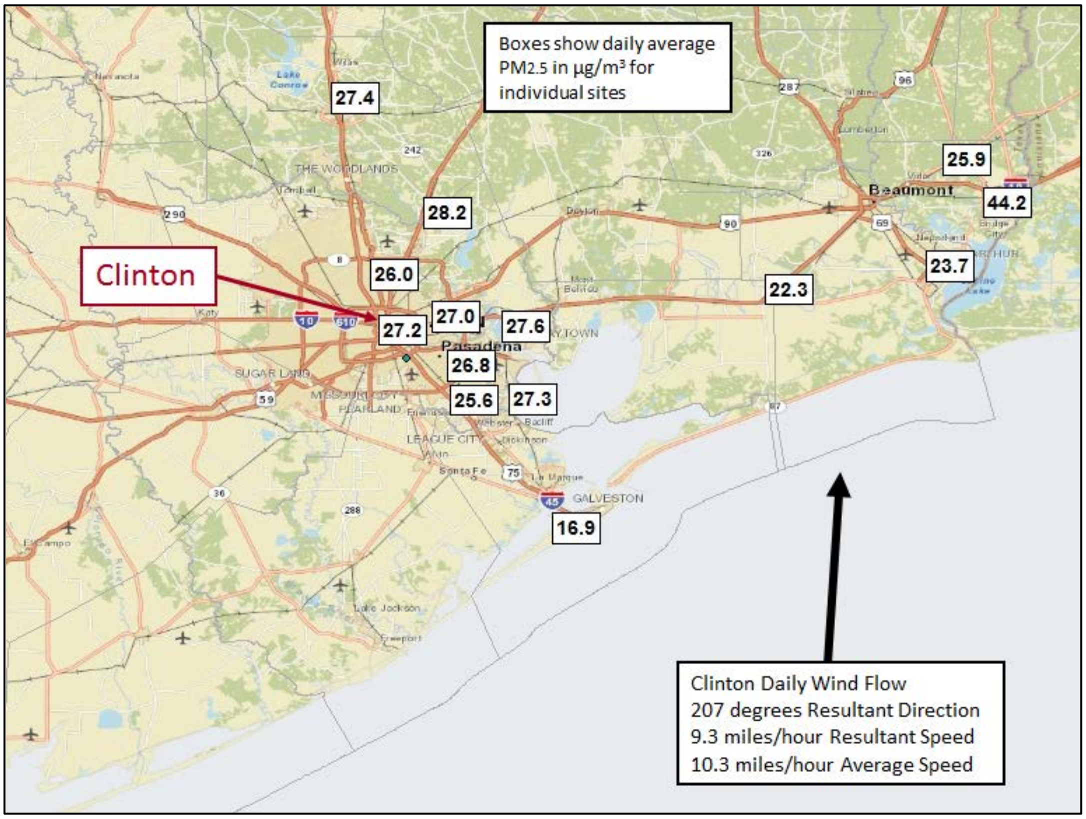

Figure 24. Map of $PM_{2.5}$ ($\mu g/m^3$) and wind measurements on July 13, 2010.

Wind directions and speeds for July 13th are depicted in Figure 25 using wind roses for selected monitoring locations in the region. The length of the bars on each wind rose indicates the frequency of winds occurring in the direction of the bar. The wind flow is along the bar toward the site. The wind roses show that winds were persistently from the south to southwest at all sites.

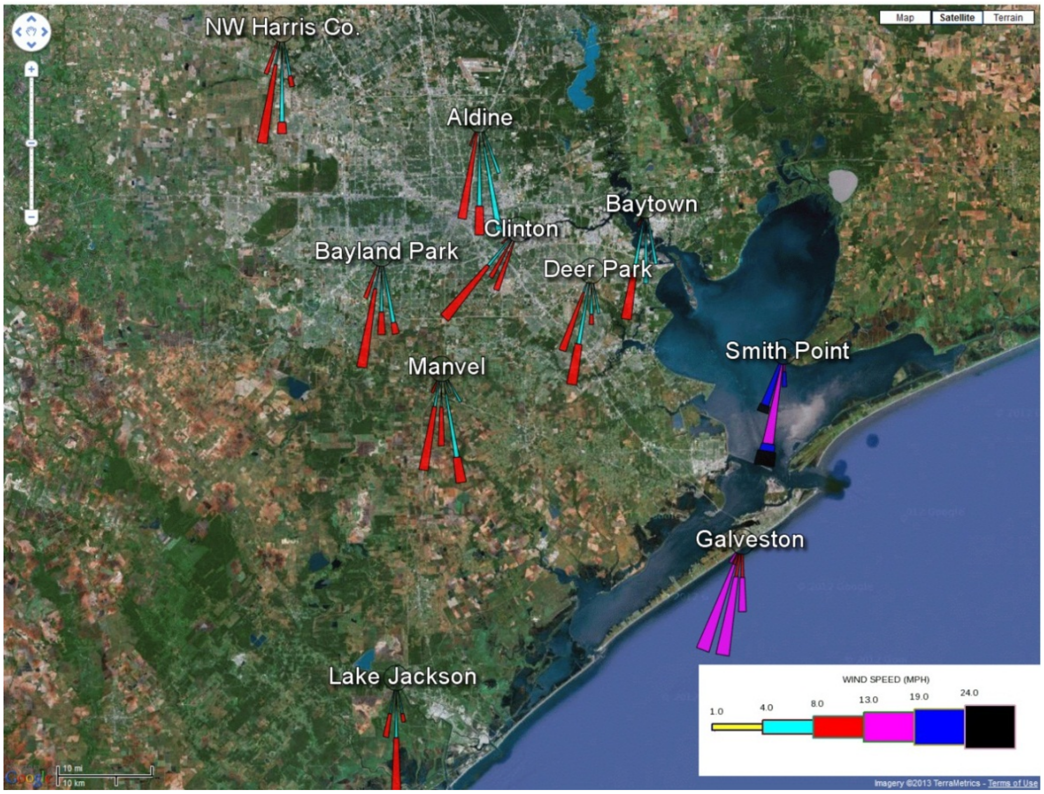

Figure 25. Wind rose plots for July 13, 2010.

$PM_{2.5}$ measurements at sites across the Houston area showed an increase in concentrations from July 8th through 17th. These measurements along with a predominant south to southeast wind flow indicate that $PM_{2.5}$ levels coming onshore from the Gulf of Mexico were very high, as illustrated in Figure 26 by the increase in $PM_{2.5}$ measurements across the area beginning on July 8th. Continuous hourly $PM_{2.5}$ measurements from all Houston sites during the time period of the event show a tight clustering of measurements as concentrations increase and decrease, providing strong evidence of a regional transport event affecting all sites, as illustrated in Figures 26 and 27. In these graphs, measurements from the Houston Clinton site are plotted with a thicker line. Variations among the sites can be caused by gradients in the incoming background levels, impacts from local emissions, and/or measurement uncertainties, all of which vary over time. Figure 26 provides a more detailed view of the Houston area continuous hourly $PM_{2.5}$ measurements from all sites during the peak of the African dust event from July 12th through 14th.

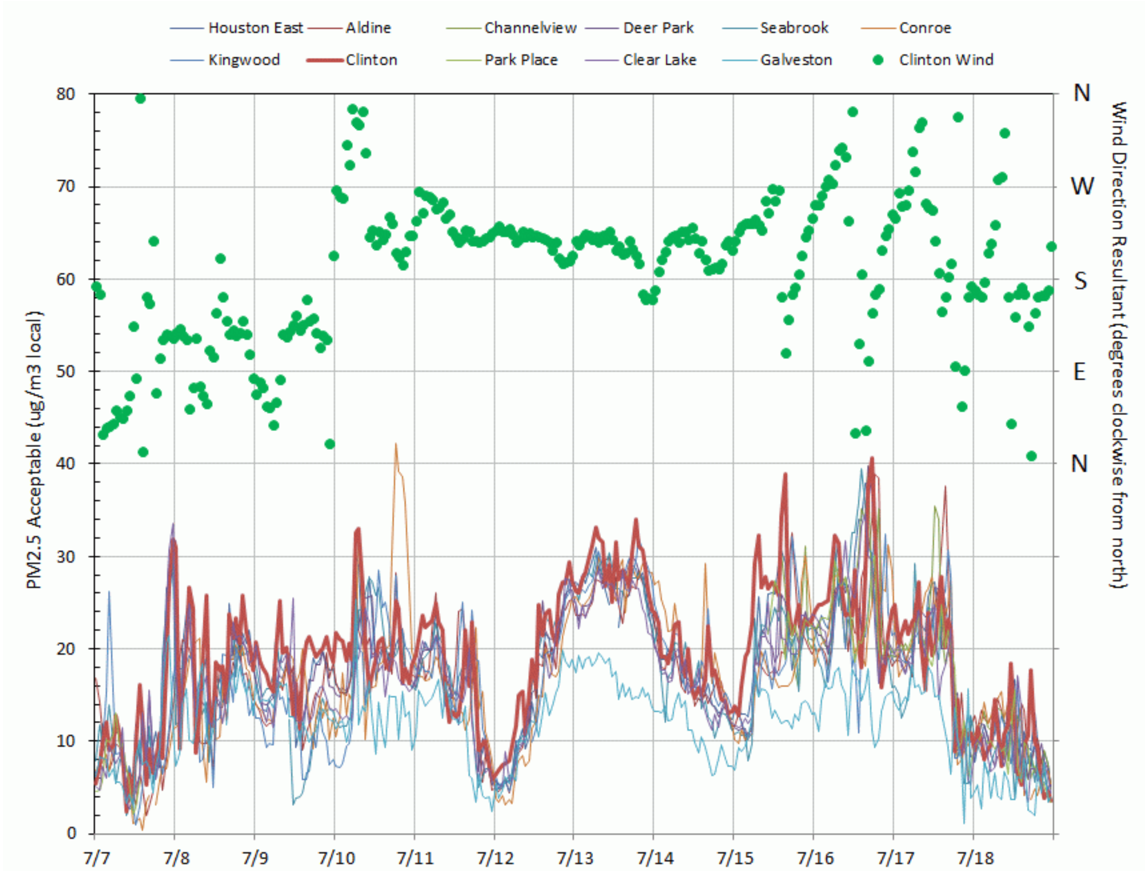

Figure 26. Houston Hourly $PM_{2.5}$ concentrations by site for July 17-18, 2010 with hourly wind direction at Houston Clinton.

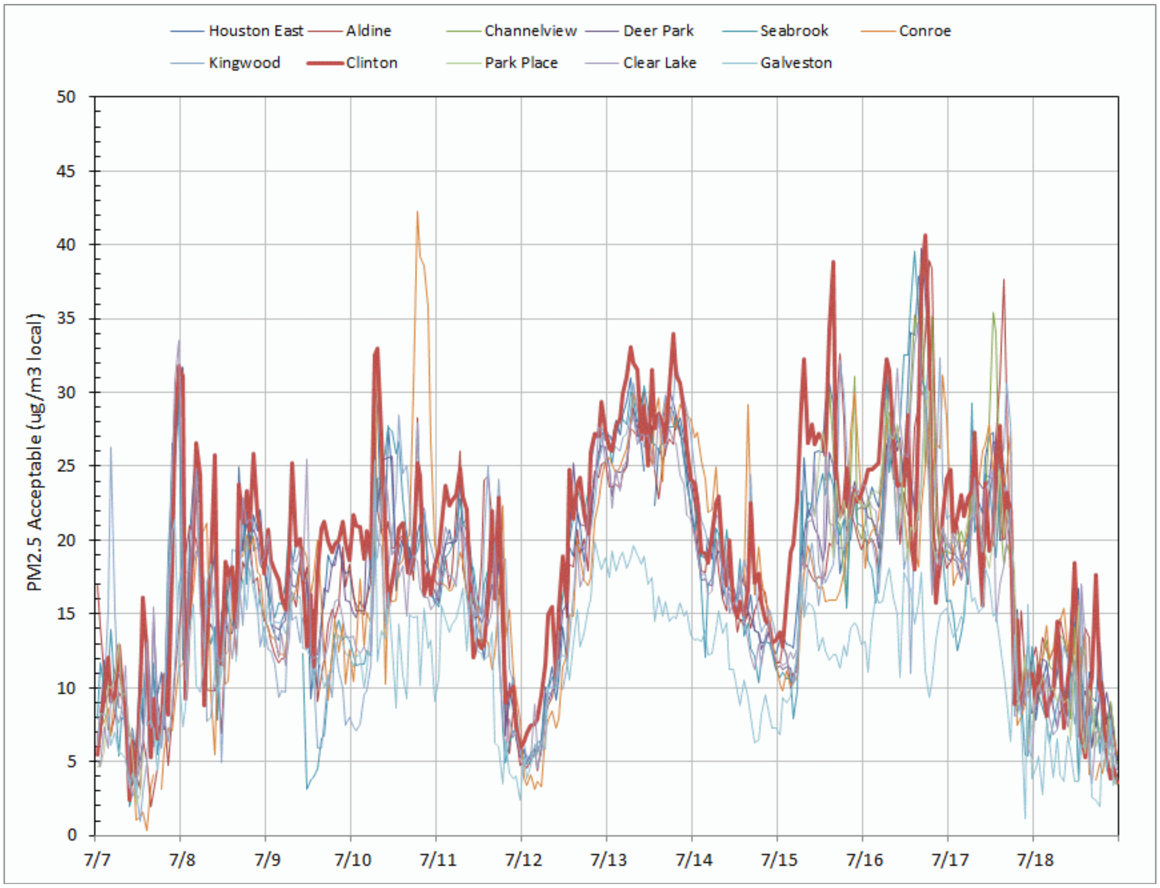

Figure 27. Houston Hourly $PM_{2.5}$ concentrations by site for July 12-14, 2010.

To bracket the beginning and end of the African dust event, hourly and daily $PM_{2.5}$ measurements from sites across the Houston area were evaluated. Daily $PM_{2.5}$ data for the Houston area shown in Table 7 indicates concentrations measured from July 8th through 17th were influenced by regional transport. Consequently, July 7th was used to indicate the initial event-free incoming background level before the African dust event and July 18th was used to indicate the event-free incoming background level at the end of the event. Figure 28 illustrates the hourly $PM_{2.5}$ concentrations before, during, and after the events and indicates the event-free background levels. The graph shows periods on July 7th, 12th, and 18th when incoming background levels were event-free. However, much of July 12th was not event-free, so the daily average was not used as the basis for the event-free baseline. The event-free daily average background levels as indicated by the second lowest Houston area daily averages on July 7th and 18th were averaged to estimate an event-free incoming background level baseline for July 13th.

Table 7. Houston daily $PM_{2.5}$ concentrations ($\mu g/m^3$) by site for July 7-18, 2010.

Site Name	Type	07/07/10	07/08/10	07/09/10	07/10/10	07/11/10	07/12/10	07/13/10	07/14/10	07/15/10	07/16/10	07/17/10	07/18/10
Galveston	AC	8.4	*13.6*	*13.2*	*13.1*	10.8	*11.5*	*16.9*	10.7	*12.6*	*14.7*	*12.9*	4.9
Seabrook	AC	11.0	*16.6*	*12.4*	*19.4*	*15.3*	*16.2*	*27.3*	*15.8*	*18.9*	*25.1*	*17.0*	7.8
Clear Lake	AC	10.6	*16.9*	*15.2*	*17.0*	*15.0*	*14.5*	*25.6*	*15.7*	*18.9*	*24.8*	*17.3*	8.3
Deer Park	AS	9.4			*17.8*			*24.5*			*21.3*		
Deer Park	AC	10.7	*16.9*	*16.1*	*20.2*	*15.7*	*15.1*	*26.8*	*16.2*	*19.1*	*24.8*	*19.0*	9.4
Baytown	FRM	9.7						*27.6*					
Channel-view	AC										*25.3*	*19.5*	9.9
Houston East	AC	11.6	*19.2*	*16.3*	*19.5*	*15.7*	*14.9*	*27.0*	*16.6*	*21.0*	*27.0*	*19.8*	10.2
Clinton	FRM	10.1	*19.2*	*17.9*	*20.7*	*16.7*	*15.6*	***27.2***	*16.7*	*22.6*	*24.2*		9.1
Clinton	AC	10.9	*19.3*	*18.6*	*20.9*	*16.8*	*17.6*	*28.9*	*18.0*	*24.3*	*26.0*	*19.5*	9.6
Park Place	AC										*23.5*	*18.2*	8.4
Aldine	FRM	8.5						*27.9*					
Aldine	AC	7.8	*15.6*	*14.6*	*19.4*	*16.4*	*14.5*	*26.0*	*16.5*	*18.5*	*24.3*	*20.1*	11.0
Kingwood	AC	8.8	*15.3*	11.2	*18.4*	*16.7*	*14.5*	*28.2*	*18.1*	*18.5*	*22.5*	*19.1*	9.1
Conroe	AC	6.0	*15.8*	*14.6*	*22.0*	*15.1*	*12.4*	*27.4*	*18.8*	*17.1*	*23.9*	*19.9*	9.8

Note: *Emphasis* indicates that a measurement is above the level of the annual $PM_{2.5}$ NAAQS.

Abbreviations:

AC Acceptable continuous

AS Acceptable speciated non-continuous

FRM Federal Reference Method

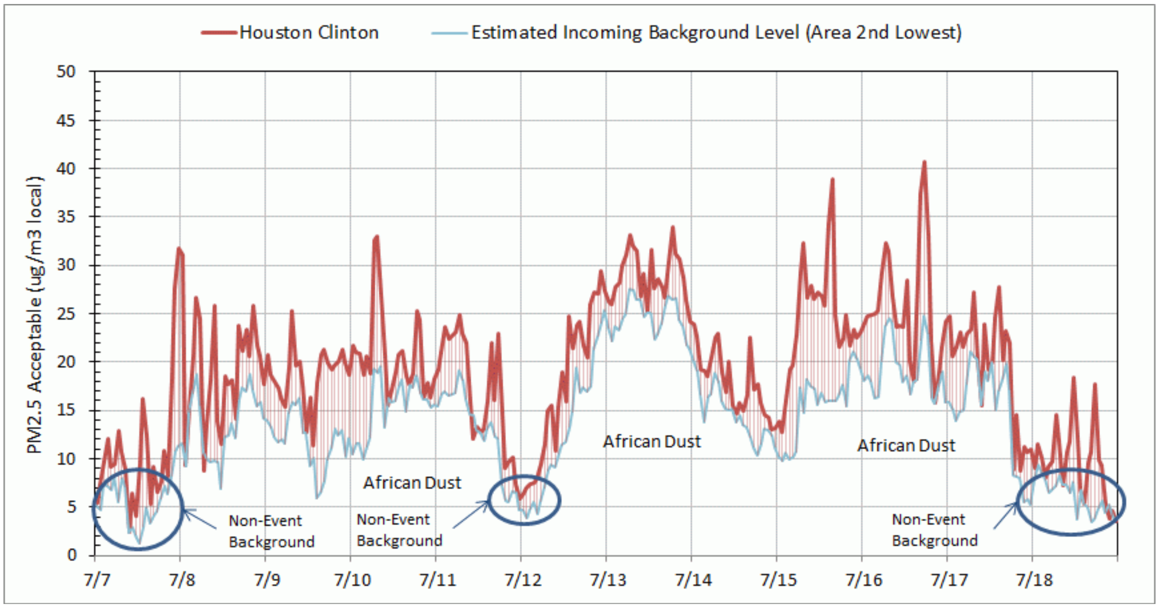

Figure 28. Houston Clinton Hourly $PM_{2.5}$ July 7-18, 2010.

In addition to increases in daily concentrations across the region, speciated measurements indicate a large increase in the IMPROVE method estimated soil levels on July 8th, indicating the arrival of African dust, and the soil levels remained high through July 17th. As mentioned previously, high silicon levels have been identified as an excellent marker for the presence of significant amounts of African dust (Goudie & et al, 2001). Figure 29 illustrates the increase in measured silicon concentrations from July 8th through 17th, with the highest silicon levels detected on July 13th, the proposed exceptional event day. Table 8 shows a summary of Houston area daily $PM_{2.5}$ measurements for July 7th through 18th, and Table 9 shows the Houston Clinton daily $PM_{2.5}$ and speciation measurements for July 7th through 18th.

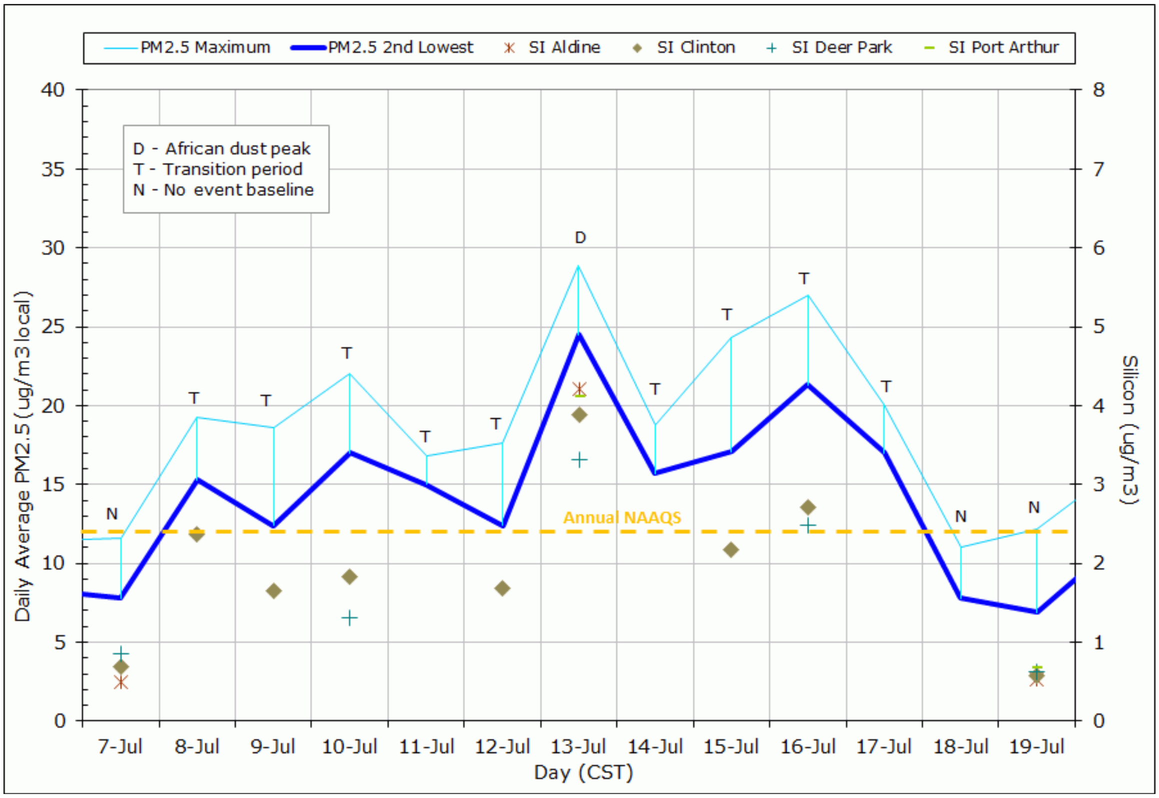

Figure 29. Houston area daily average $PM_{2.5}$ and silicon (SI) concentrations at four speciation sites, July 7 through 19, 2010.

Table 8. Summary of Houston area daily $PM_{2.5}$ measurements for July 7th through 18th ($\mu g/m^3$).

Houston Area Daily Average $PM_{2.5}$ Concentrations	07/07/10	07/08/10	07/09/10	07/10/10	07/11/10	07/12/10	07/13/10	07/14/10	07/15/10	07/16/10	07/17/10	07/18/10
Maximum	11.6	*19.3*	*18.6*	*22.0*	*16.8*	*17.6*	*28.9*	*18.8*	*24.3*	*27.0*	*20.1*	11.0
Second Lowest	7.8	*15.3*	*12.4*	*17.0*	*15.0*	*12.4*	*24.5*	*15.7*	*17.1*	*21.3*	*17.0*	7.8
Lowest	6.0	*13.6*	11.2	*13.1*	10.8	11.5	*16.9*	10.7	*12.6*	*14.7*	*12.9*	4.9

Note: *Emphasis* indicates that a measurement is above the level of the annual $PM_{2.5}$ NAAQS.

Table 9. Houston Clinton daily $PM_{2.5}$ and speciation measurements for July 7th through 18th (µg/m^3).

Speciation Measurements	07/07/10	07/08/10	07/09/10	07/10/10	07/11/10	07/12/10	07/13/10	07/14/10	07/15/10	07/16/10	07/17/10	07/18/10
$PM_{2.5}$	10.1	*19.2*	*17.9*	*20.7*	*16.7*	*15.6*	***27.2***	*16.7*	*22.6*	*24.2*		9.1
Soil	3.3	10.6	7.7	8.8		8.1	*17.7*		10.6	*12.4*		
OC	1.5	1.5	1.9	3.4		1.0	1.4		1.9	2.4		
AS	2.8	4.2	5.3	6.8		2.5	3.1		5.8	4.6		
Silicon	0.7	2.4	1.6	1.8		1.7	3.9		2.2	2.7		
Aluminum	0.3	1.1	0.8	0.8		0.8	1.7		1.0	1.2		
Iron	0.3	0.8	0.6	0.7		0.6	1.2		0.8	0.9		

Note: *Emphasis* indicates that a measurement is above the level of the annual $PM_{2.5}$ NAAQS.

Abbreviations:

$PM_{2.5}$ Clinton FRM $PM_{2.5}$ measurement

Soil IMPROVE estimate of soil component of speciation data

OC IMPROVE estimate of organic carbon component of speciation data

AS IMPROVE estimate of ammonium sulfate component of speciation data

Evaluation of the Clinton $PM_{2.5}$ concentrations but for the event requires calculation of both the non-event incoming background and local contributions. The baseline non-event incoming background level was estimated using an average of the second lowest Houston area measurement from the non-event days before and after the event, on July 7th and July 18th. Incoming regional $PM_{2.5}$ background levels were estimated to be three times higher on July 13th than during non-event days before and after the African dust event. Figures 30 and 31 illustrate an increase in regional background levels from July 8th through July 17th compared to non-event days before and after the African dust event. In addition, these figures show graphically the increase in soil SAF at the Clinton site corresponding with the increase in measured $PM_{2.5}$ during the proposed African dust event.

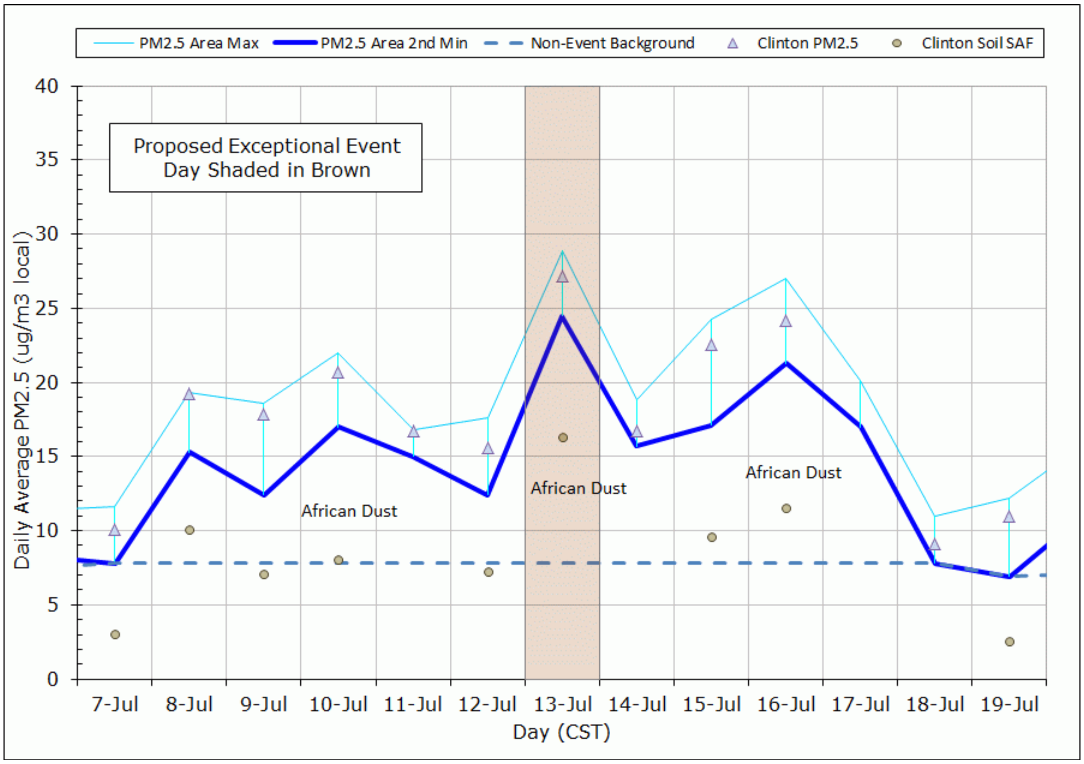

Figure 30. Houston area maximum and 2nd lowest 24-hour $PM_{2.5}$ concentrations with Clinton soil SAF, July 7-19, 2010.

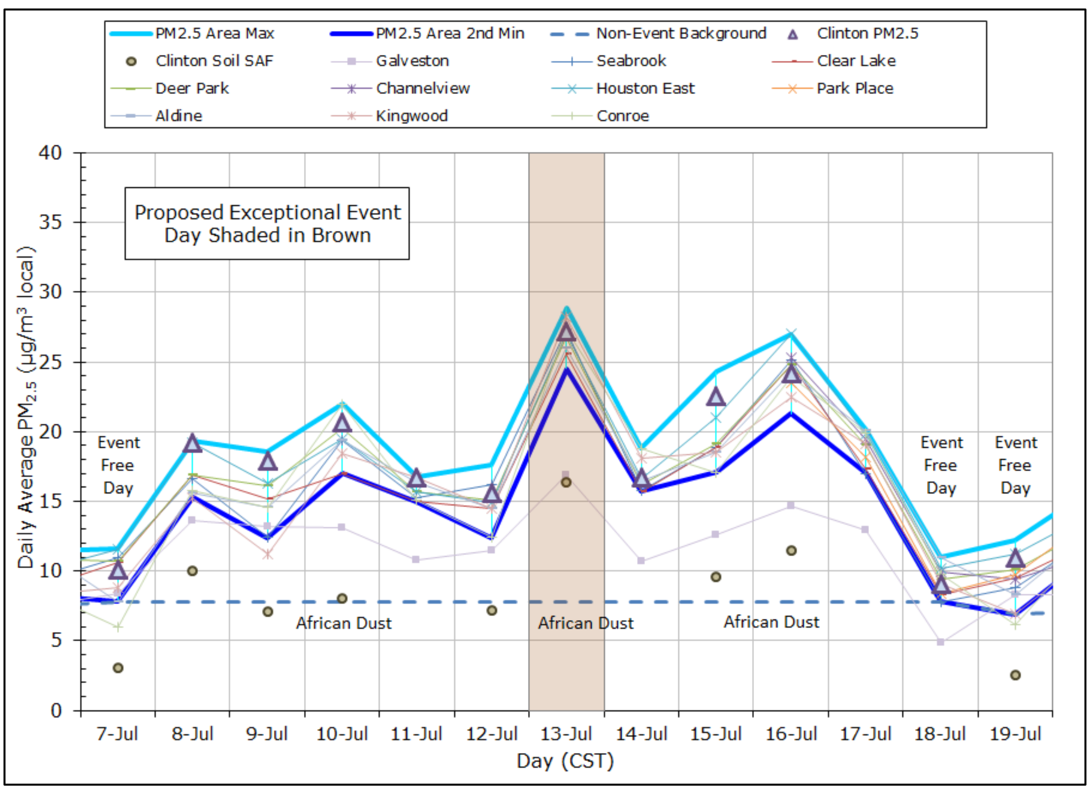

Figure 31. Houston area $PM_{2.5}$ concentrations and Clinton soil SAF, July 7-19, 2010.

The second half of the "but for" calculation is estimating local contributions at the Clinton site. The local contribution for each day during this time period was calculated by subtracting the Houston area second lowest measurement from the Clinton $PM_{2.5}$ measurement for that day. The calculated local contributions were then added to the baseline non-event incoming background estimates for each day of the event, representing the Clinton "but for" $PM_{2.5}$ values. The Clinton "but for" $PM_{2.5}$ values were below the annual standard on all days of the event. Table 10 shows a summary of Houston daily $PM_{2.5}$ measurements for July 7th through 18th, and Table 11 shows the Houston Clinton "but for" calculations for July 7th through 18th. This analysis indicates that Clinton $PM_{2.5}$ would not have exceeded the annual standard on the proposed exceptional event day on July 13th without the occurrence of this African dust event.

Table 10. Summary of Houston daily $PM_{2.5}$ measurements for July 7th through 18th ($\mu g/m^3$).

Houston Area Daily Average $PM_{2.5}$ Concentrations	07/07/10	07/08/10	07/09/10	07/10/10	07/11/10	07/12/10	07/13/10	07/14/10	07/15/10	07/16/10	07/17/10	07/18/10
Maximum	11.6	*19.3*	*18.6*	*22.0*	*16.8*	*17.6*	*28.9*	*18.8*	*24.3*	*27.0*	*20.1*	11.0
Second Lowest	7.8	*15.3*	*12.4*	*17.0*	*15.0*	*12.4*	*24.5*	*15.7*	*17.1*	*21.3*	*17.0*	7.8
Incoming Background Non-Event (BNE2)	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8

Notes:

BNE2 is the average of the second lowest concentration before and after an event.

Emphasis indicates that a measurement is above the level of the annual $PM_{2.5}$ NAAQS.

Table 11. Houston Clinton "but for" calculations for July 7th through 18th ($\mu g/m^3$).

Clinton "But For" Calculations	07/07/10	07/08/10	07/09/10	07/10/10	07/11/10	07/12/10	07/13/10	07/14/10	07/15/10	07/16/10	07/17/10	07/18/10
Clinton FRM $PM_{2.5}$ measurement	10.1	*19.2*	*17.9*	*20.7*	*16.7*	*15.6*	***27.2***	*16.7*	*22.6*	*24.2*		9.1
Difference between Clinton $PM_{2.5}$ measurement and Houston's second lowest concentration (DIF2)	2.3	3.9	5.5	3.7	1.7	3.2	2.7	1.0	5.5	2.9		1.3
But for Clinton concentration (BFE2)	10.1	9.6	11.2	9.4	7.4	8.9	8.4	6.7	11.2	8.6		9.1

Notes:

DIF2 is the estimate of the local contribution.

BFE2 is the sum of BNE2 from Table 10 and DIF2 from Table 11.

Emphasis indicates that a measurement is above the level of the annual $PM_{2.5}$ NAAQS.

Exceptional Events Demonstration

Affects Air Quality

All of the proposed exceptional event days for 2010 had measured concentrations over 25 µg/m^3, well above the annual $PM_{2.5}$ standard of 12.0 µg/m^3. These days were also above the 95th percentile of all FRM $PM_{2.5}$ measurements (22.5 µg/m^3) at the Houston Clinton site during the period from 2008 through 2010. Thus, these measurements were among the highest five percent of measurements over the three-year period ending with 2010 at the Houston Clinton FRM $PM_{2.5}$ monitor. The preamble to the Exceptional Event rule (72 *Federal Register* 13569) states:

"For extremely high concentrations relative to historical values (e.g., concentrations greater than the 95th percentile), a lesser amount of documentation or evidence may be required to demonstrate that the event affected air quality."

Figure 32 shows the 1,002 Houston Clinton FRM $PM_{2.5}$ valid daily measurements for the period from 2008 through 2010 and indicates the three proposed 2010 exceptional event days. There were two other high days in 2010 on January 13th and February 1st that were not found to have high incoming background levels and therefore were not proposed as exceptional events.

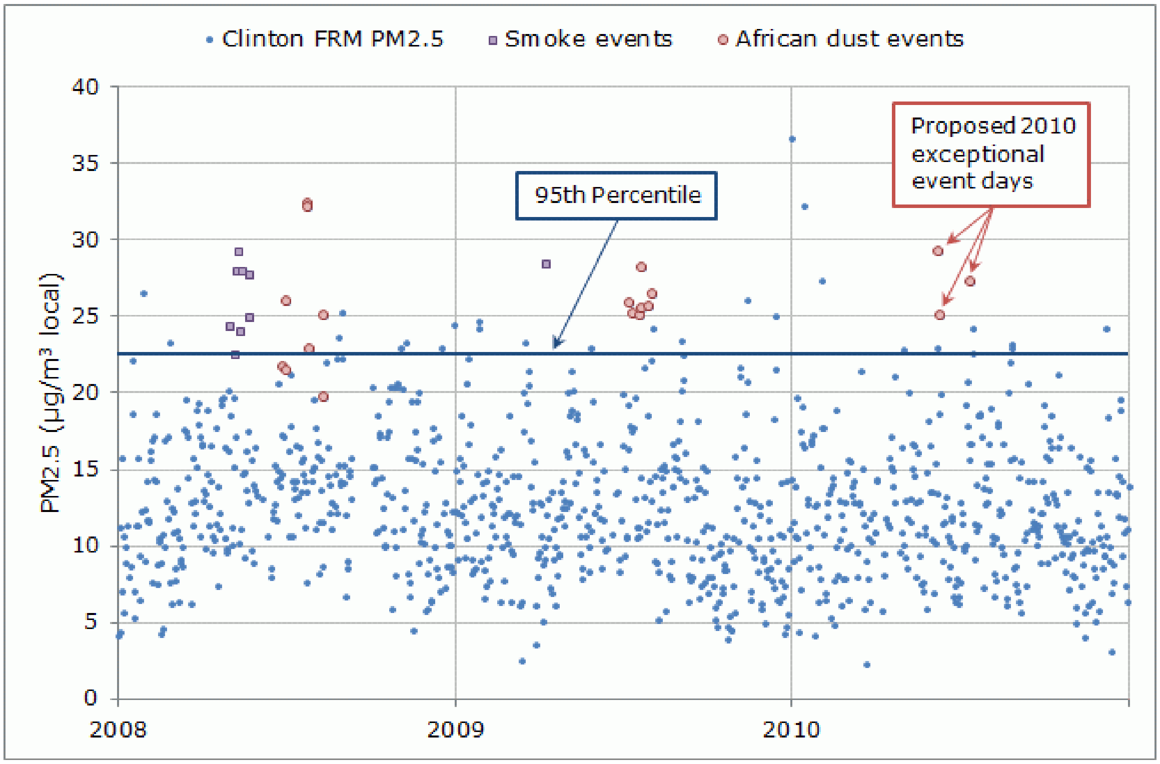

Figure 32. Houston Clinton FRM $PM_{2.5}$ daily measurements from 2008 through 2010, with symbols showing analyzed events from African dust and from smoke from agricultural burning in Mexico and Central America.

Not Reasonably Controllable or Preventable

All of the proposed events had incoming regional background levels greatly exceeding the annual standard as indicated by the second lowest area daily measurement (see Figures 21 and 30). Local source controls could not affect these high incoming levels. Also, satellite imagery and back trajectories show the transport of large amounts of fine particulate from uncontrollable sources outside of the United States and Texas associated with African dust as shown in Appendices B and C and discussed further below. The “but for” analysis presented below provides strong evidence that these exceedances of the $PM_{2.5}$ annual standard would not have occurred but for the African dust events.

Natural Events

All three of the proposed exceptional event flags for 2010 are for African dust events, which are natural events. African dust impacts the Houston area every year, mainly in the summer, with typically three to six intense episodes that are characterized by high incoming background levels and lasting one to three days or more. Satellite imagery provides good visual evidence of African dust moving across the Atlantic Ocean, through the Caribbean, and into the Gulf of Mexico. Figure 33 shows an example satellite image of a large African dust cloud as it departed Africa. NASA's description of this image states, "On May 29, 2010, dust plumes continued blowing westward across the Atlantic Ocean. The Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite captured this natural color image on May 29, 2010. The dust, which likely arose far inland in the Sahara Desert, extends from Dakar, Senegal, well past Cape Verde." (Scott, 2010)

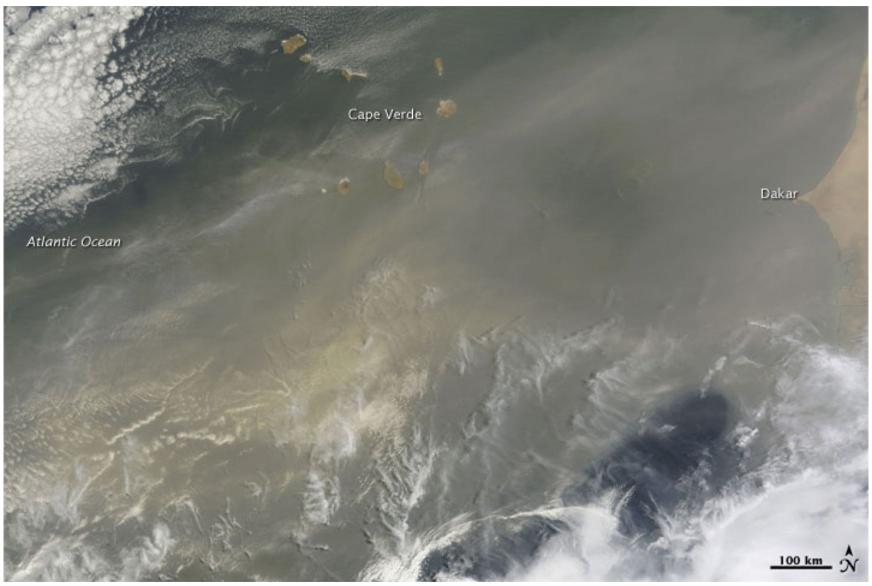

Figure 33. Natural color image of the large dust cloud that reached Houston on June 8-10 as it entered the Atlantic Ocean from Africa. (Scott, 2010)

Clear Causal Relationship

Speciated $PM_{2.5}$ data show a very large contribution of soil species consistent with African dust on all three days as discussed in the Event Summary section. In addition, satellite imagery, backward air trajectories, and aerosol modeling confirm the transport of dust from Africa across the Atlantic, Caribbean Sea, and Gulf of Mexico and into the Houston area as shown in Appendices B and C. The visible satellite imagery and aerosol model output provide a daily record of dust cloud locations back to Africa. The back trajectories provide additional confirmation of the path of the air. Figure 34 shows backward-in-time air parcel trajectories for air arriving in the Houston area mid-day on each of the proposed exceptional event days (NOAA ARL, 2013). These back trajectories are not allowed to run more than

312 hours backward in time, but provide supporting evidence that the air came from Africa and show a good agreement with satellite tracking of the African dust. Figure 35 shows an example of NRL aerosol model output for June 1, 2010, showing the dust cloud that arrived in the Houston area on June 9-10, 2010, as it was moving into the Lesser Antilles from the tropical Atlantic Ocean.

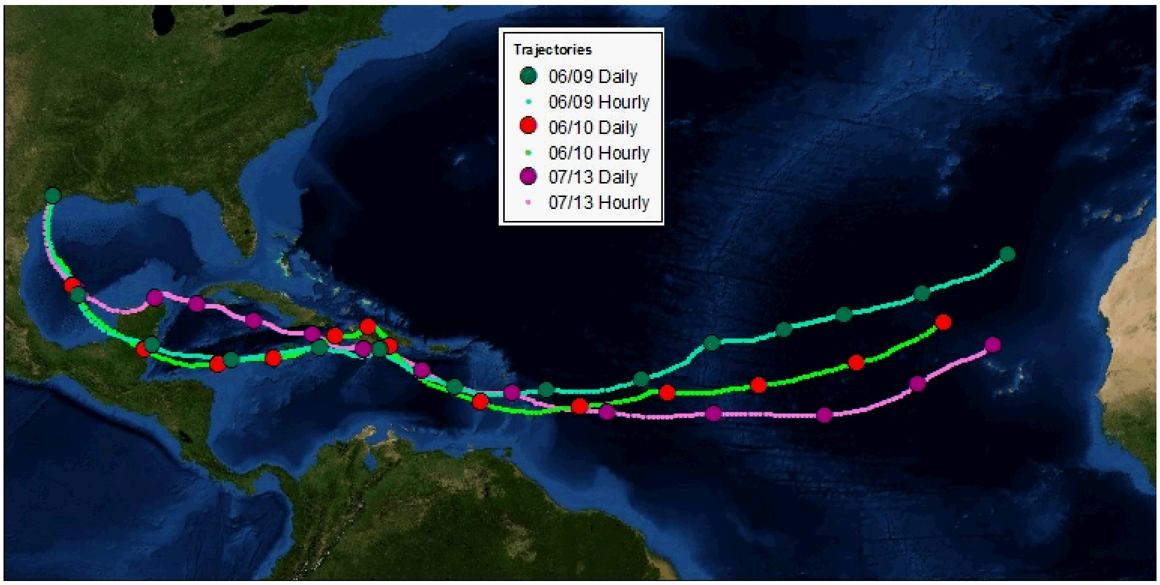

Figure 34. Plot of HYSPLIT model backward-in-time air parcel trajectories for each 2010 exceptional event day, for air arriving at noon Central Standard Time (mid-point of the EPA calendar day) each day (NOAA ARL, 2013)

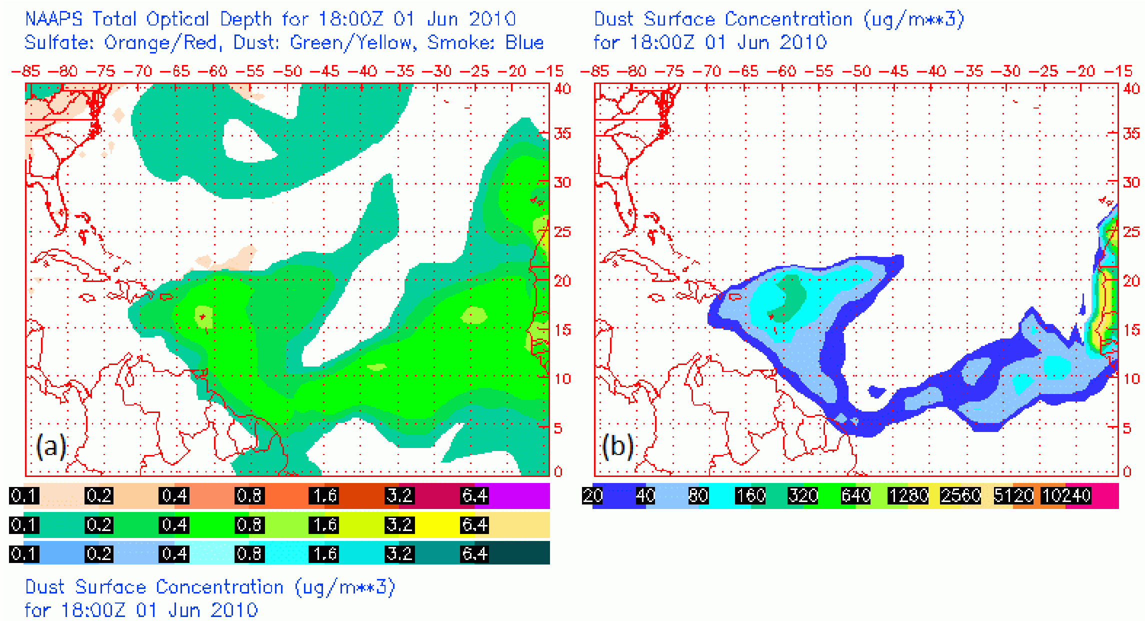

Figure 35. Example of NRL aerosol model output for June 1, 2010, showing (a) aerosol optical depth and (b) dust surface concentration, for the dust cloud that arrived in Houston on June 9-10 as it was moving into the Lesser Antilles.

Sequences of satellite images provided in Appendix B indicate that this is the dust cloud that arrived in the Houston area on June 9 and 10, 2010. Figure 36 shows the same dust cloud as it approached the Lesser Antilles on June 1st with a trail of dust extending back to Africa behind it. The dust appears brownish-grayish in these images and clouds are bright white. Cloud-free areas over the ocean are normally very dark blue in these natural color images when no dust or haze is present.

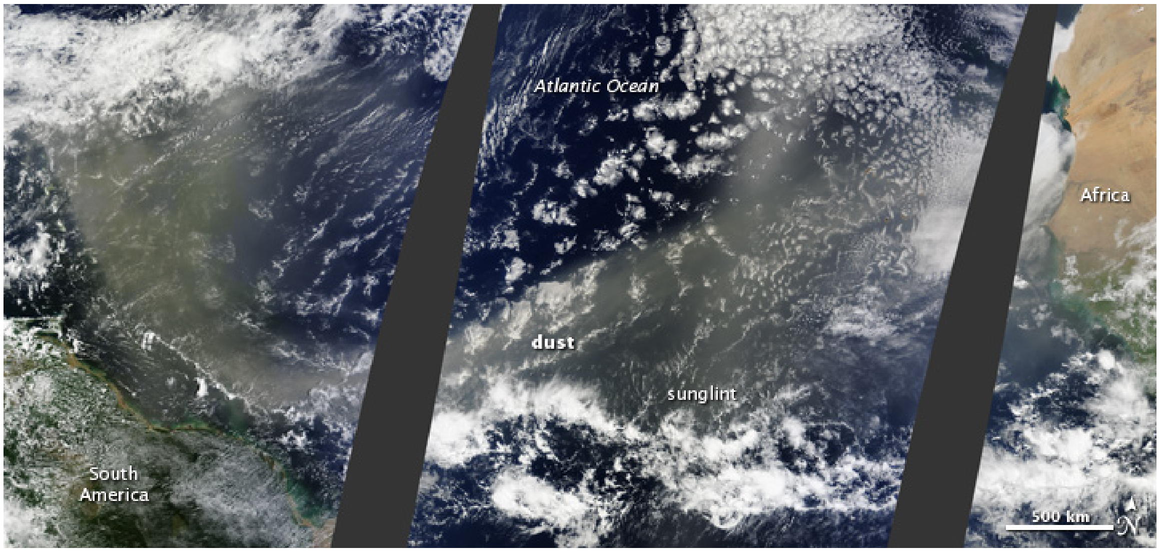

Figure 36. NASA MODIS natural color satellite image composite showing African dust approaching the Lesser Antilles and stretching across the Atlantic Ocean to Africa (Lindsey, 2010).

Silicon is an excellent marker for African dust events in Southeast Texas because it remains low except during transported dust events as previously described and shown in Figure 7. Silicon levels were elevated by a factor of five to ten in the Houston area on the African dust events marked with a "D" as compared to typical days without African dust before and after each event as shown in Figure 37.

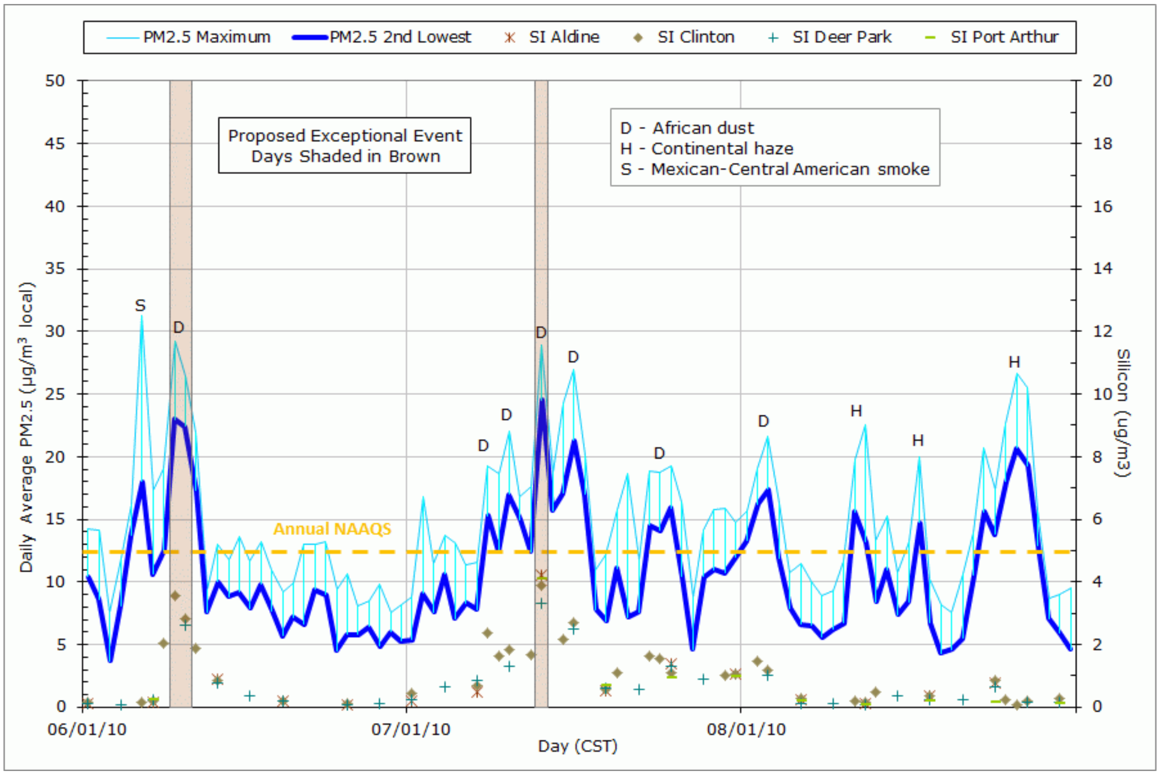

Figure 37. Houston area maximum and second lowest $PM_{2.5}$ levels each day (blue lines) based on both FRM and Tapered Element Oscillating Microbalance (TEOM) data, along with all available speciated silicon (SI) measurements (symbols) for the summer of 2010.

$PM_{2.5}$ levels were high at all Houston area sites on the proposed African dust exceptional event days and estimated incoming background levels were also very high. Incoming background levels were estimated using the Houston area second lowest measurement out of 10 to 15 measurements each day. The estimated incoming $PM_{2.5}$ background levels (area second lowest measurements) were over 20 µg/m^3 and the SAF soil contribution alone was over 12 µg/m^3 on each of the proposed exceptional event days as shown in Figure 38. During all of the proposed African dust exceptional event days, the Houston Clinton $PM_{2.5}$ concentration and estimated incoming background levels were two to three times higher than levels in the intervening period.

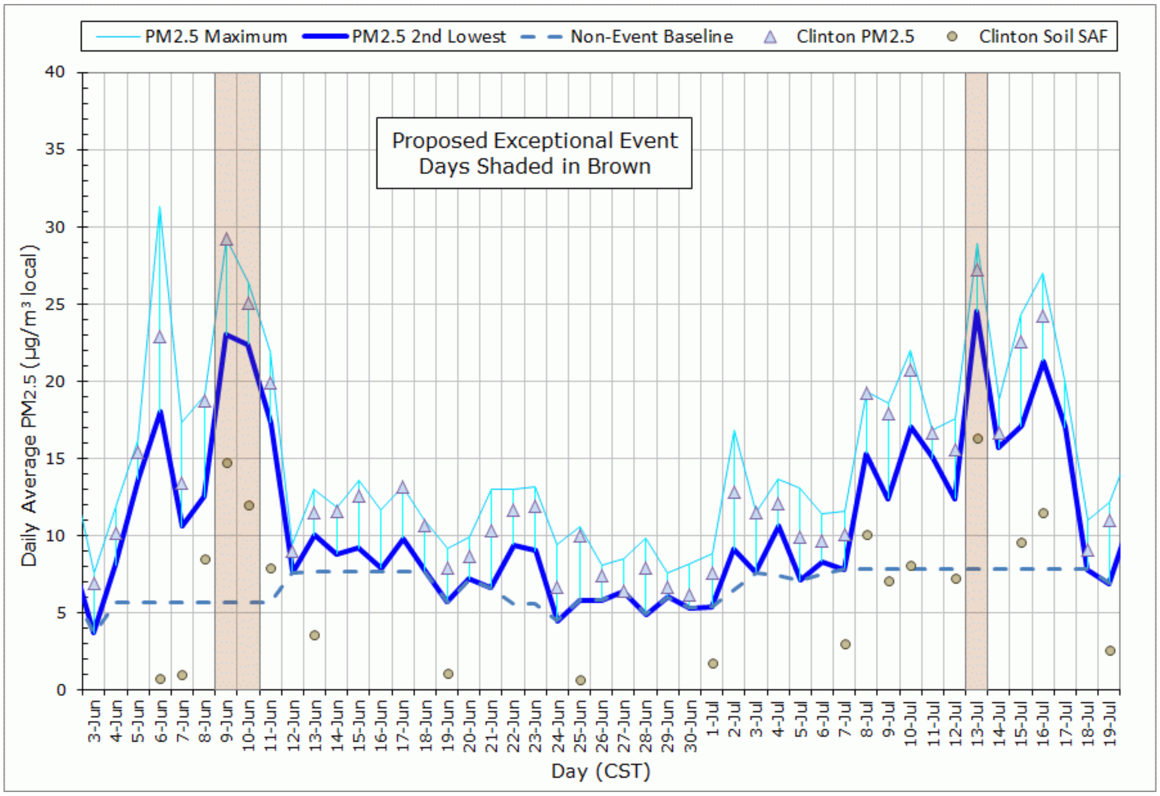

Figure 38. Houston area maximum and second lowest $PM_{2.5}$ levels, estimated non-event baseline $PM_{2.5}$ levels, Clinton $PM_{2.5}$ levels, and soil SAF from June 3 through July 19, 2010.

All together, the satellite imagery, aerosol model output, backward-in-time air trajectories, and speciated $PM_{2.5}$ data provide clear evidence that increased $PM_{2.5}$ concentrations at the Houston Clinton site on the proposed exceptional events were related to these African dust events.

Event In Excess of Normal Historical Fluctuations

As mentioned in the Affects Air Quality section, $PM_{2.5}$ concentrations during the proposed exceptional event days were well above normal historical measurements. Statistics for the Houston Clinton FRM $PM_{2.5}$ monitor for 1,002 measurements over the three-year period from 2008 through 2010 show a 95th percentile concentration of 22.5 µg/m^3. Measurements on all three proposed exceptional events days were well above this 95th percentile and therefore were well in excess of normal historical fluctuations. See Figure 32 above for a comparison of the proposed exceptional event days to all Houston Clinton $PM_{2.5}$ measurements for 2008 through 2010.

No Exceedance But For the Event

Title 40 CFR 50.14(c)(3)(iv)(D) states the demonstration to justify exceptional event designation shall provide evidence that "there would have been no exceedance or violation but for the event."

TCEQ used two methods for estimating the daily $PM_{2.5}$ concentration at the Houston Clinton site but for the African dust events in June and July 2010. First, a mathematical analysis was used to determine the Houston Clinton site's $PM_{2.5}$ concentration without the effect of the exceptional event. This value was derived by adding the estimated local contribution impacting the Houston Clinton site and an estimated Houston area baseline non-event incoming background level. The local contribution was estimated by taking the Houston Clinton daily measurement and subtracting the Houston area second lowest daily measurement for the same day. The Houston area baseline non-event incoming background level was derived by averaging the second lowest area measurement on days not impacted by significant transport events before and after the proposed exceptional event day. All values are provided in Tables 5 and 10 of the Event Summary section. Further, Figure 39 shows the estimated Clinton "but for" concentration (triangles) and the estimated baseline non-event incoming background level (blue line) for the period including the three proposed exceptional events. The daily difference between these two estimates is the estimated local contribution to the $PM_{2.5}$ measurement at Houston Clinton (pink vertical line). This analysis shows the Houston Clinton estimated "but for" concentration did not exceed the annual NAAQS on the three proposed exceptional event days and therefore meet the "but for" requirement. The daily numerical measurements for all area sites were previously shown in Tables 2 and 7 and resulting daily "but for" estimates were shown previously in Tables 6 and 11.

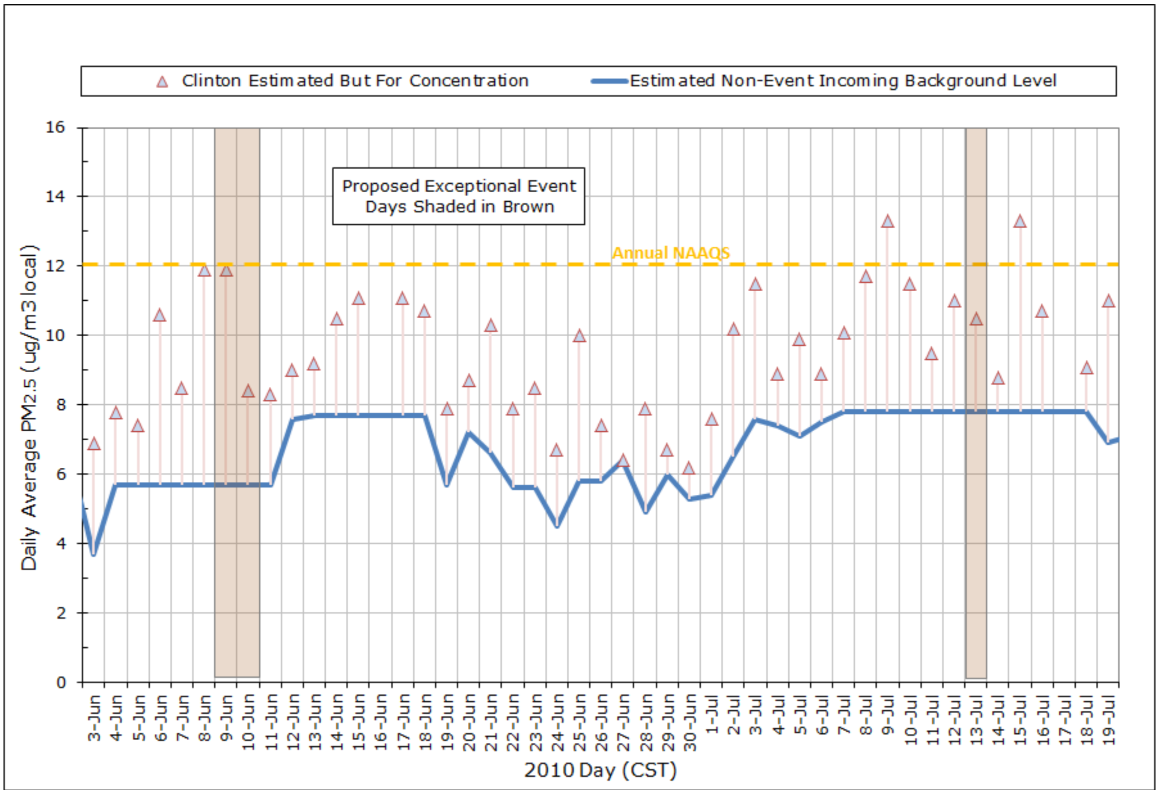

Figure 39. Houston Clinton daily estimated $PM_{2.5}$ but for event concentrations June 3 through July 19, 2010.

Second, TCEQ evaluated the impact to the Houston Clinton $PM_{2.5}$ daily average during the summer of 2010 after removing all days with an indicated African dust impact. A baseline soil SAF level was derived by calculating the 98th percentile of soil SAF levels from the speciated $PM_{2.5}$ data for monitoring conducted from September through May during 2005 through 2011. Using this method, the baseline soil SAF was calculated at 2.38 $\mu g/m^3$, however to be conservative a baseline soil SAF of 4 $\mu g/m^3$ was used to indicate days with an African dust impact. Applying this baseline soil SAF level, those days with measured soil SAF levels of 4 $\mu g/m^3$ or higher at Houston Clinton were identified for removal from the June through August 2010 data due to an indicated African dust impact. Based on all 91 valid measurements at the Houston Clinton site for June through August 2010, the average $PM_{2.5}$ concentration was 13.4 $\mu g/m^3$. As shown in Figure 40, there were 19 days identified by the speciated data as having an African dust impact at Houston Clinton with an average $PM_{2.5}$ concentration of 19.9 $\mu g/m^3$. Using the Houston area daily second lowest measurements, the average incoming background level during these 19 days is estimated at 16.4 $\mu g/m^3$. Removing these 19 days results in a $PM_{2.5}$ daily average of 11.8 $\mu g/m^3$ for the Houston Clinton site during the summer of 2010. This average should be conservatively high because it does not exclude days where speciation data were not available during African dust events, as well as days where other types of transport events such as smoke from Mexico and Central America and continental haze occurred. This analysis provides further supporting evidence that the daily $PM_{2.5}$ would not have exceeded the level of the annual NAAQS but for the African dust events.

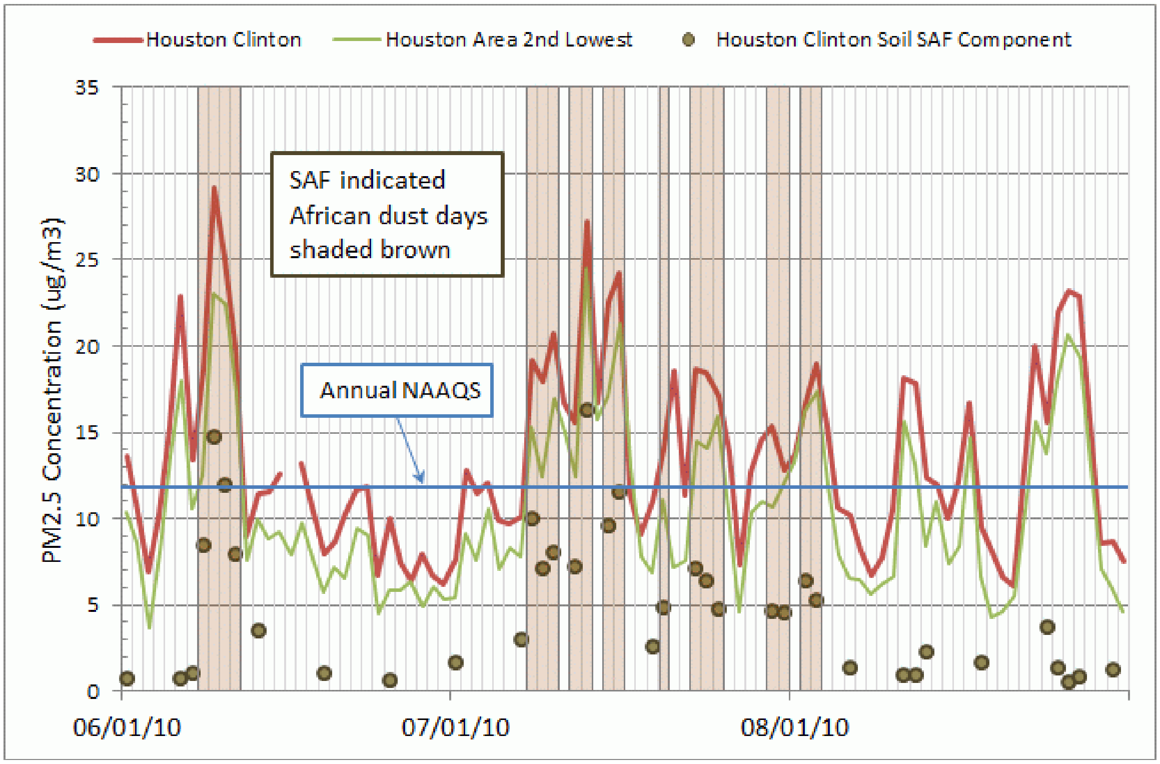

Figure 40. The 19 high African dust days removed from the 2010 Clinton $PM_{2.5}$ summer average "but for" analysis are shaded in light brown.

Mitigation of Exceptional Events

Title 40 CFR 51.930 requires that "a State requesting to exclude air quality data due to exceptional events must take appropriate and reasonable actions to protect public health from exceedances or violations of the national ambient air quality standards." Three specific requirements are described in this regulation and are addressed individually below.

Prompt Public Notification

The first requirement is to "provide for prompt public notification whenever air quality concentrations exceed or are expected to exceed an applicable ambient air quality standard." The TCEQ provides ozone, $PM_{2.5}$, and PM_{10} Air Quality Index (AQI) forecasts for today and the next three days for 14 areas in Texas including Houston. These forecasts are available to the public on the Today's Texas Air Quality Forecast Web page of the TCEQ Web site (http://www.tceq.texas.gov/airquality/monops/forecast_today.html) and on the EPA AIRNOW Web site (http://airnow.gov/). The TCEQ provides near real-time hourly $PM_{2.5}$ measurements from monitors across the state, including Houston, that are available to the public on the Current PM-2.5 Levels - Soot, Dust, and Smoke in Your Metro Area Web page of the TCEQ Web site (http://www.tceq.state.tx.us/cgi-bin/compliance/monops/texas_pm25.pl). Finally, the TCEQ also publishes an AQI Report on the Air Quality Index Web page of the TCEQ Web site (http://www.tceq.state.tx.us/cgi-bin/compliance/monops/aqi_rpt.pl) that displays the latest and historical daily AQI measurements. These measures allow the public to assess forecast, current, and past $PM_{2.5}$ air quality levels.

Public Education

The second requirement is to "provide for public education concerning actions that individuals may take to reduce exposures to unhealthy levels of air quality during and following an exceptional event." Links to TCEQ and EPA Web pages describing recommended actions for individuals to reduce exposure to $PM_{2.5}$ whenever it is high (EPA3, 2013) are included on TCEQ web displays of forecast and measured AQI levels, including TCEQ's Air Pollution from Particulate Matter web page (http://www.tceq.texas.gov/airquality/sip/criteria-pollutants/sip-pm) and EPA's AQI - A Guide to Air Quality and Your Health web page (http://www.airnow.gov/index.cfm?action=aqibasics.aqi). EPA also provides similar links on the AIRNOW Web pages where TCEQ forecasts and current data are displayed.

Implement Measures to Protect Public Health

The third requirement is to “provide for the implementation of appropriate measures to protect public health from exceedances or violations of ambient air quality standards caused by exceptional events.” Since 2005, the TCEQ has pursued voluntary reduction efforts in the Houston Clinton vicinity that have greatly reduced local impacts on $PM_{2.5}$ at the site as discussed in more detail in the Local Source Contributions section above. As a result, the local $PM_{2.5}$ contributions at Houston Clinton have declined by as much as 50 percent from 2006 to 2010. The TCEQ will continue to seek efficient, timely, and effective voluntary control measures in the future as necessary.

Conclusion

The information provided in this document demonstrates that the proposed exceptional events flags for $PM_{2.5}$ data at the Houston Clinton site on June 9, June 10, and July 13, 2010, meet all of the requirements for exceptional events. Measured $PM_{2.5}$ concentrations on these days were well above the 95^{th} percentile of 2008 through 2010 measurements and thus affected air quality in excess of normal historical fluctuations. The level of $PM_{2.5}$ transported into the Houston area on these days from African dust were not reasonably preventable and were due to a natural event. As indicated by satellite imagery, back trajectories, aerosol modeling, and measurement statistics, African dust clearly caused exceedances of the annual $PM_{2.5}$ NAAQS on these days. Estimates of local contribution and non-event baseline, as well as the average summer concentration with African dust events removed, indicate that $PM_{2.5}$ on the proposed exceptional event days would not have exceeded the level of the annual NAAQS without the African dust events. The TCEQ therefore requests EPA's concurrence on these three exceptional event days and to have these days removed from consideration when making attainment or nonattainment determinations for the annual $PM_{2.5}$ NAAQS.

References

Eldred, B. (2003). *Evaluation of the Equation for Soil Composite.* IMPROVE Program.

EPA1. (2013). *Technology Transfer Network (TTN) Air Quality System (AQS)*. Retrieved 2013, from U.S. Environmentla Protection Agency: http://www.epa.gov/ttn/airs/airsaqs/

EPA2. (2013). *AIRNOW*. Retrieved 04 2013, from AIRNOW: http://airnow.gov/

EPA3. (2013). *Air Quality Index (AQI) - A Guide to Air Quality and Your Health*. Retrieved 2013, from AIRNOW: http://www.airnow.gov/index.cfm?action=aqibasics.aqi

Formenti, P., & et al. (2011). Recent Progress in Understanding Physical and Chemical Properties of African and Asian Mineral Dust. *Atmospheric Chemistry and Physics*.

Goudie, A. S., & et al. (2001). Saharan Dust Storms: Nature and Consequences. *Earth-Science Reviews*, 179-204.

Lambeth, B. (2010). Assessing PM2.5 Background Levels and Local Add-On. *2010 National Air Quality Conferences: Air Quality Forecasting, Mapping, and Monitoring, and Communicating Air Quality.* Raleigh, NC: U.S. EPA.

Lindsey, R. (2010, June 1). *Saharan Dust Crosses the Atlantic*. Retrieved April 10, 2013, from NASA Earth Observatory: http://earthobservatory.nasa.gov/IOTD/view.php?id=44169

NASA Earth Observatory. (2013). *Natural Hazards*. Retrieved 2013, from NASA Earth Observatory: http://earthobservatory.nasa.gov/NaturalHazards/

Nielsen-Gammon, J. W., & et al. (2005). *A Conceptual Model for Eight-Hour Ozone Exceedances in Houston, Texas Part I: Background Ozone Levels in Eastern Texas.* College Station, TX: Texas A&M University.

NOAA. (2013). *NOAA Satellites*. Retrieved 2013, from National Oceanic and Atmospheric Administration: http://www.noaa.gov/satellites.html

NOAA ARL. (2013). *HYSPLIT - Hybrid Single Particle Lagrangian Integrated Trajectory Model*. Retrieved 2013, from NOAA Air Resources Laboratory: http://www.arl.noaa.gov/HYSPLIT_info.php

Parrish, D. D., & et al. (2009). Overview of the Second Texas Air Quality Study (TexAQS II) and the Gulf of Mexico Atmospheric Composition and Climate Study (GoMACCS). *Journal of Geophysical Research*.

Scott, M. (2010, May 29). *Saharan Dust Crosses the Atlantic*. Retrieved April 10, 2013, from NASA Earth Observatory: http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=44159

Sullivan, D. W., & et al. (2013). Success in Reducing PM2.5 in the Neighborhood North of the Houston Ship Channel - Voluntary Efforts Based on Field Study Results and Source Attribution. *Journal of the Air and Waste Management Association*.

TCEQ. (2013). *Texas Meteorological Satellite Images - GOES*. Retrieved 2013, from TCEQ: http://www.tceq.texas.gov/assets/public/compliance/monops/air/goes.html

TCEQ1. (2013). *Today's Texas Air Quality Forecast*. Retrieved 2013, from TCEQ: http://www.tceq.texas.gov/airquality/monops/forecast_today.html

TCEQ2. (2013). *Current PM-2.5 Levels - Soot, Dust, and Smoke in Your Metro Area*. Retrieved 2013, from TCEQ: http://www.tceq.state.tx.us/cgi-bin/compliance/monops/texas_pm25.pl

TCEQ3. (2013). *Air Quality Index*. Retrieved 2013, from TCEQ: http://www.tceq.state.tx.us/cgi-bin/compliance/monops/aqi_rpt.pl

Appendix A: Proposed 2010 Houston $PM_{2.5}$ Exceptional Event Flags

Table A-1. Proposed 2010 Houston PM2.5 Exceptional Event Flags

Date	Site ID	Site Name	POC	$PM_{2.5}$	Flag	Description
06/09/10	482011035	Clinton C403	1	29.2	RA	African dust
06/10/10	482011035	Clinton C403	1	25.1	RA	African dust
07/13/10	482011035	Clinton C403	1	27.2	RA	African dust

Abbreviations:

Site ID - EPA site identification number

POC - EPA Parameter Occurrence Code

$PM_{2.5}$ - daily average concentration in micrograms per cubic meter local conditions

Appendix B: Source Analysis for June 9 and June 10

Back Trajectories

Figures B-1 and B-1 show HYSPLIT back trajectories. Each trajectory shows the approximate path of air arriving in the Houston area at 1200 CST on the date indicated and going backward in time 312 hours. Both trajectories indicate the air came from Africa. The NOAA web site where the trajectories were produced does not allow them to run past 312 hours. So, it is not possible to follow the air parcels all the way back into Africa. These back trajectories corroborate well with satellite imagery in tracking the African dust.

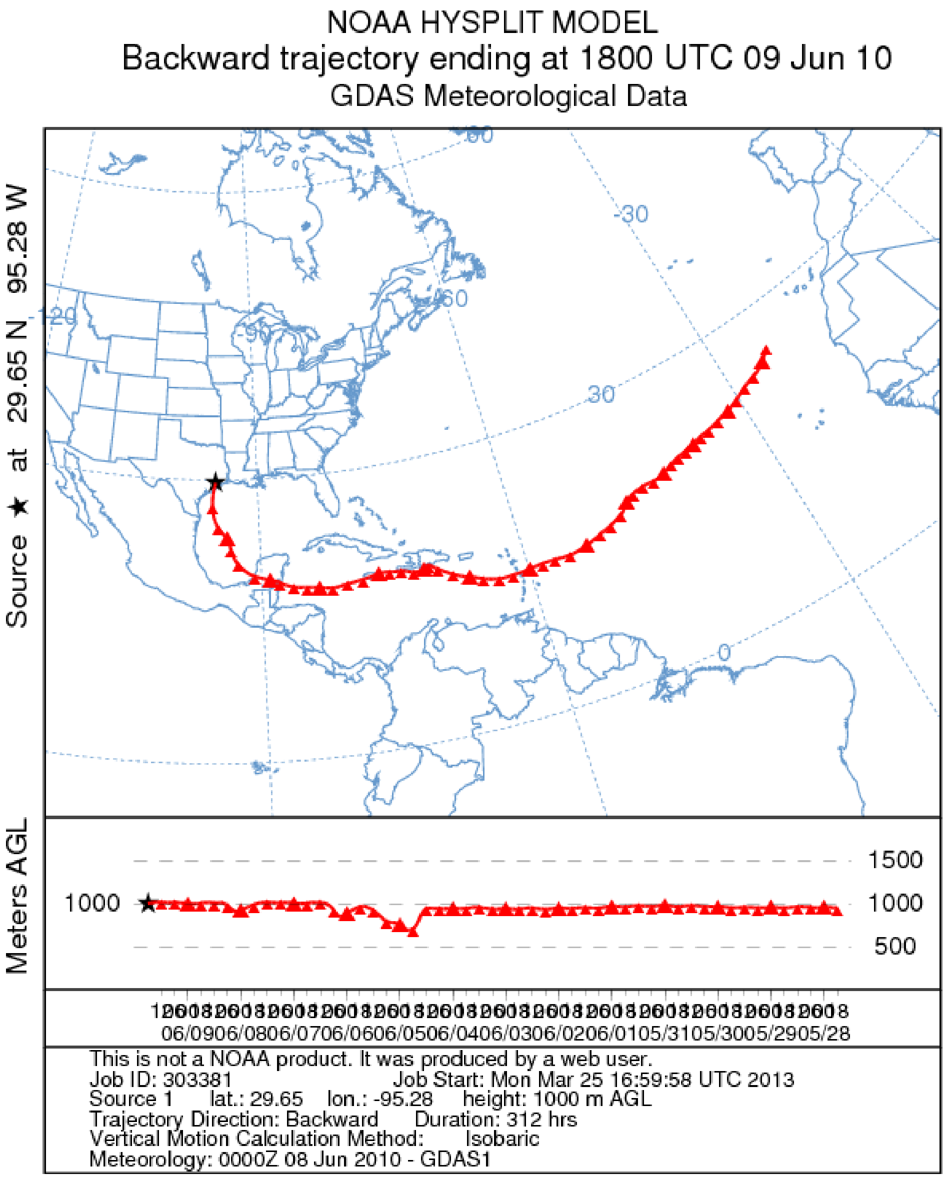

Figure B-1. Backward-in-time air trajectory for June 9, 2010.

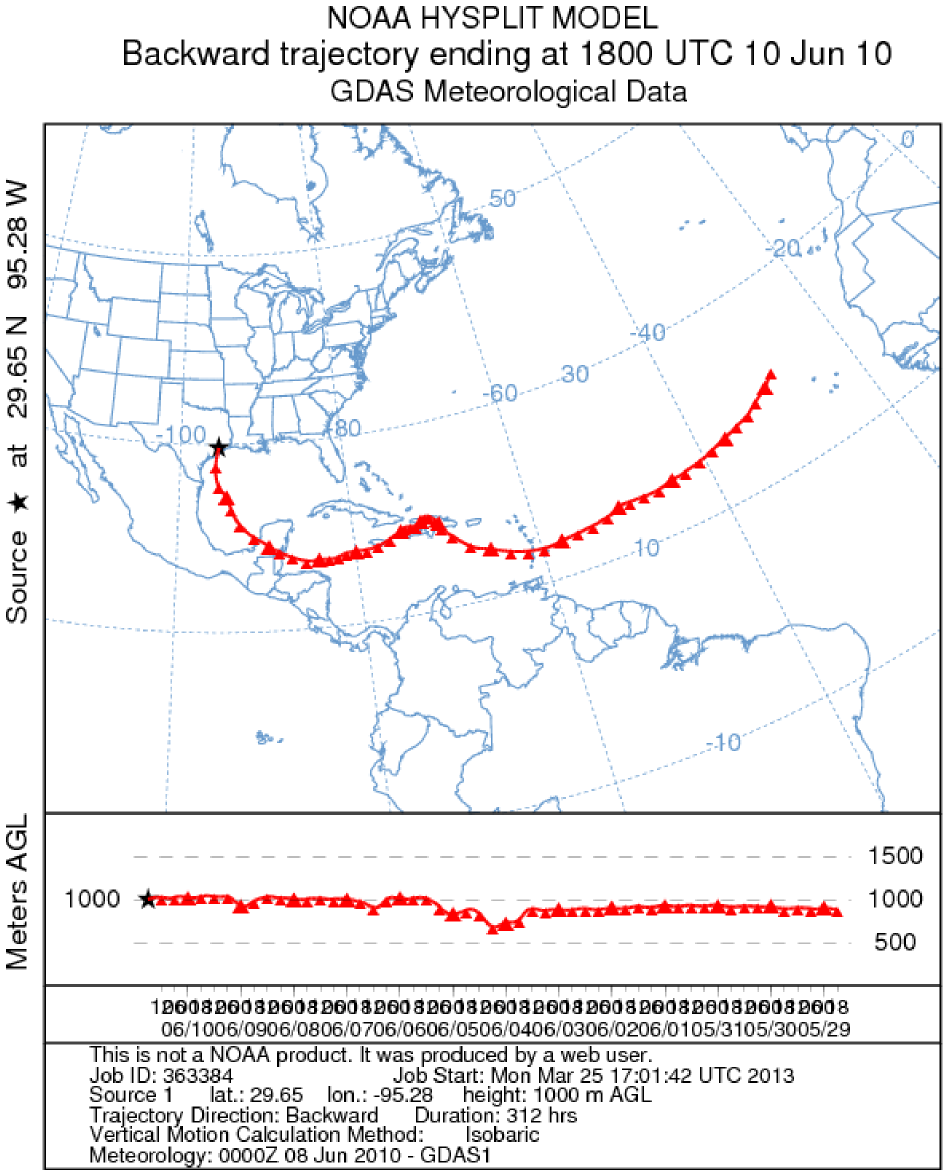

Figure B-2. Backward-in-time air trajectory for June 10, 2010.

Satellite Imagery

Figures B-3 through B-20 provide geostationary satellite images showing the African dust cloud as it progressed across the Atlantic, Caribbean Sea, and Gulf of Mexico. The image times are listed in Universal Time Coordinates (UTC) which is five hours ahead of Central Daylight Time. On these images, most clouds are bright white with sharp edges and ocean water is normally very dark away from clouds. Dust in the air makes the ocean look much brighter when present, giving it a milky appearance with soft indistinct edges to the dust cloud. The satellite imagery corroborates well with the back trajectories shown previously.

The satellite imagery shows a large and intense African dust cloud had emerged into the eastern Atlantic Ocean from the African coast by May 28, 2010. The dust cloud of interest is labeled number “2” in all of the satellite images. This dust cloud tracked across the Atlantic Ocean reaching the Lesser Antilles on June 1st and began moving into the Gulf of Mexico on June 5th. The dust cloud arrived in the Houston area on June 8th and continued moving across the area through June 11th. The imagery also shows smoke from agricultural burning in Mexico and Central America, indicated with the letter “S”, covering much of the western Gulf of Mexico on June 5th through 7th.

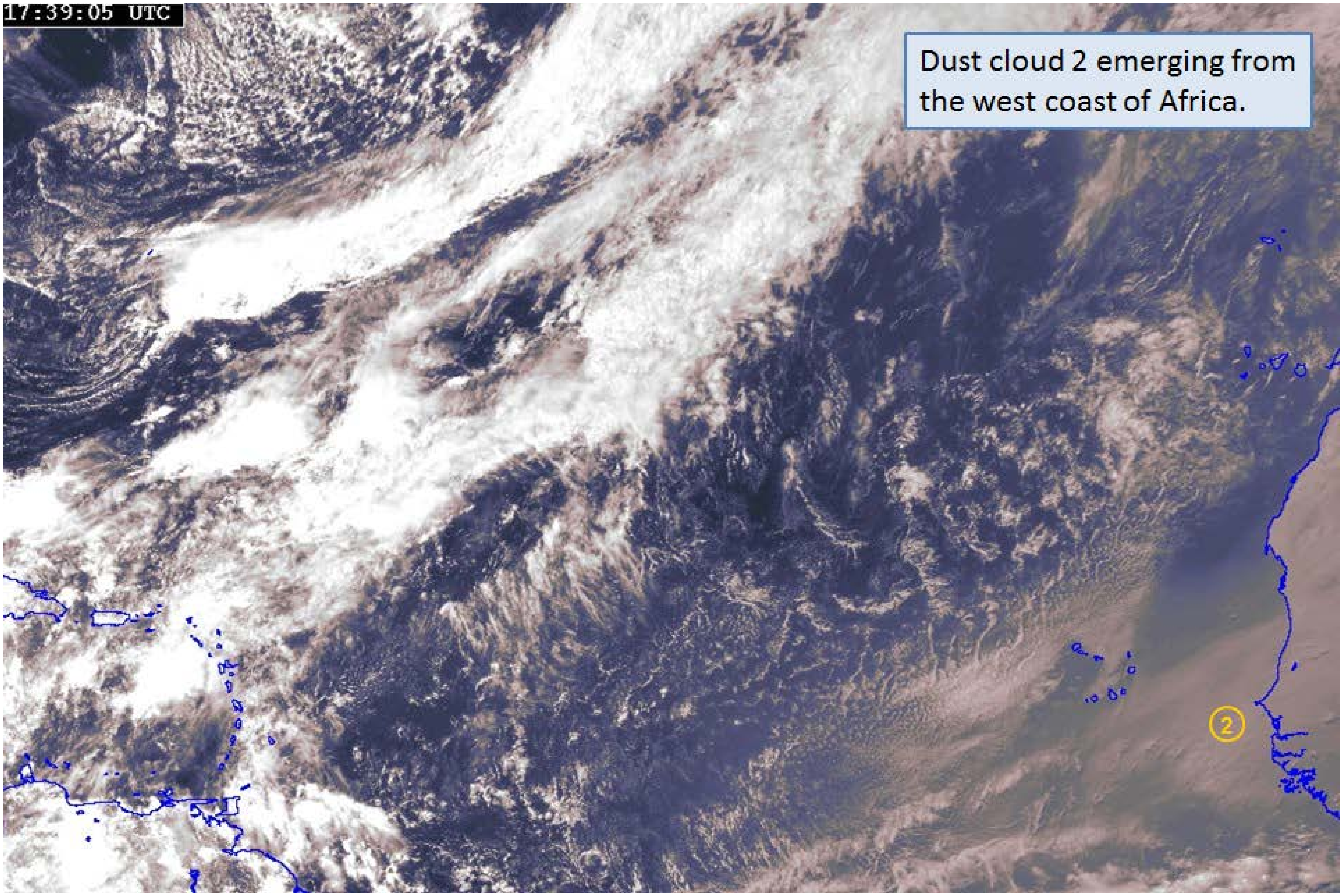

Figure B-3. Visible satellite image for 1745 UTC on May 28, 2010.

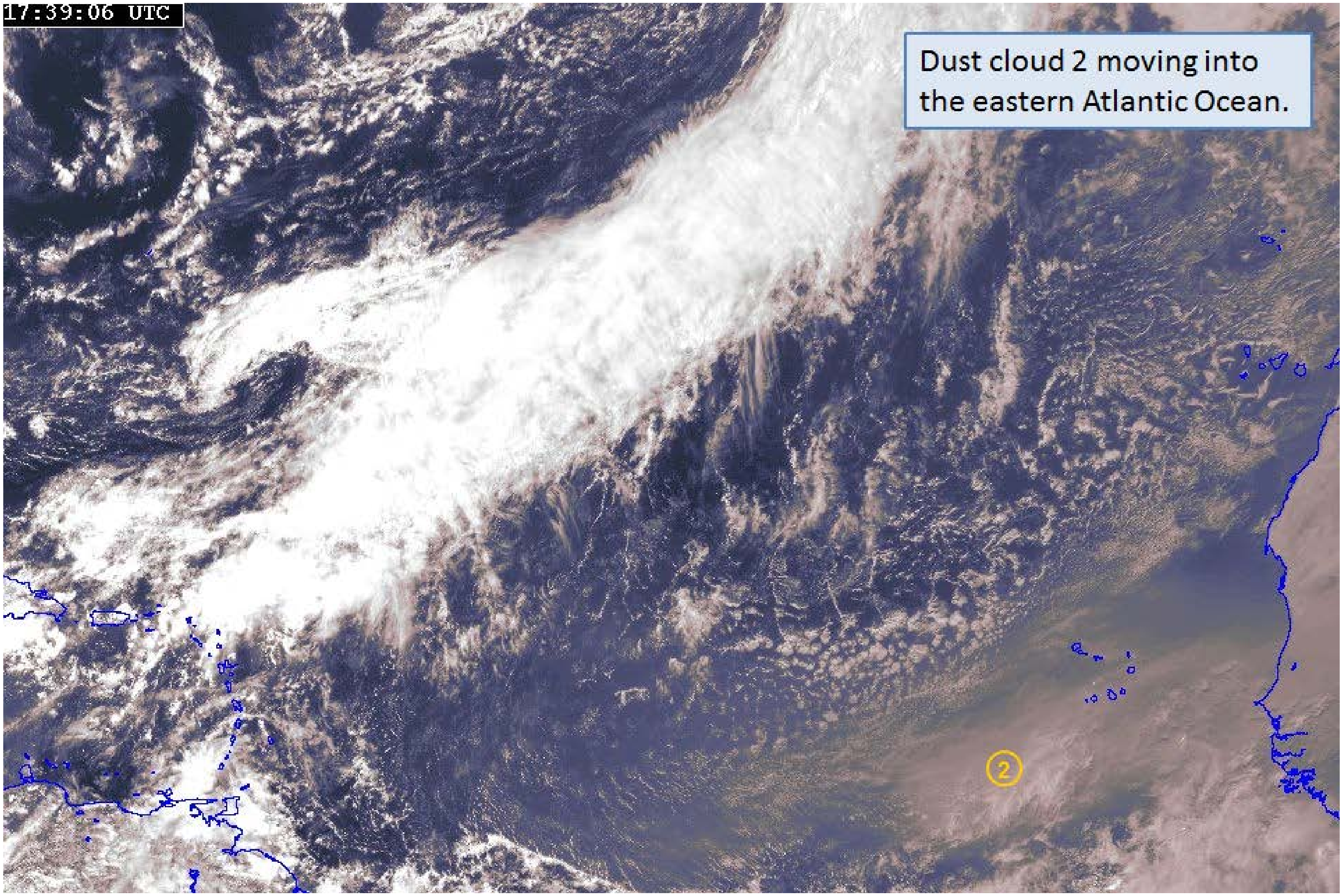

Figure B-4. Visible satellite image for 1745 UTC on May 29, 2010.

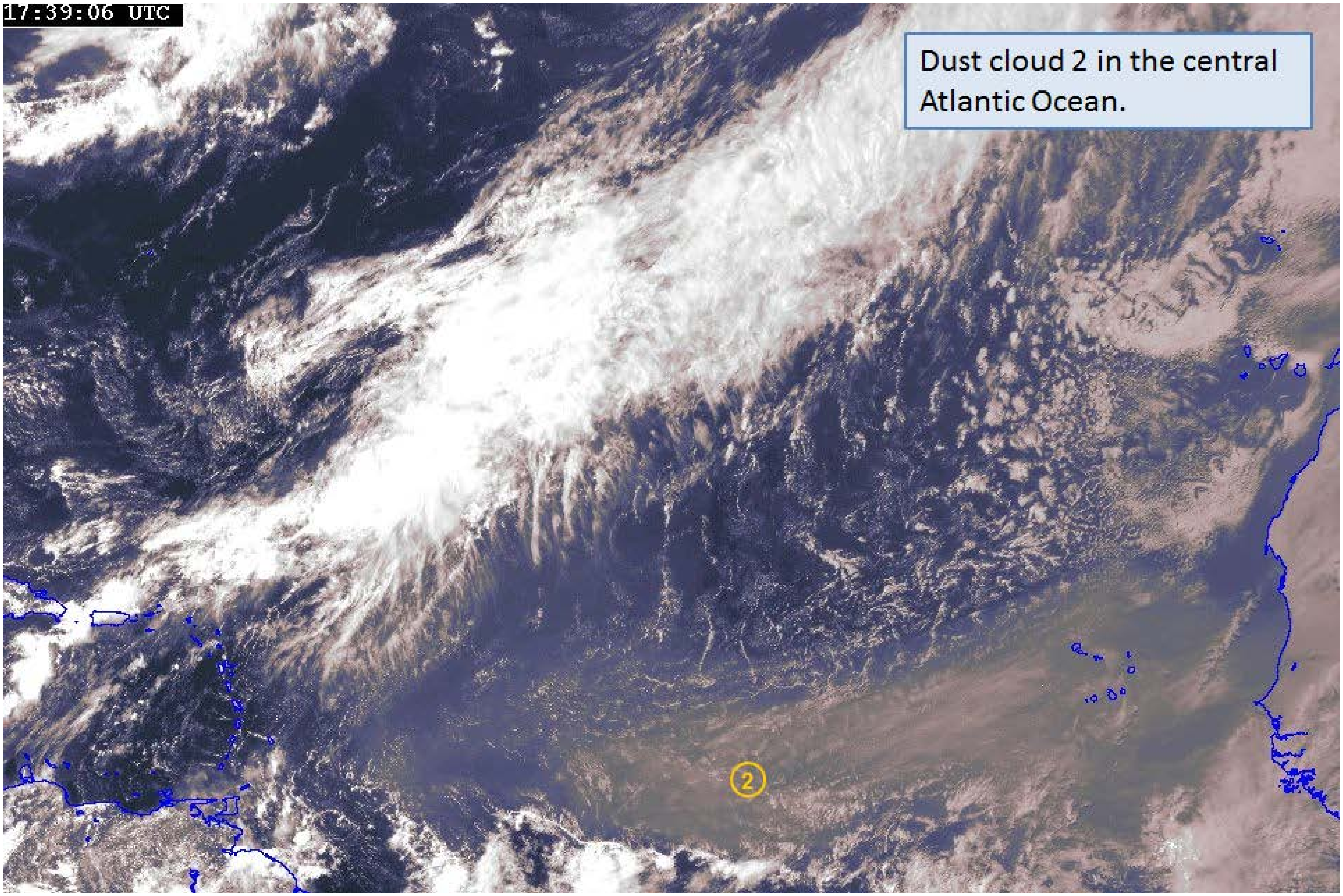

Figure B-5. Visible satellite image for 1745 UTC on May 30, 2010.

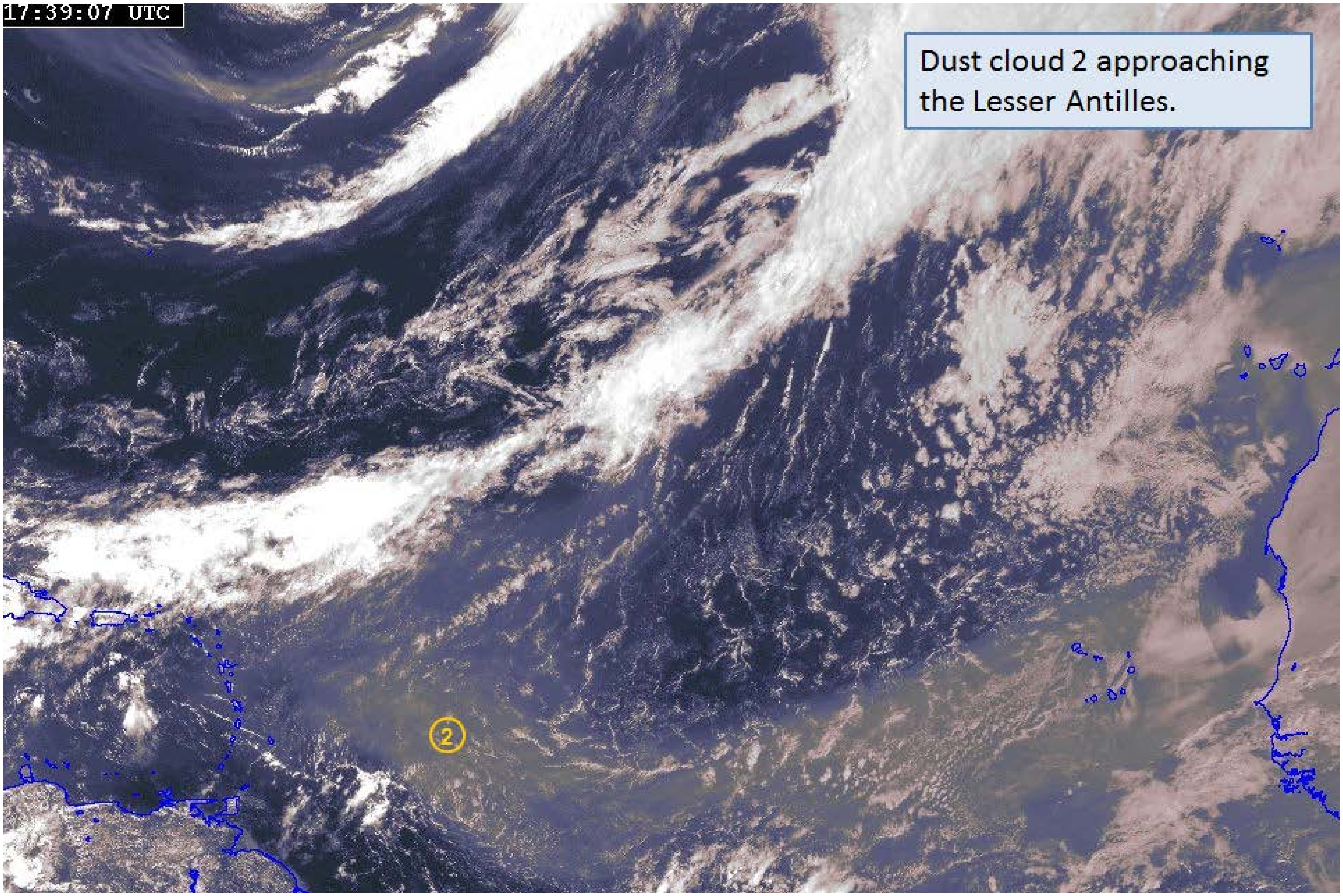

Figure B-6. Visible satellite image for 1745 UTC on May 31, 2010.

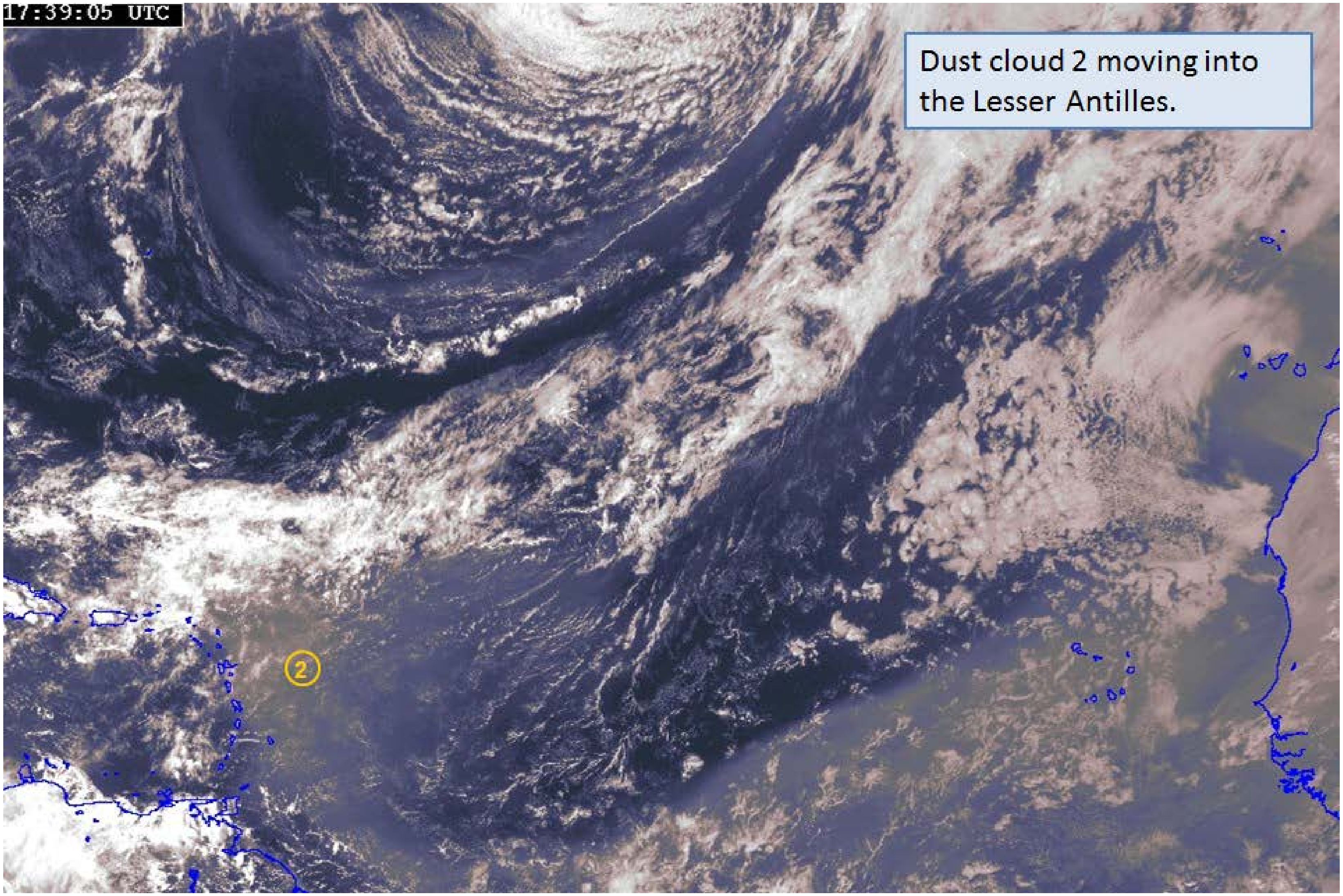

Figure B-7. Visible satellite image for 1745 UTC on June 1, 2010.

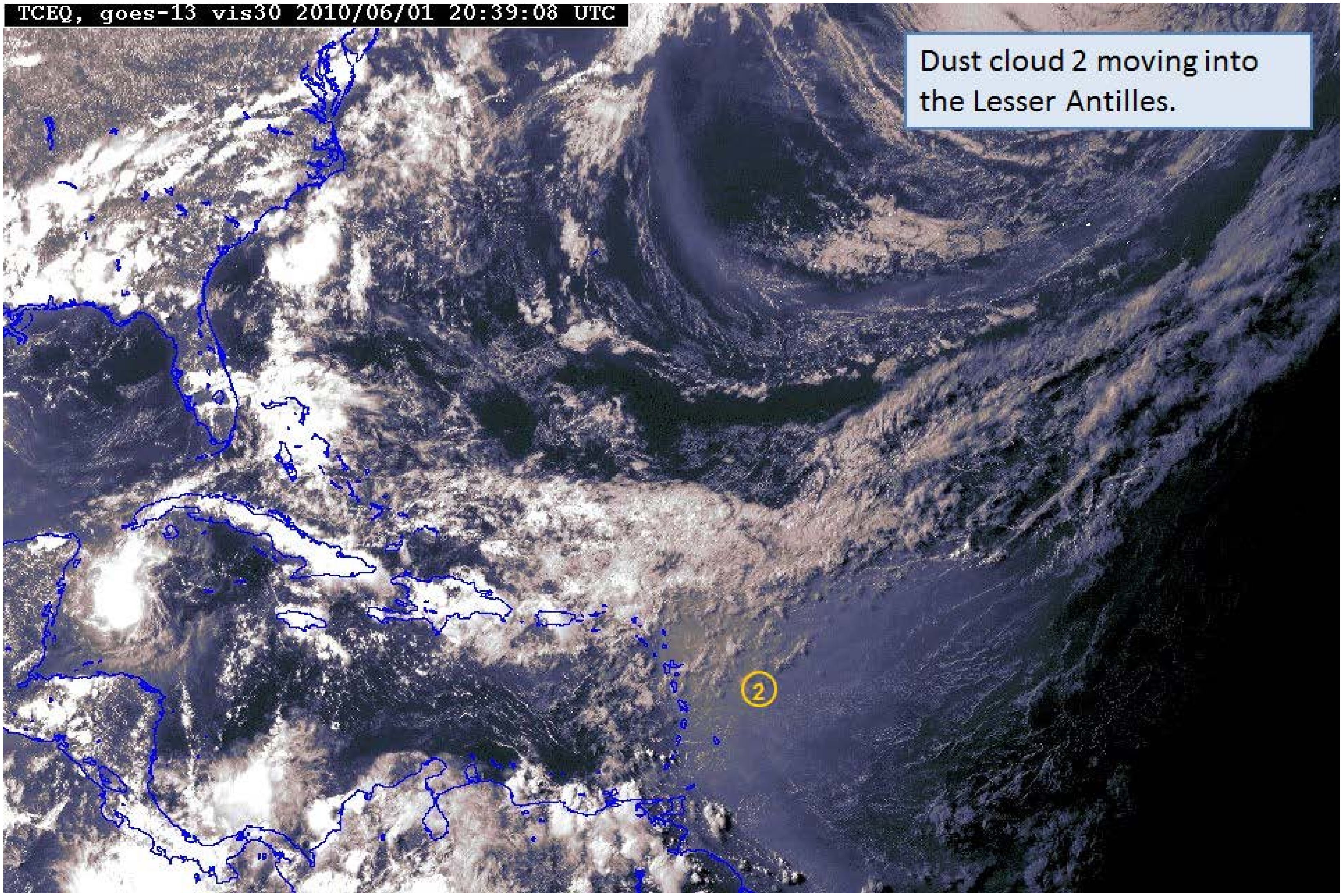

Figure B-8. Visible satellite image for 2045 UTC on June 1, 2010.

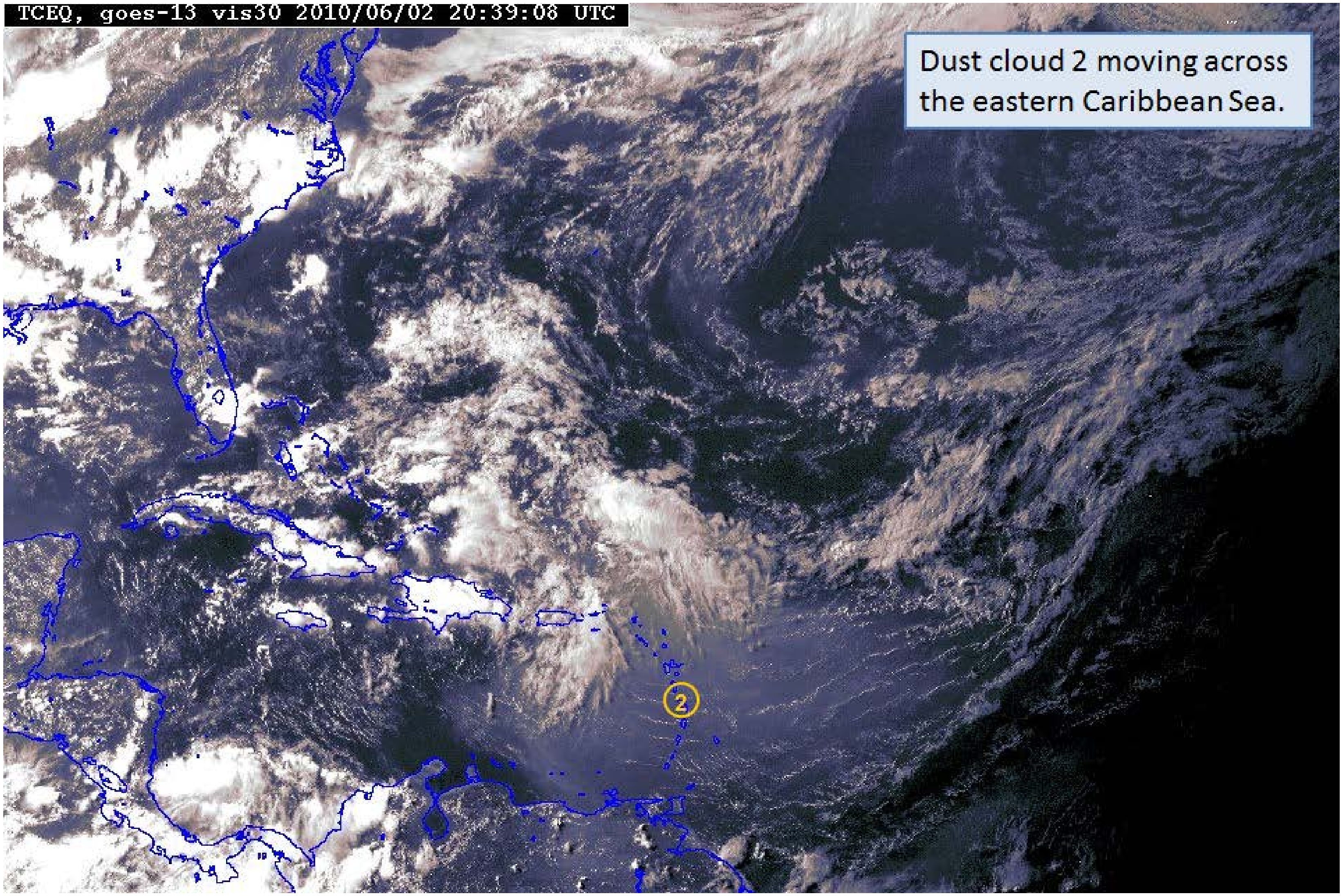

Figure B-9. Visible satellite image for 2045 UTC on June 2, 2010.

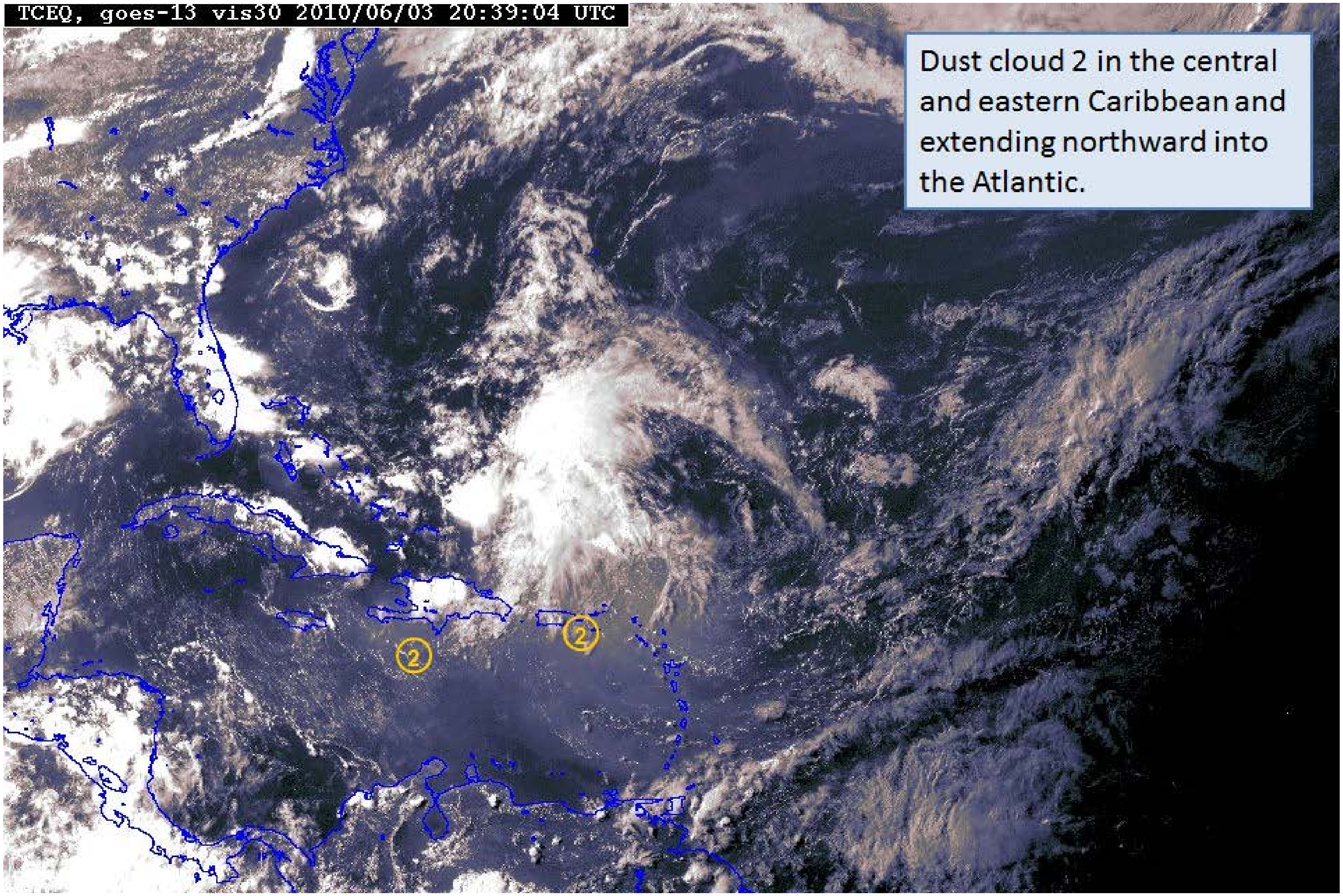

Figure B-10. Visible satellite image for 2045 UTC on June 3, 2010.

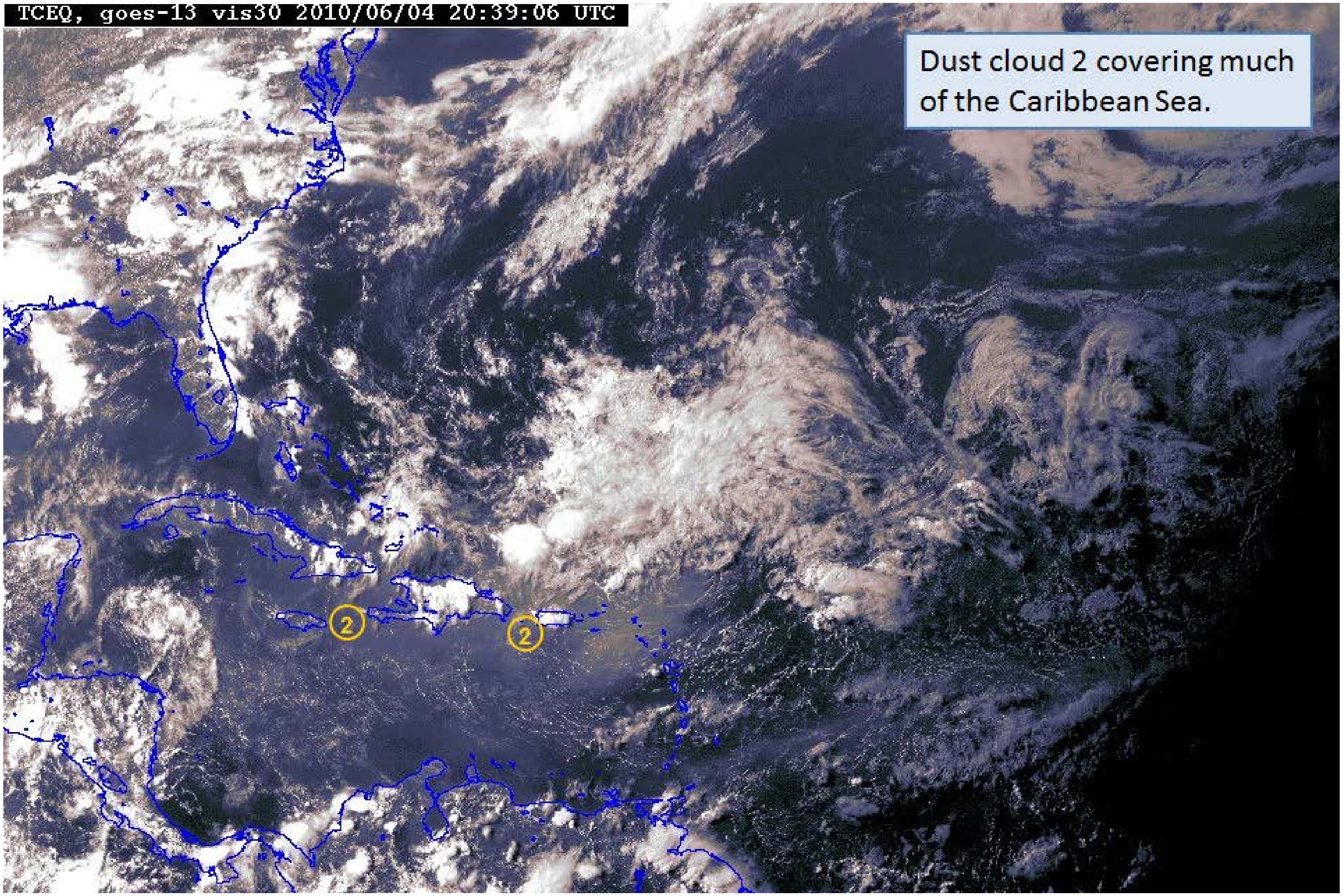

Figure B-11. Visible satellite image for 2045 UTC on June 4, 2010.

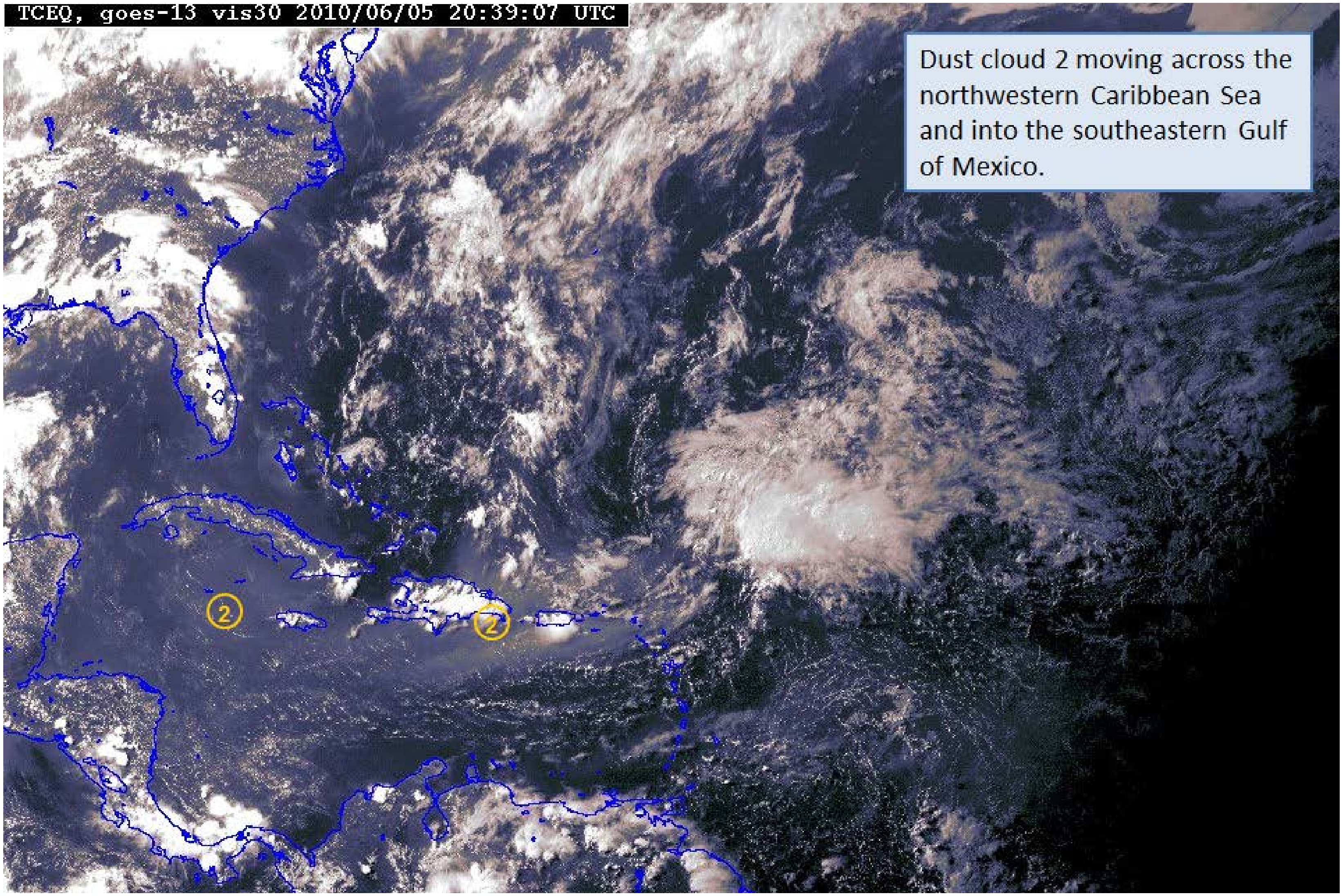

Figure B-12. Visible satellite image for 2045 UTC on June 5, 2010.

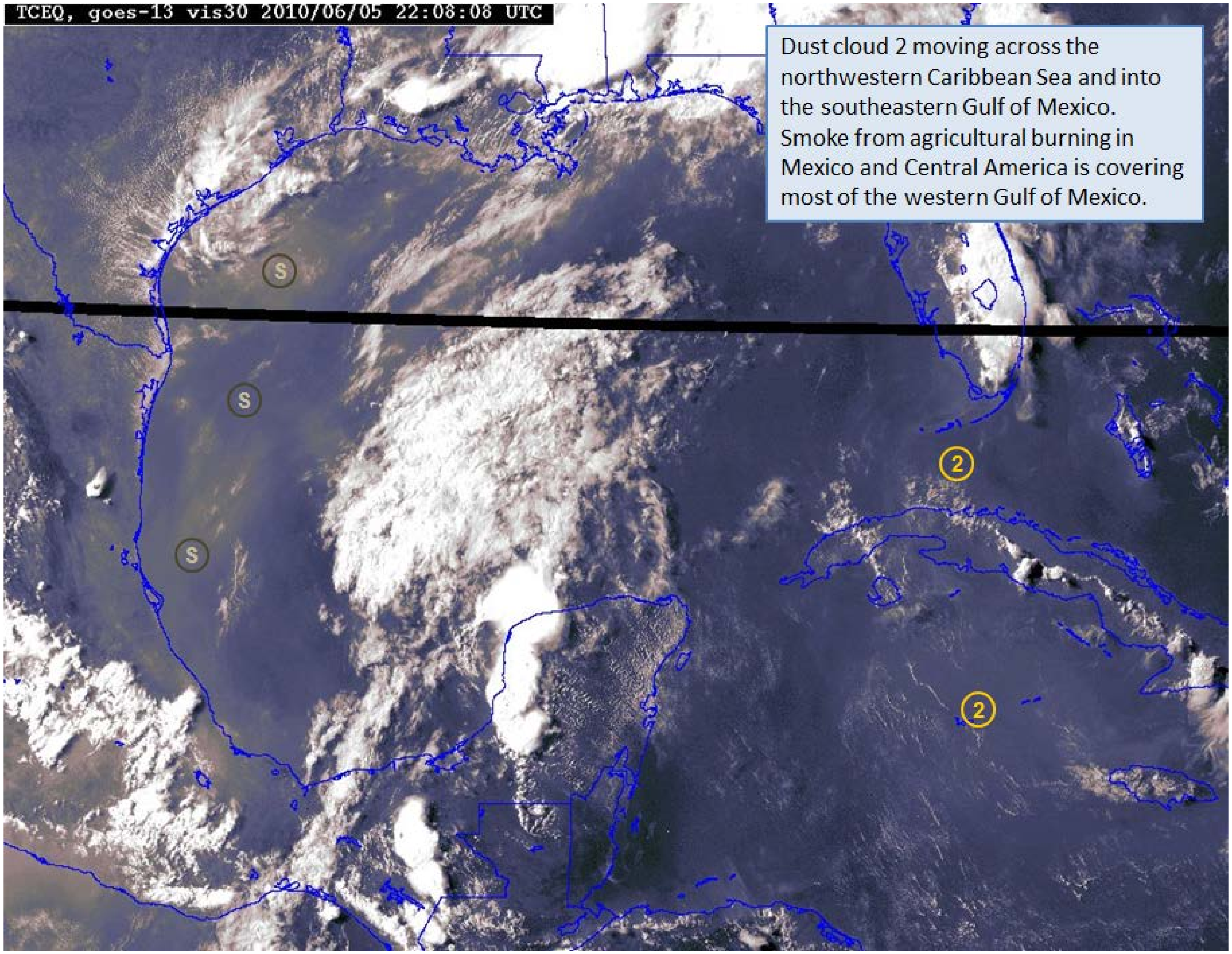

Figure B-13. Visible satellite image for 2215 UTC on June 5, 2010.

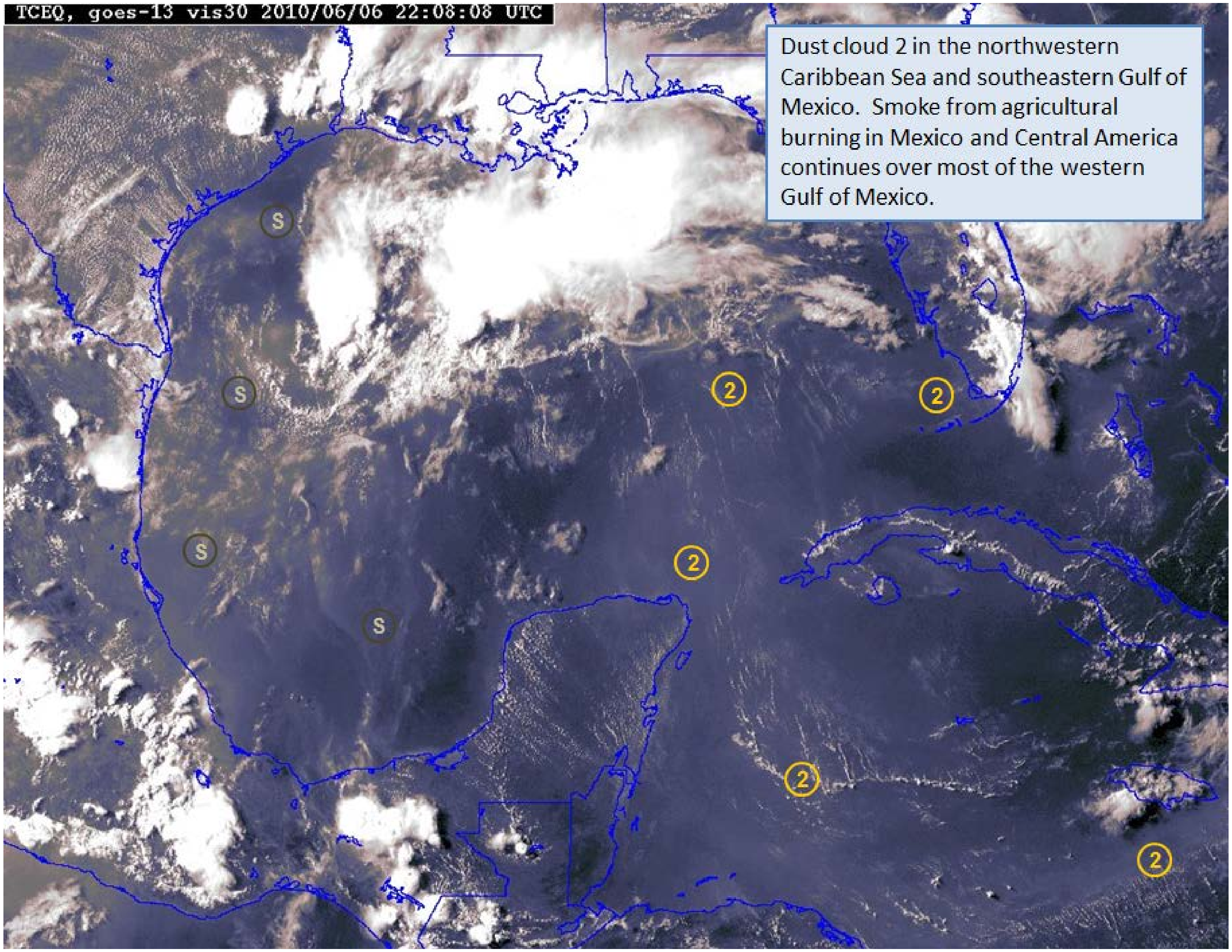

Figure B-14. Visible satellite image for 2215 UTC on June 6, 2010.

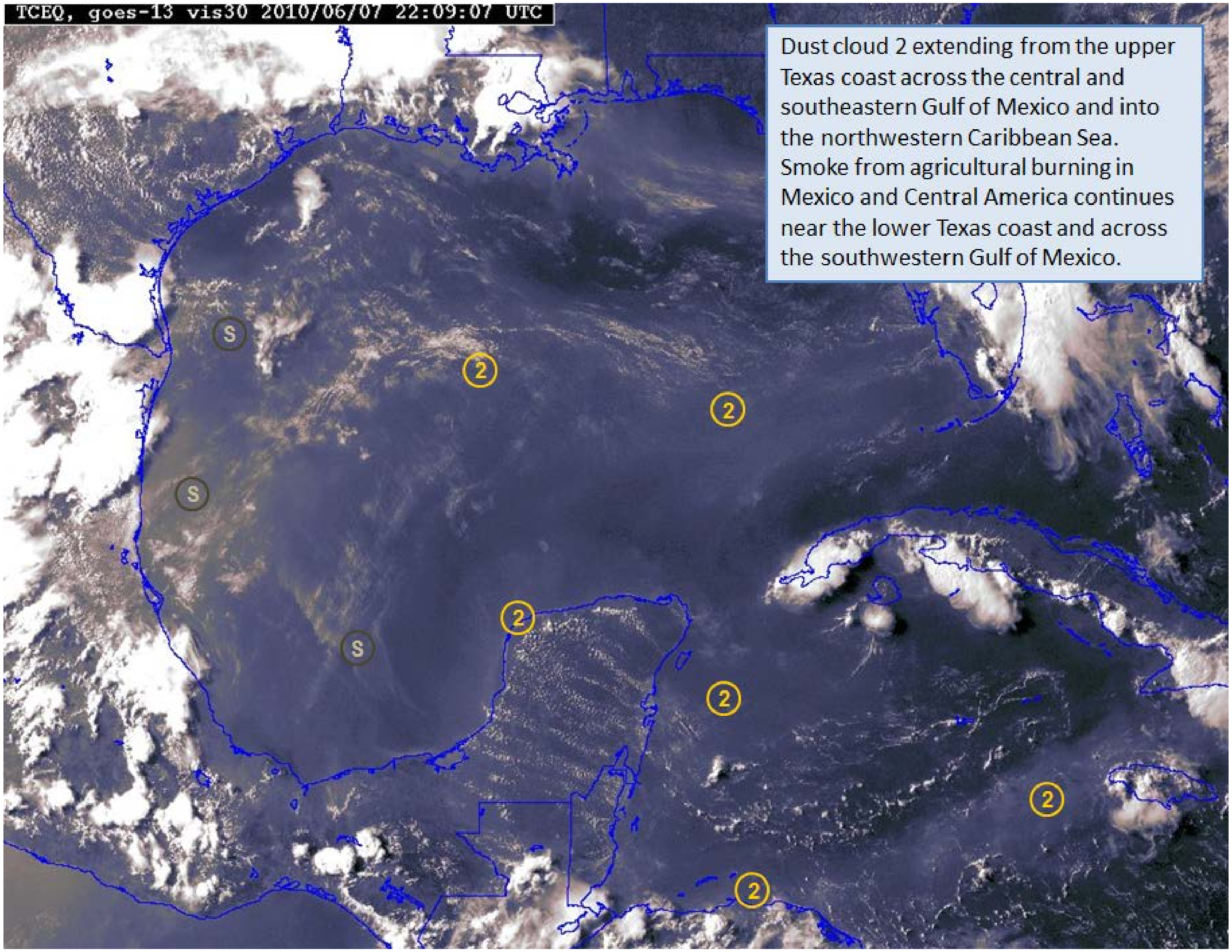

Figure B-15. Visible satellite image for 2215 UTC on June 7, 2010.

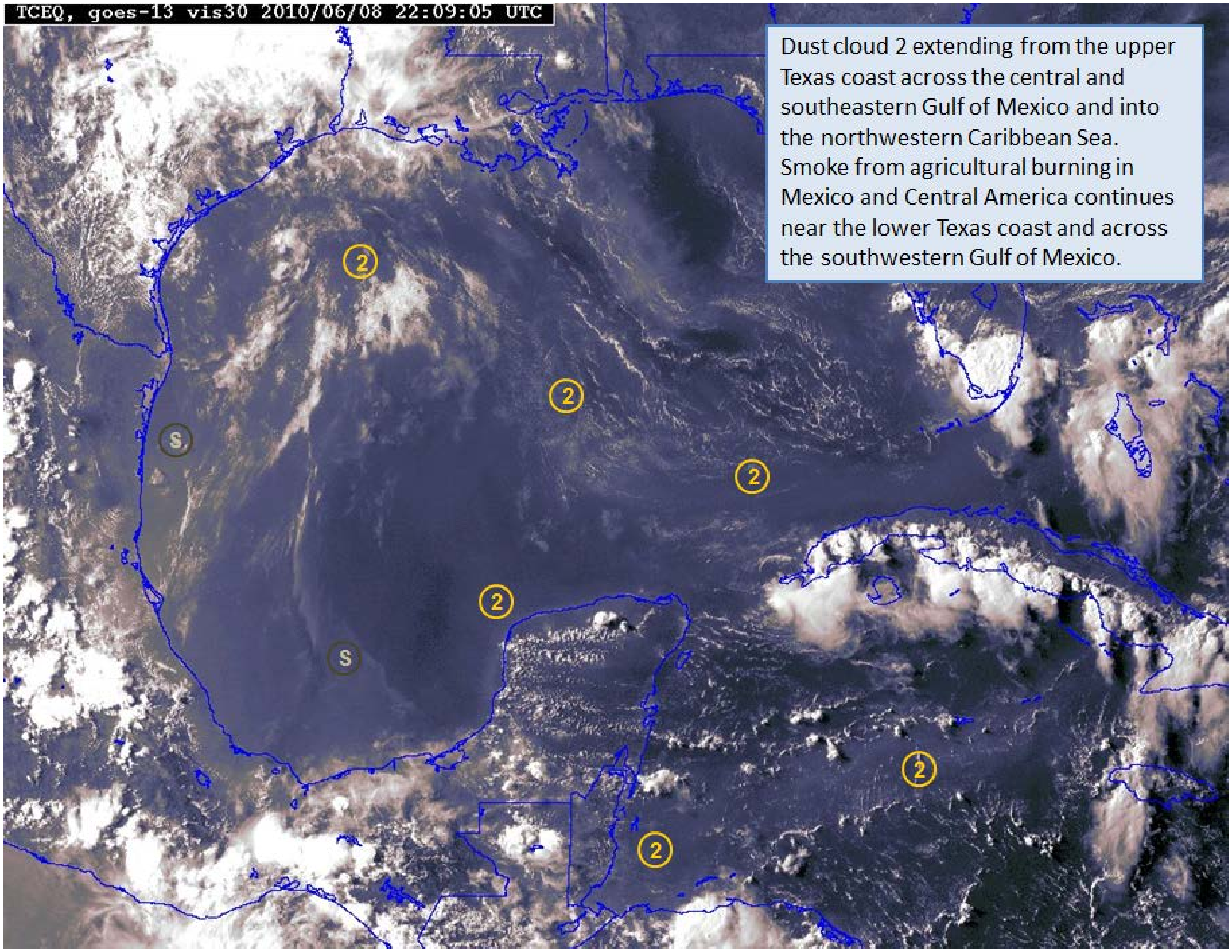

Figure B-16. Visible satellite image for 2215 UTC on June 8, 2010.

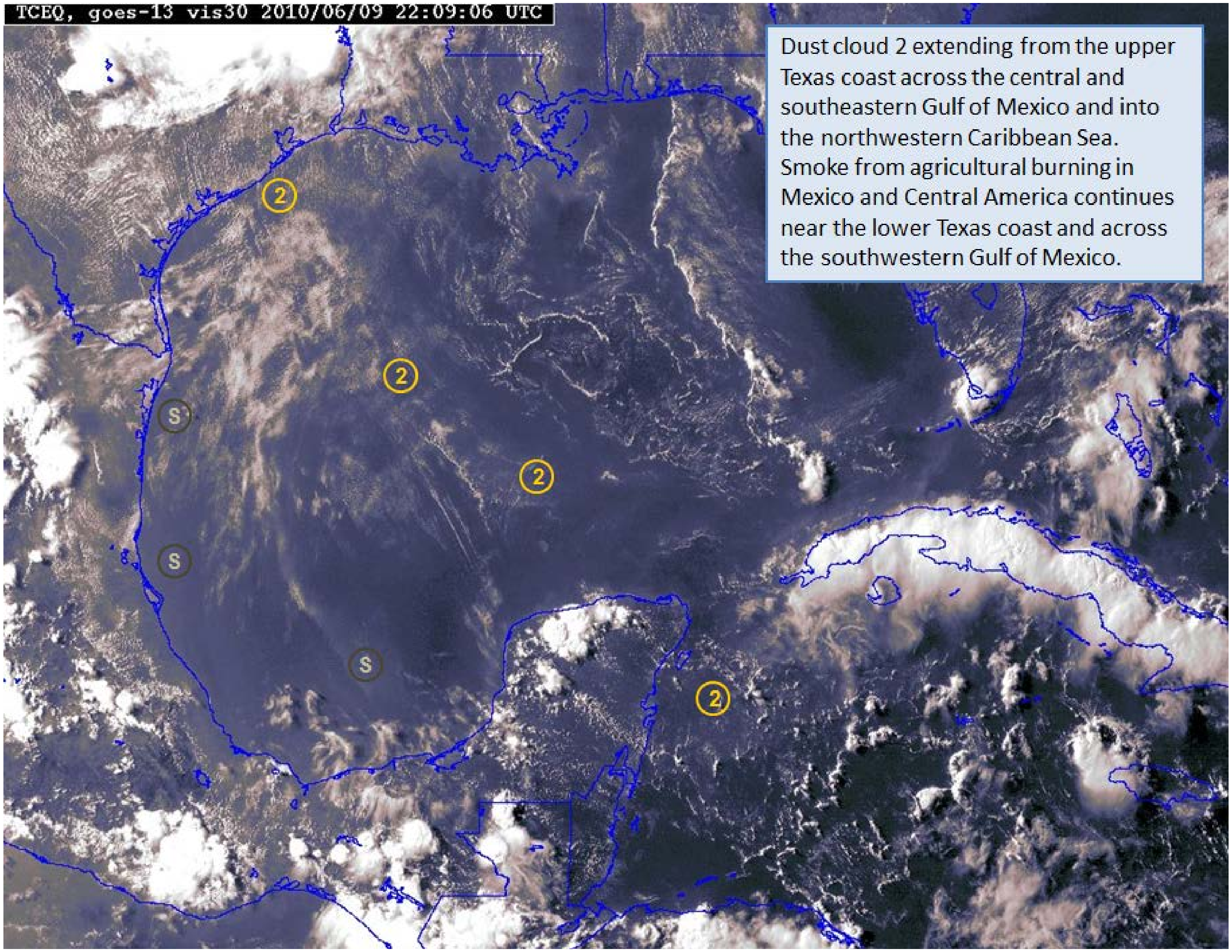

Figure B-17. Visible satellite image for 2215 UTC on June 9, 2010.

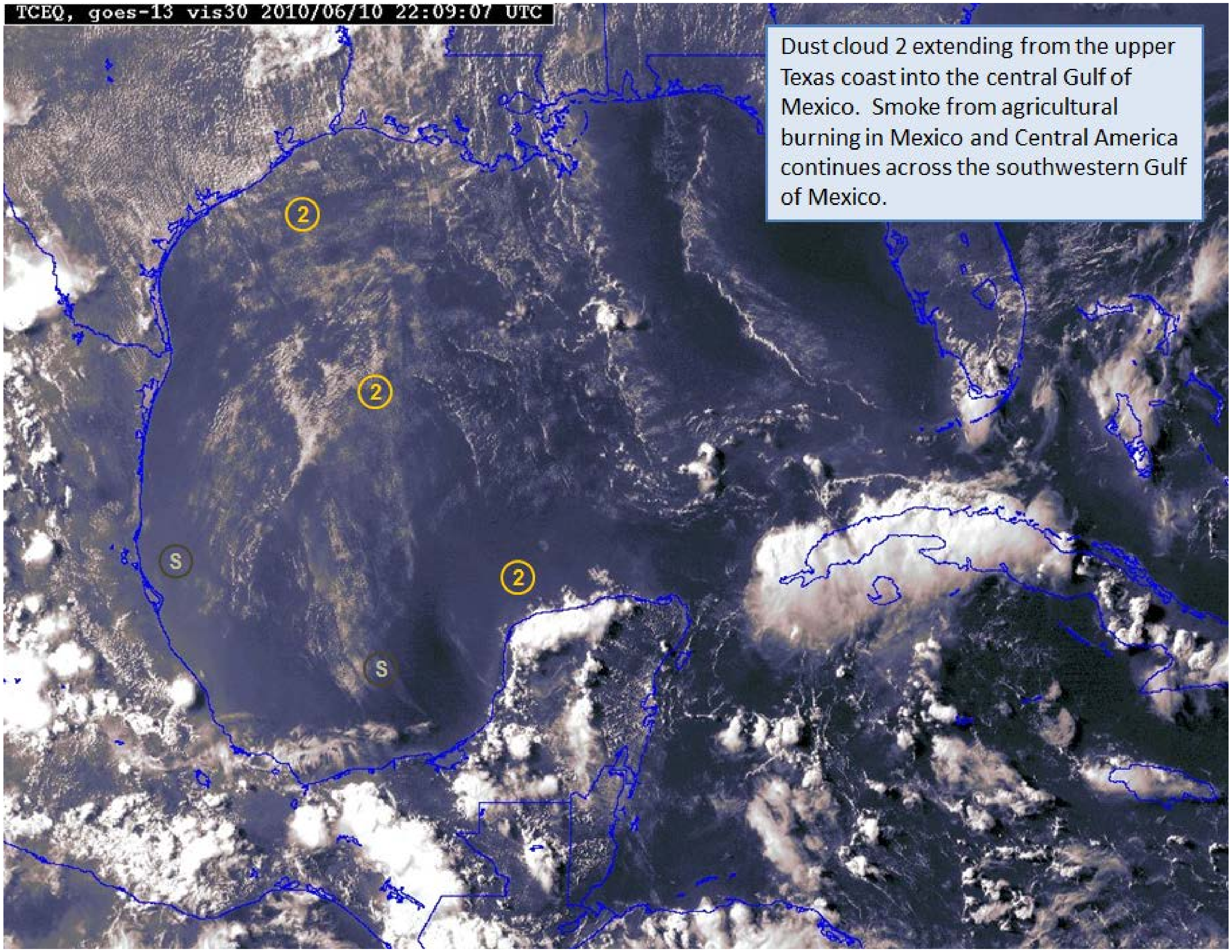

Figure B-18. Visible satellite image for 2215 UTC on June 10, 2010.

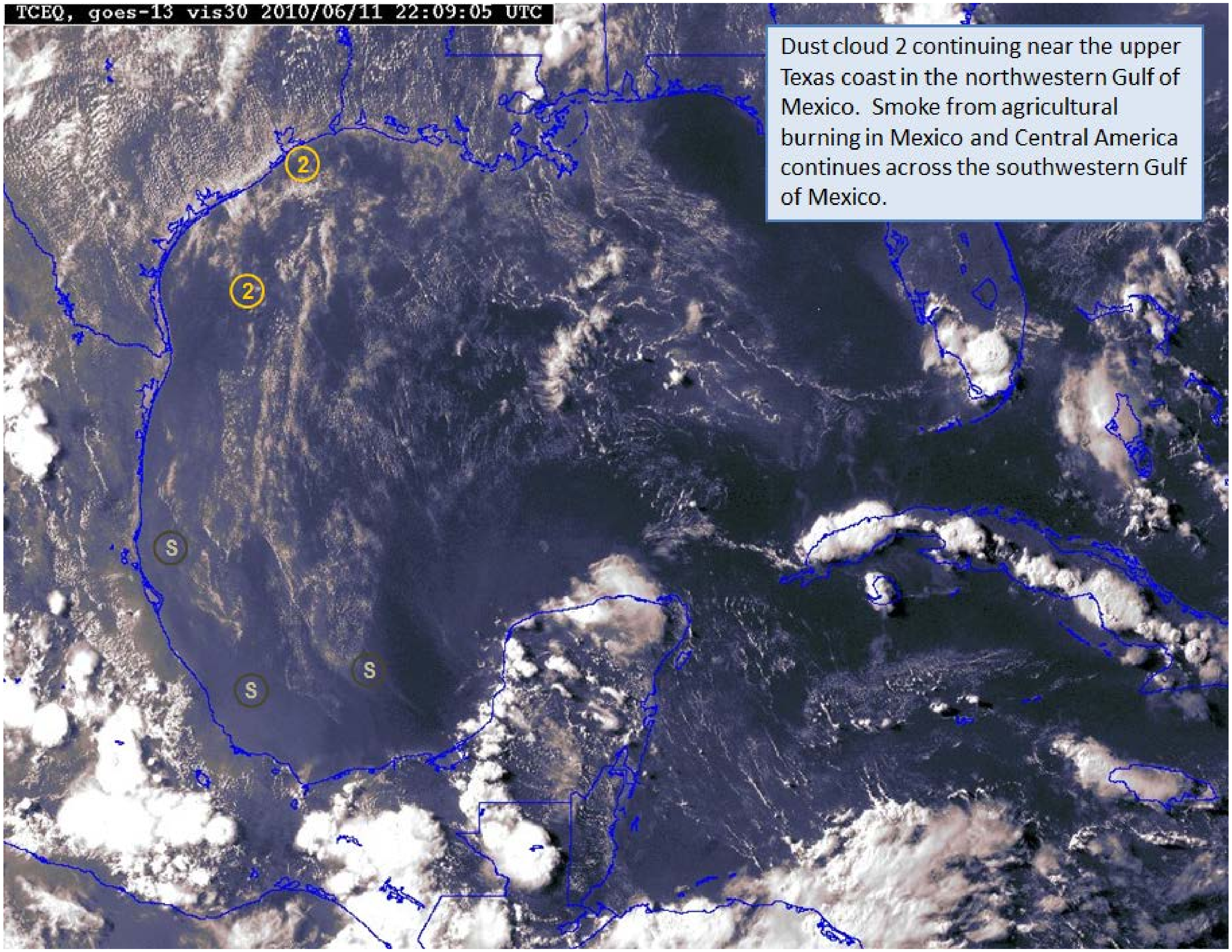

Figure B-19. Visible satellite image for 2215 UTC on June 11, 2010.

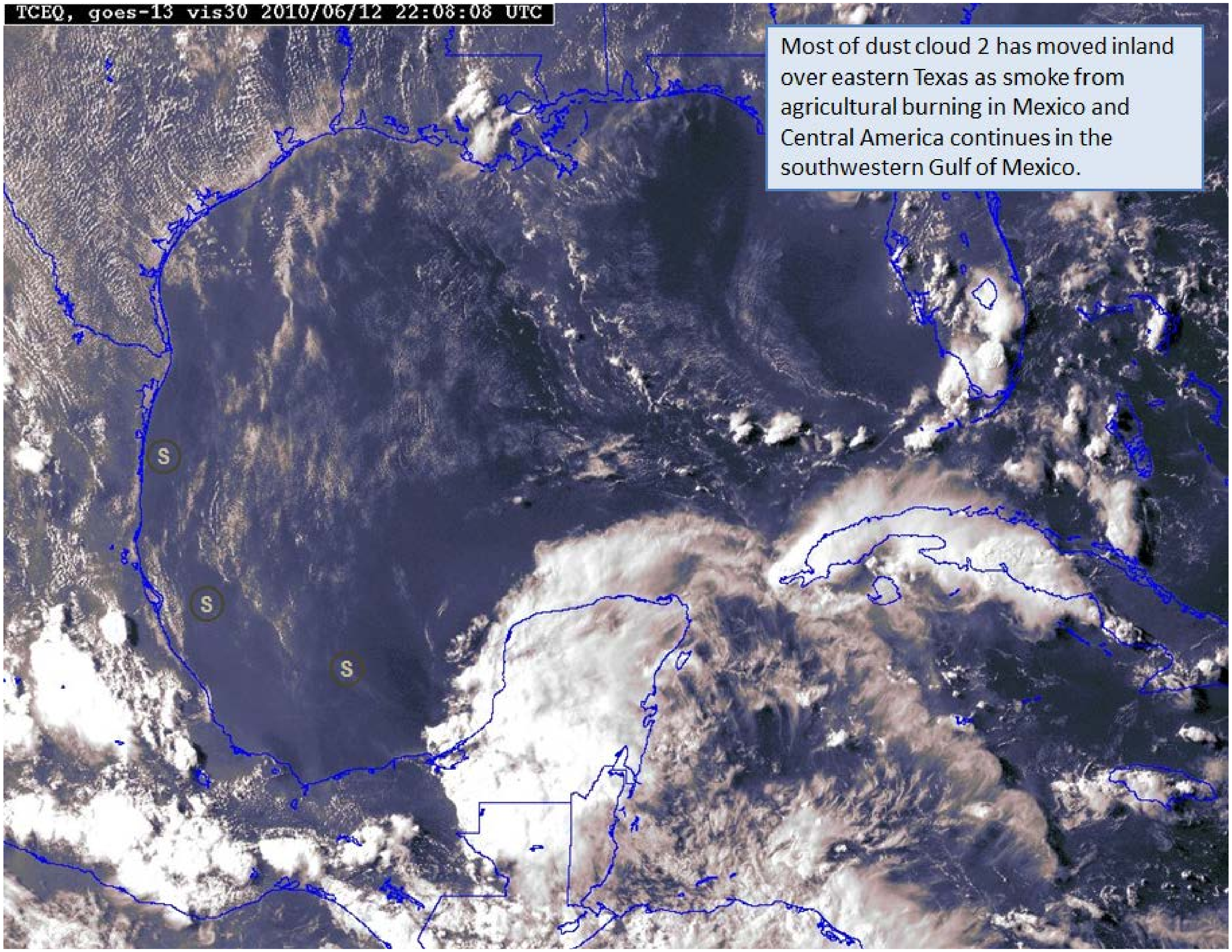

Figure B-20. Visible satellite image for 2215 UTC on June 12, 2010.

Aerosol Analyses

Figures B-21 through B-38 provide aerosol analyses from the Naval Research Laboratory (NRL) showing the African dust cloud that arrived in the Houston area on June 9-10 as it progressed across the Atlantic, Caribbean Sea, and Gulf of Mexico. The satellite derived optical depth from dust is shown in shades of green and yellow in the upper left panel of each figure. The same numbering system used to identify the dust cloud on the previous satellite imagery is used in these figures for comparison. These aerosol analyses corroborate well with the satellite imagery and back trajectories shown previously.

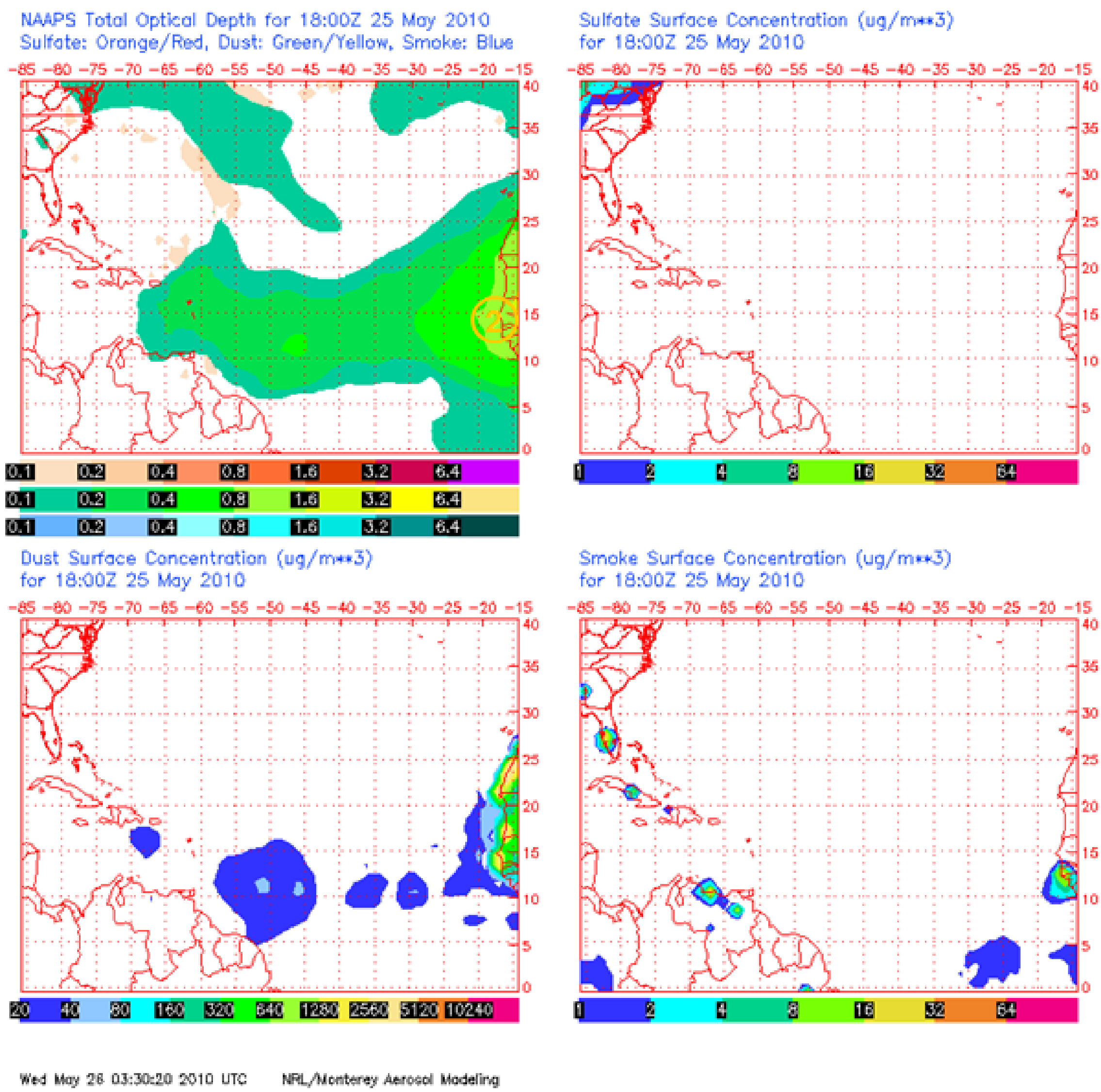

Figure B-21. NRL aerosol analysis 2010 May 25 showing the African dust cloud emerging from the African coast.

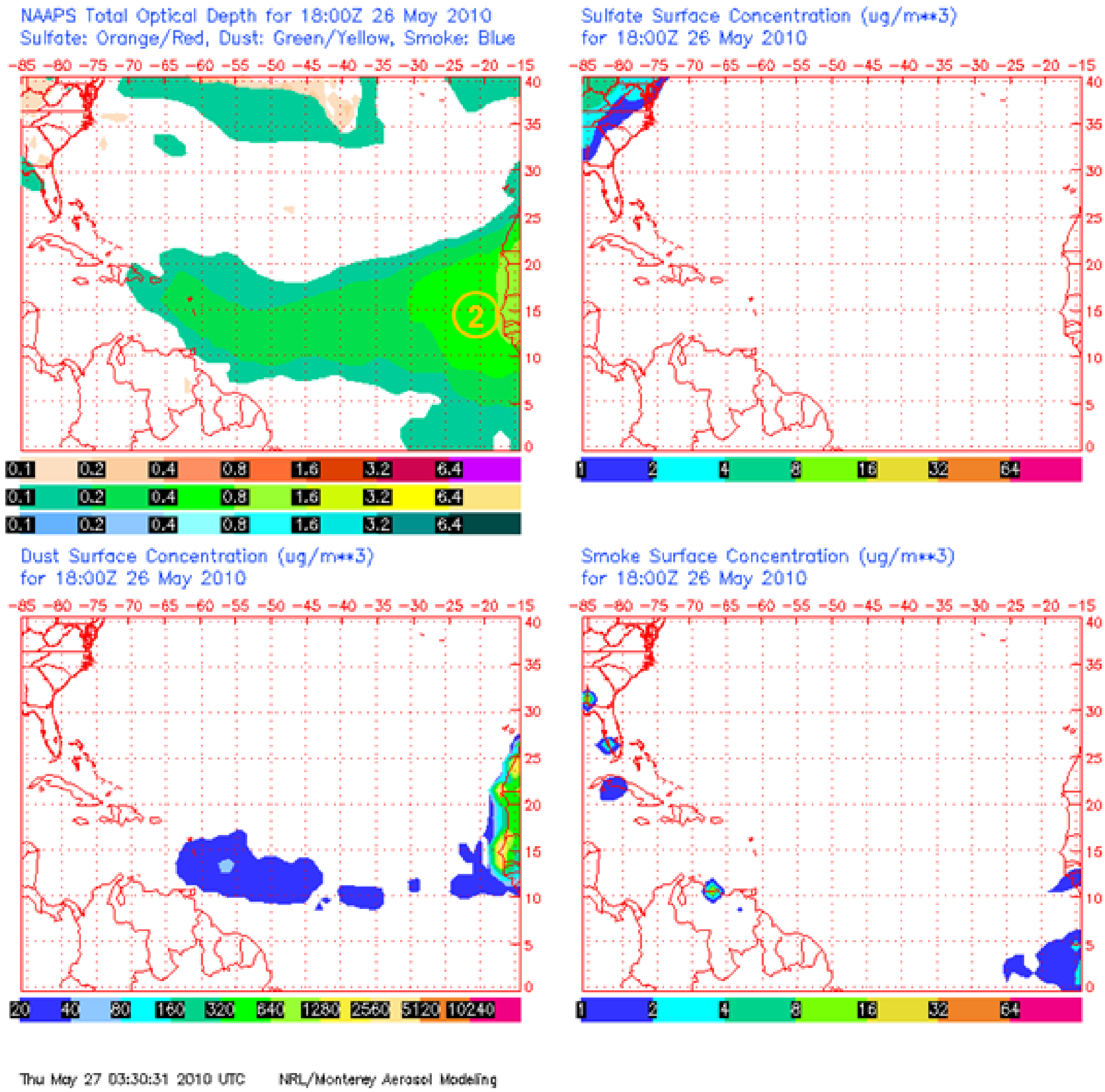

Figure B-22. NRL aerosol analysis 2010 May 26 showing the African dust cloud moving into the eastern Atlantic Ocean.

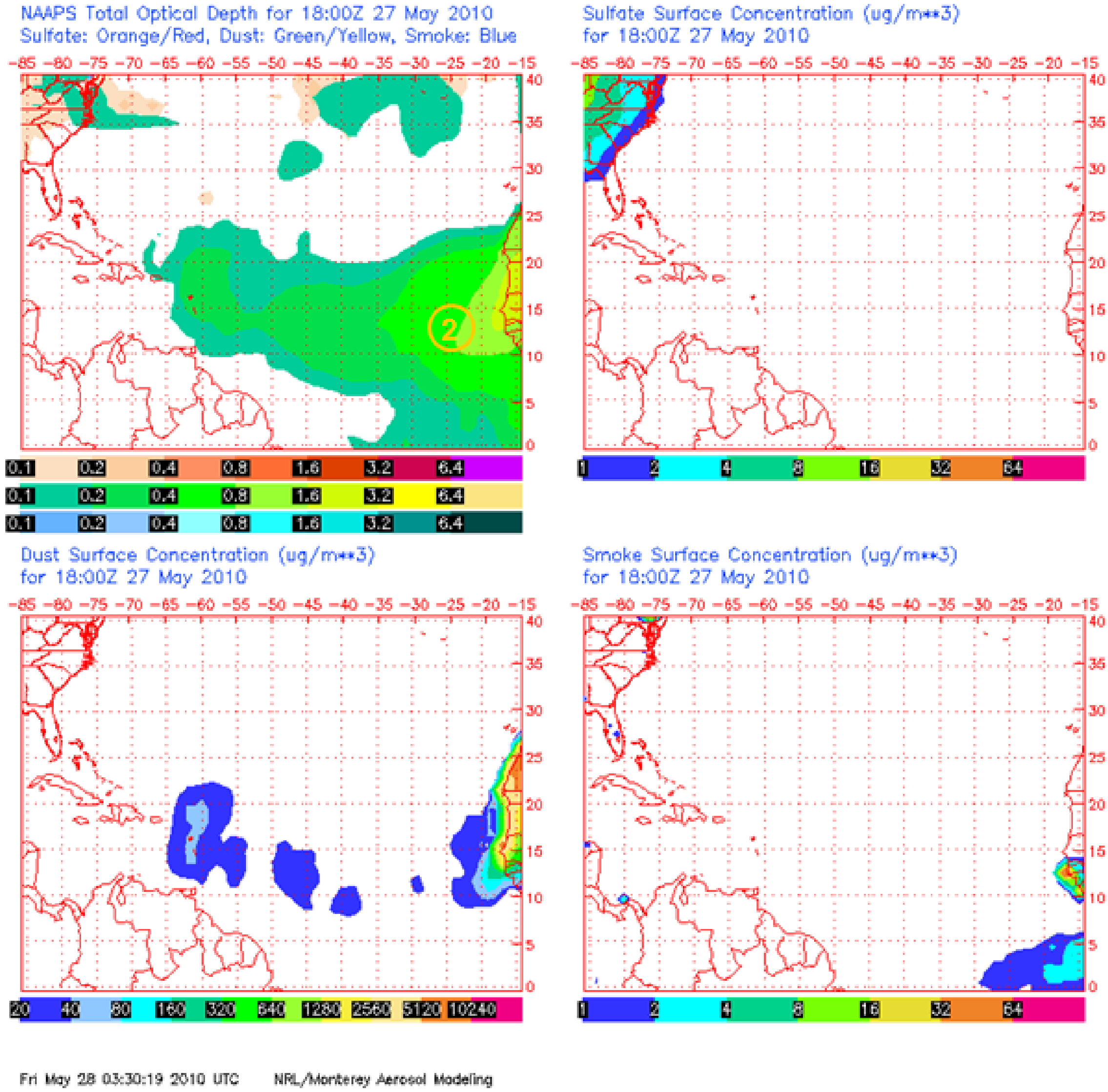

Figure B-23. NRL aerosol analysis 2010 May 27 showing the African dust cloud moving into the eastern Atlantic Ocean.

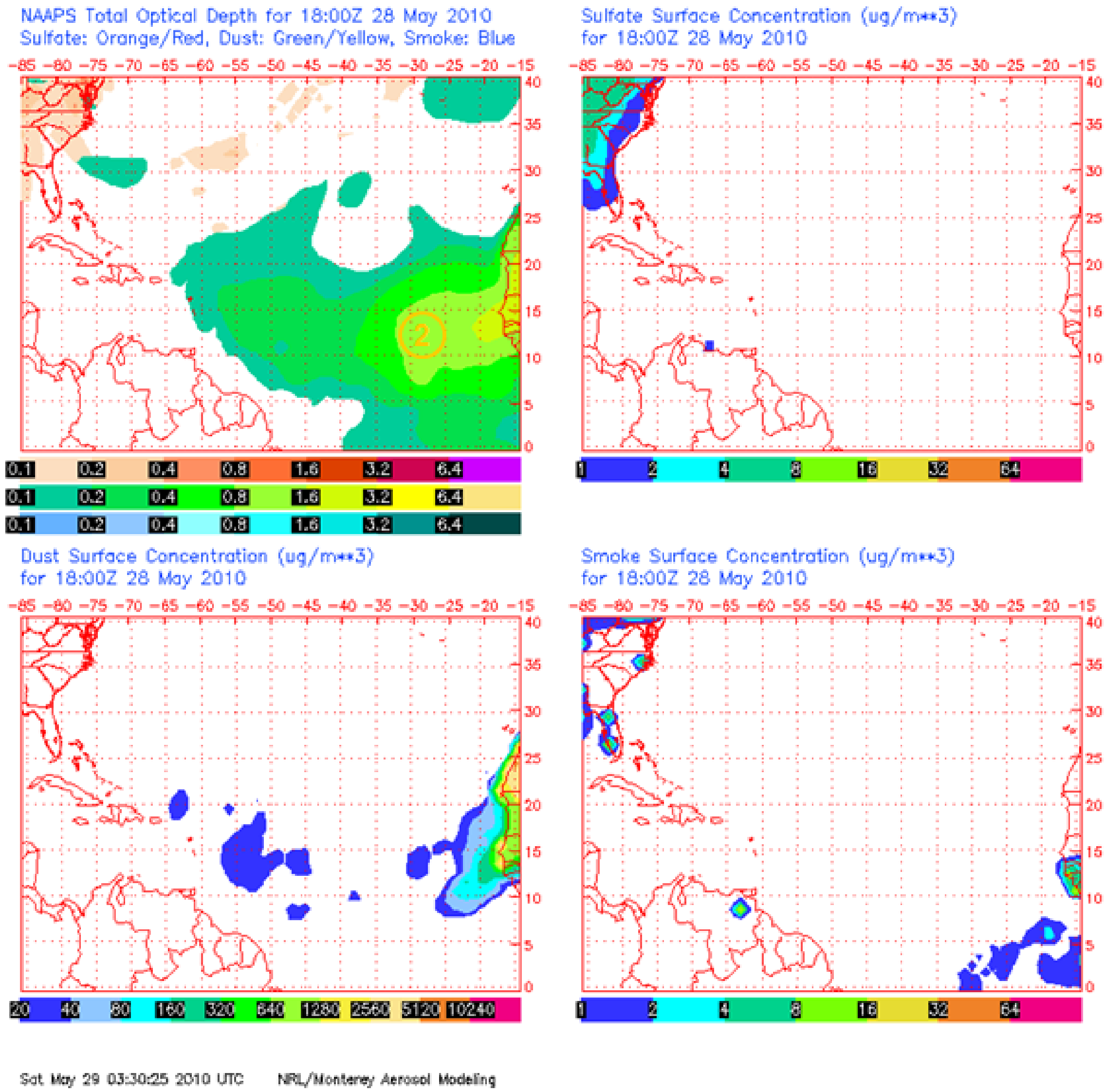

Figure B-24. NRL aerosol analysis 2010 May 28 showing the African dust cloud moving through the eastern Atlantic Ocean.

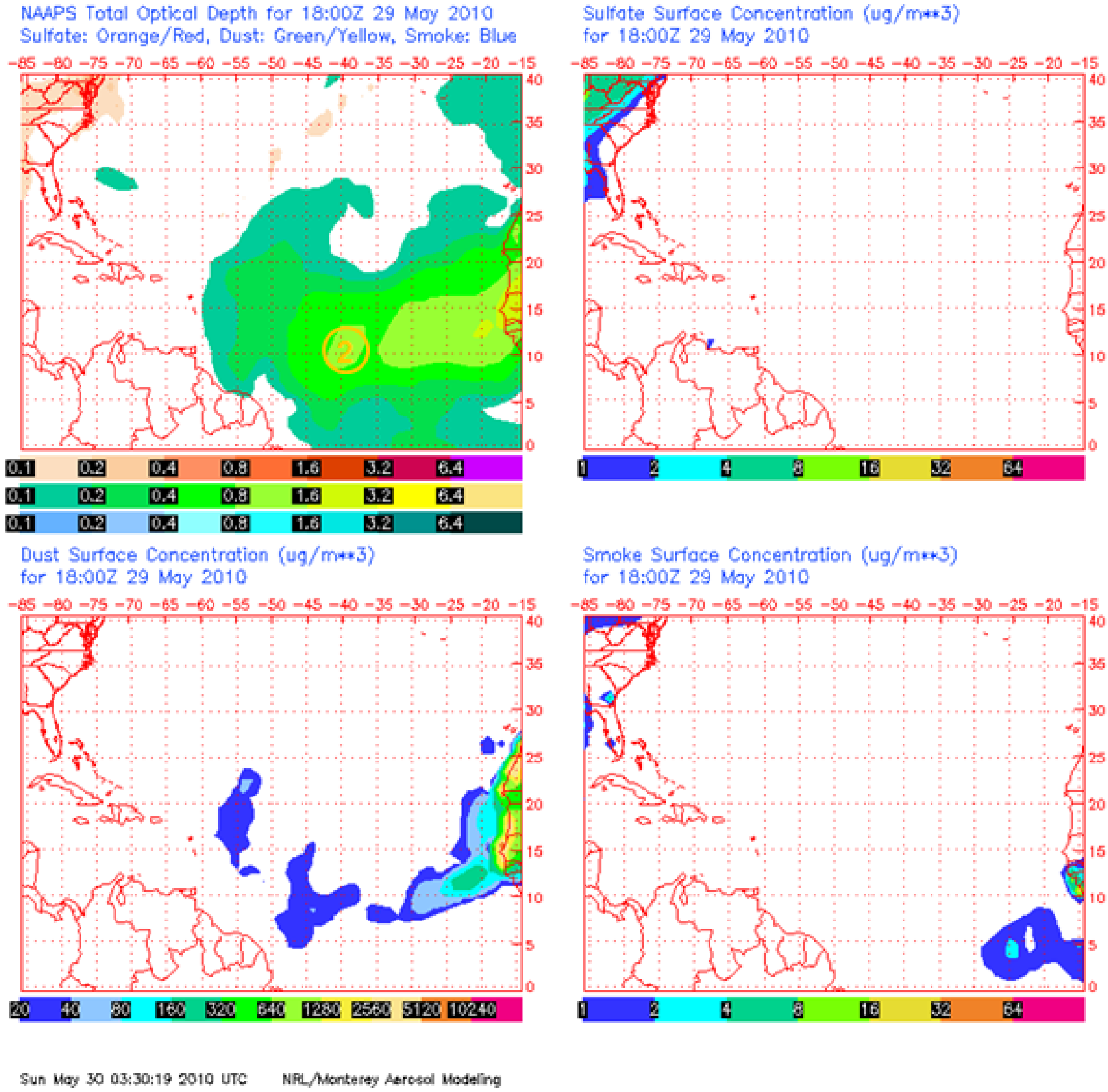

Figure B-25. NRL aerosol analysis 2010 May 29 showing the African dust cloud moving into the central Atlantic Ocean.

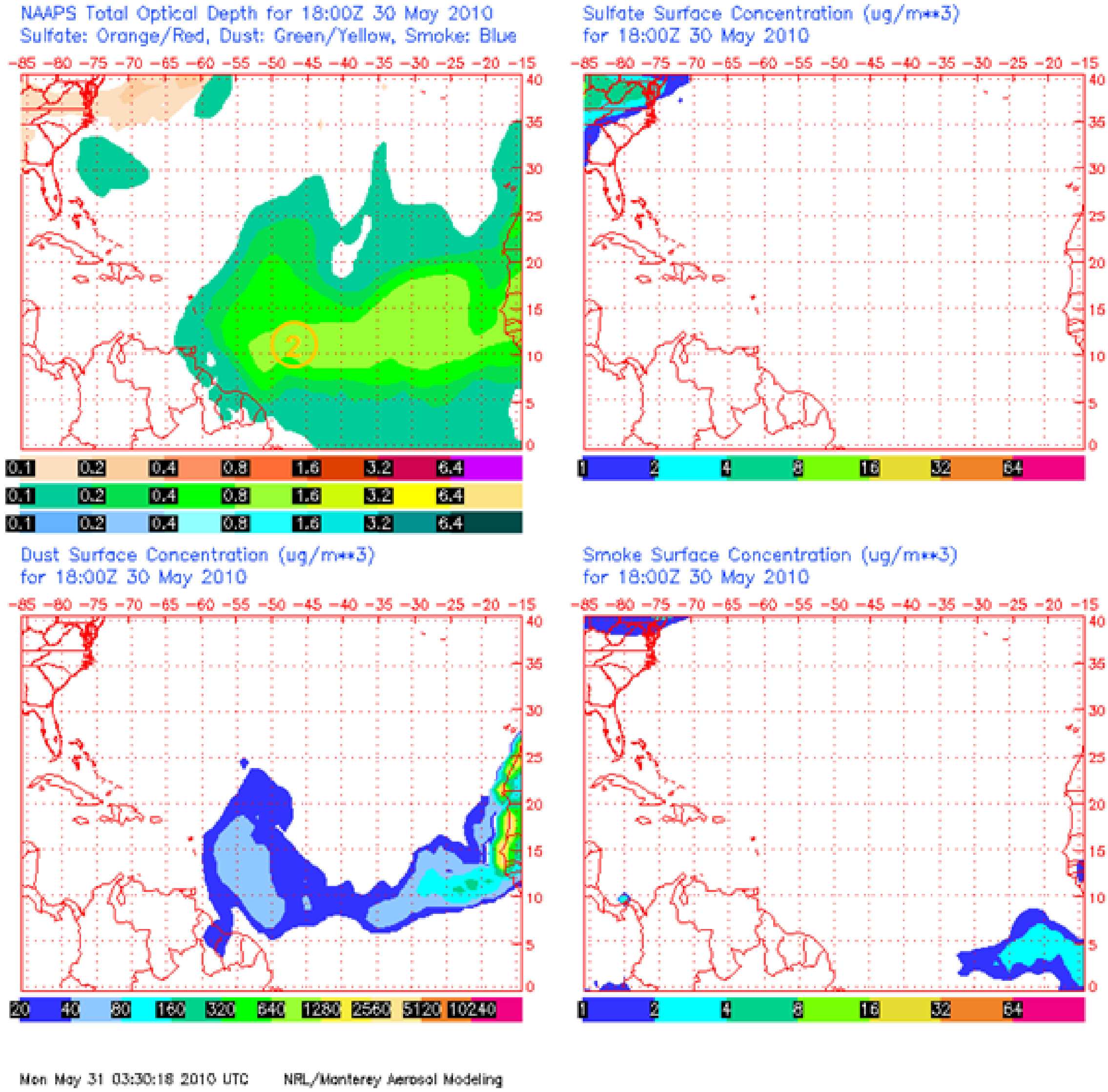

Figure B-26. NRL aerosol analysis 2010 May 30 showing the African dust cloud approaching the Lesser Antilles.

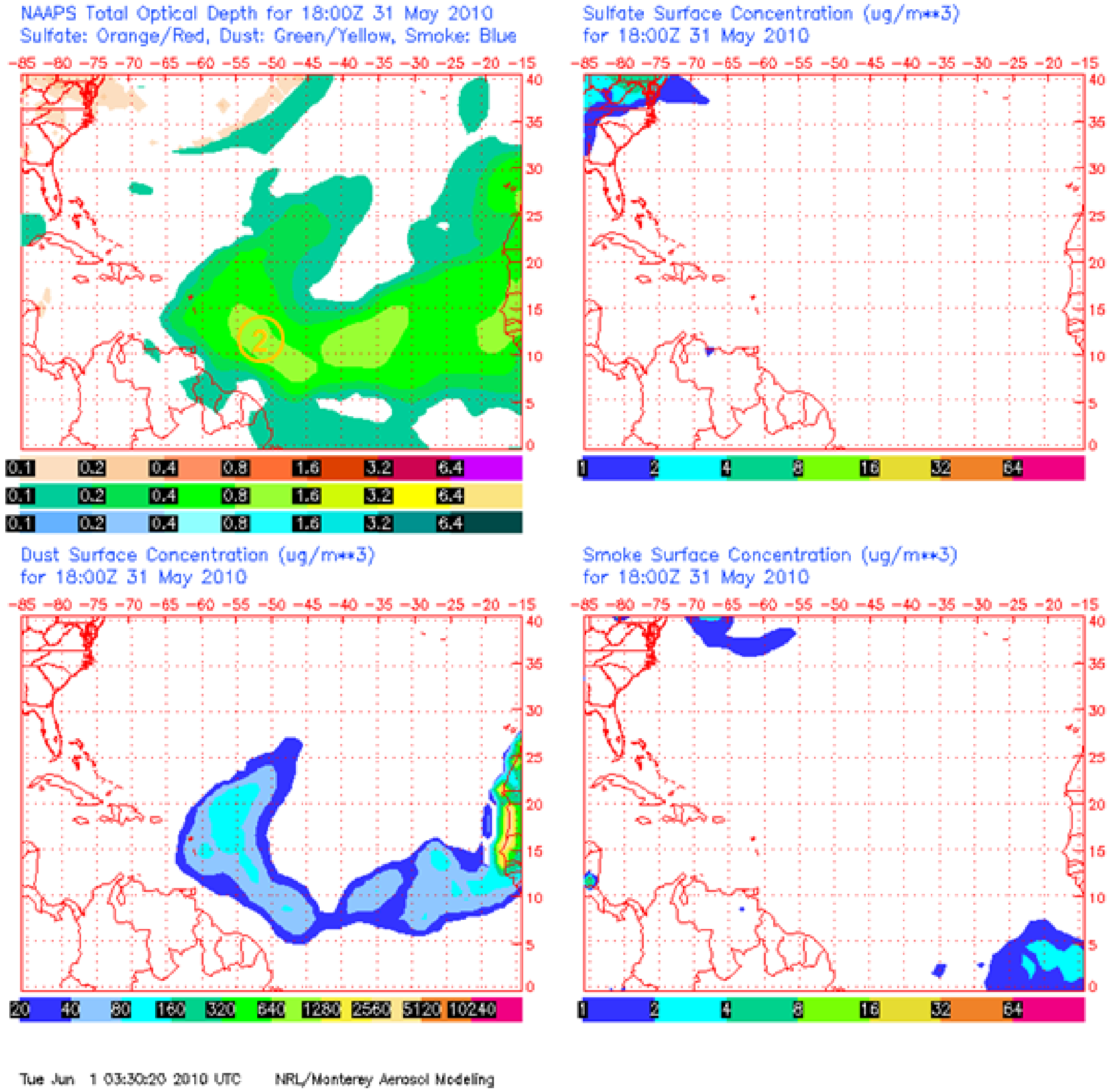

Figure B-27. NRL aerosol analysis 2010 May 31 showing the African dust cloud approaching the Lesser Antilles.

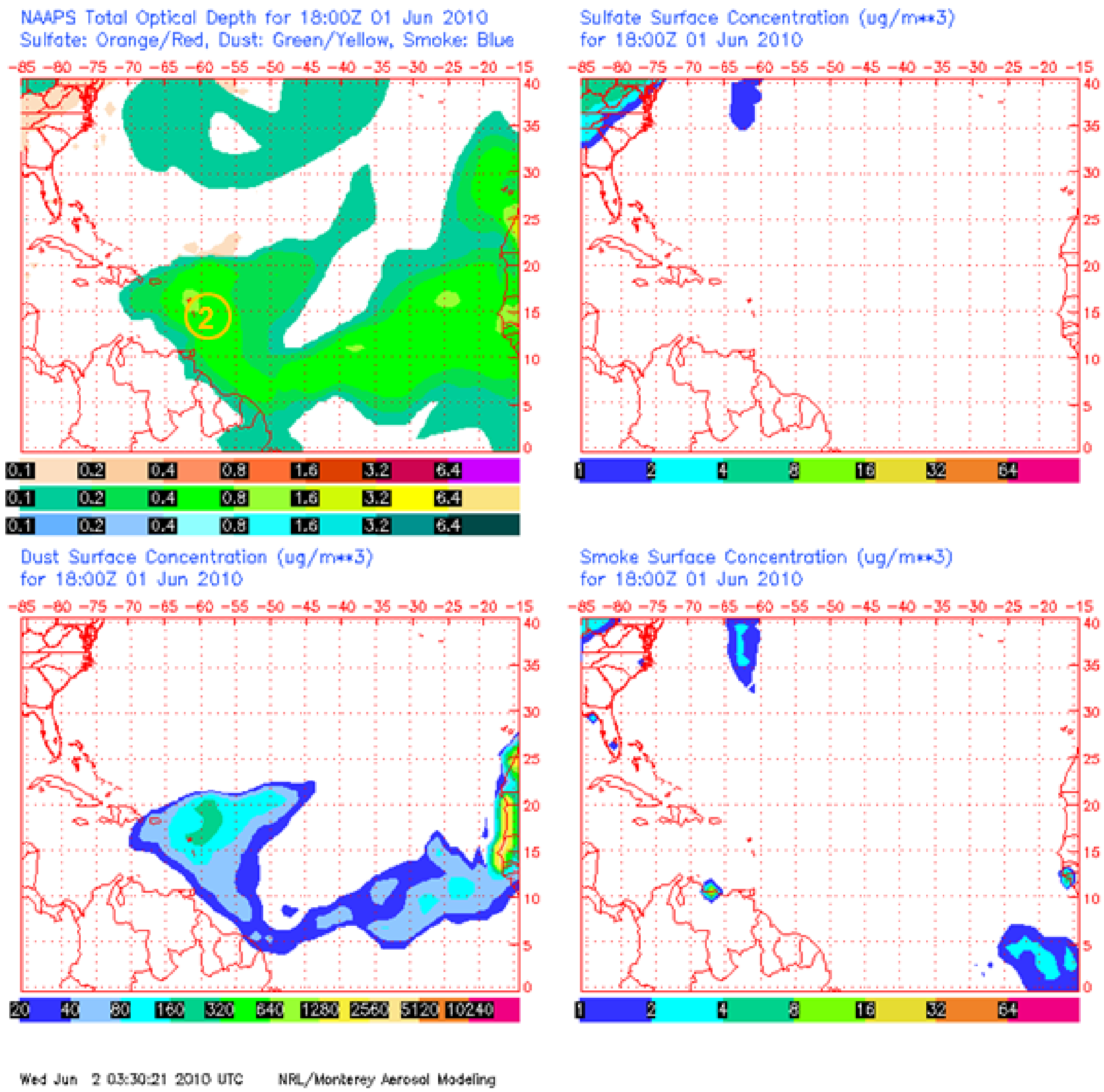

Figure B-28. NRL aerosol analysis 2010 June 1 showing the African dust cloud moving into the Lesser Antilles.

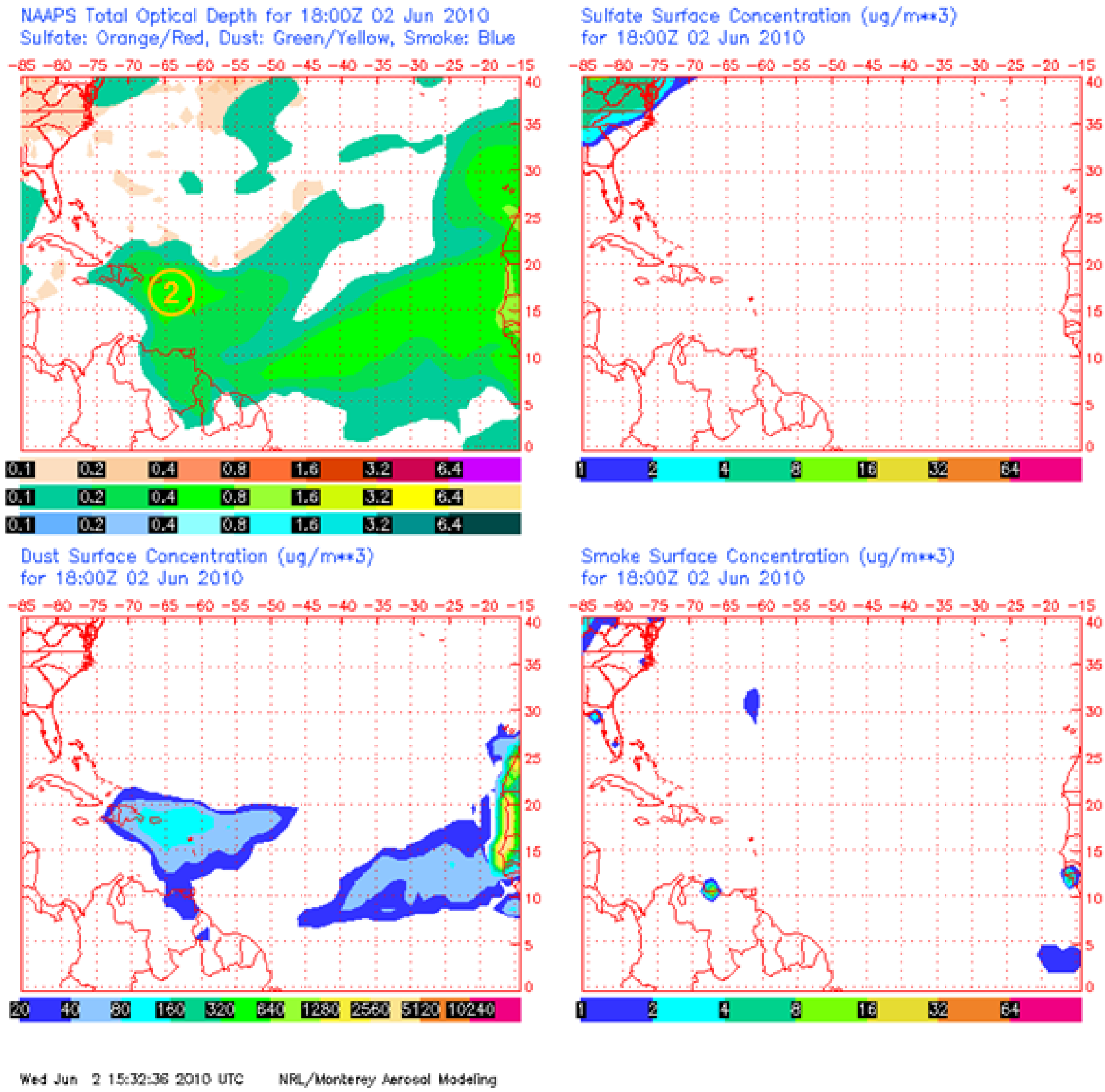

Figure B-29. NRL aerosol analysis 2010 June 2 showing the African dust cloud moving into the eastern Caribbean Sea.

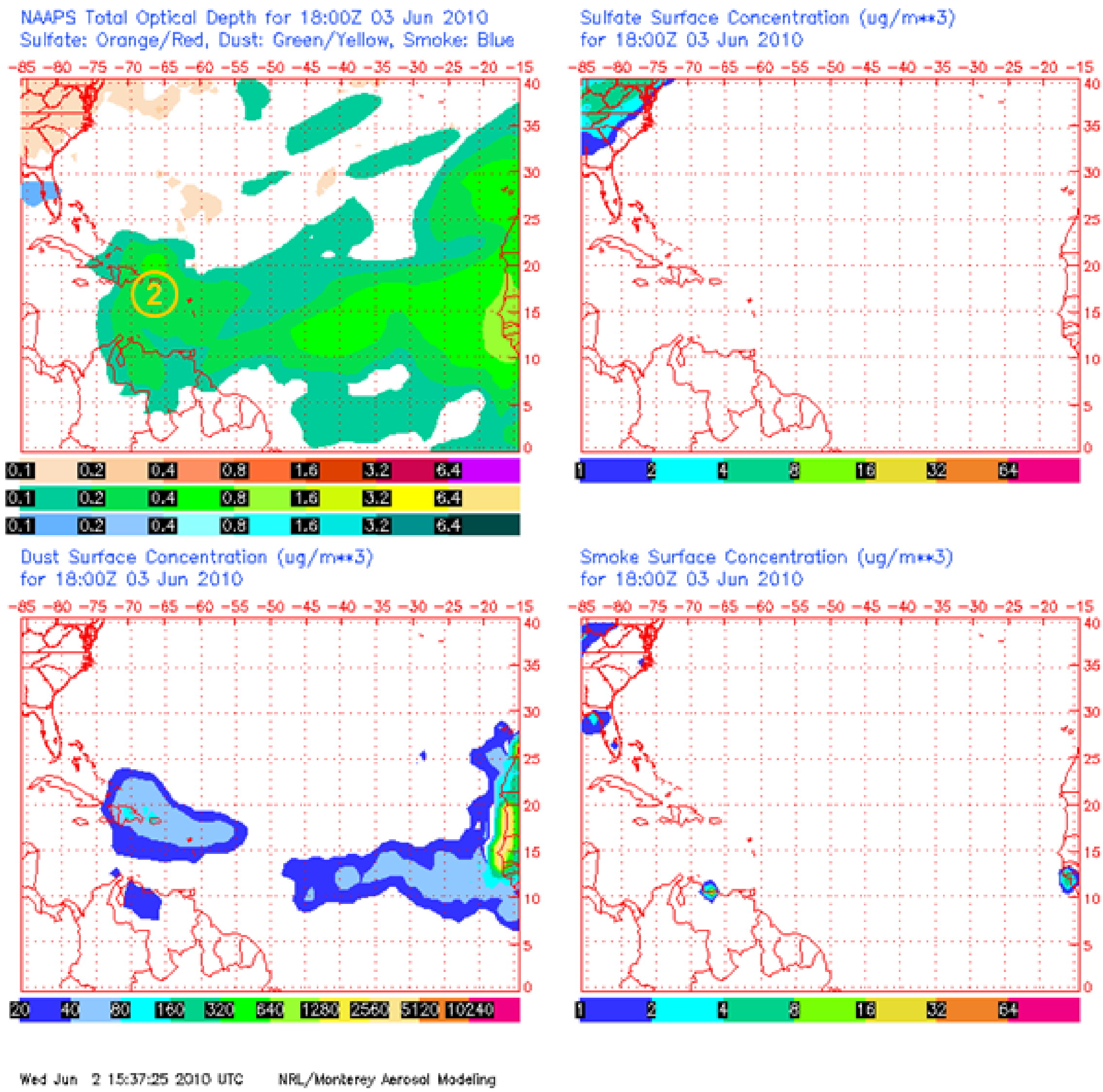

Figure B-30. NRL aerosol analysis 2010 June 3 showing the African dust cloud in the eastern Caribbean Sea.

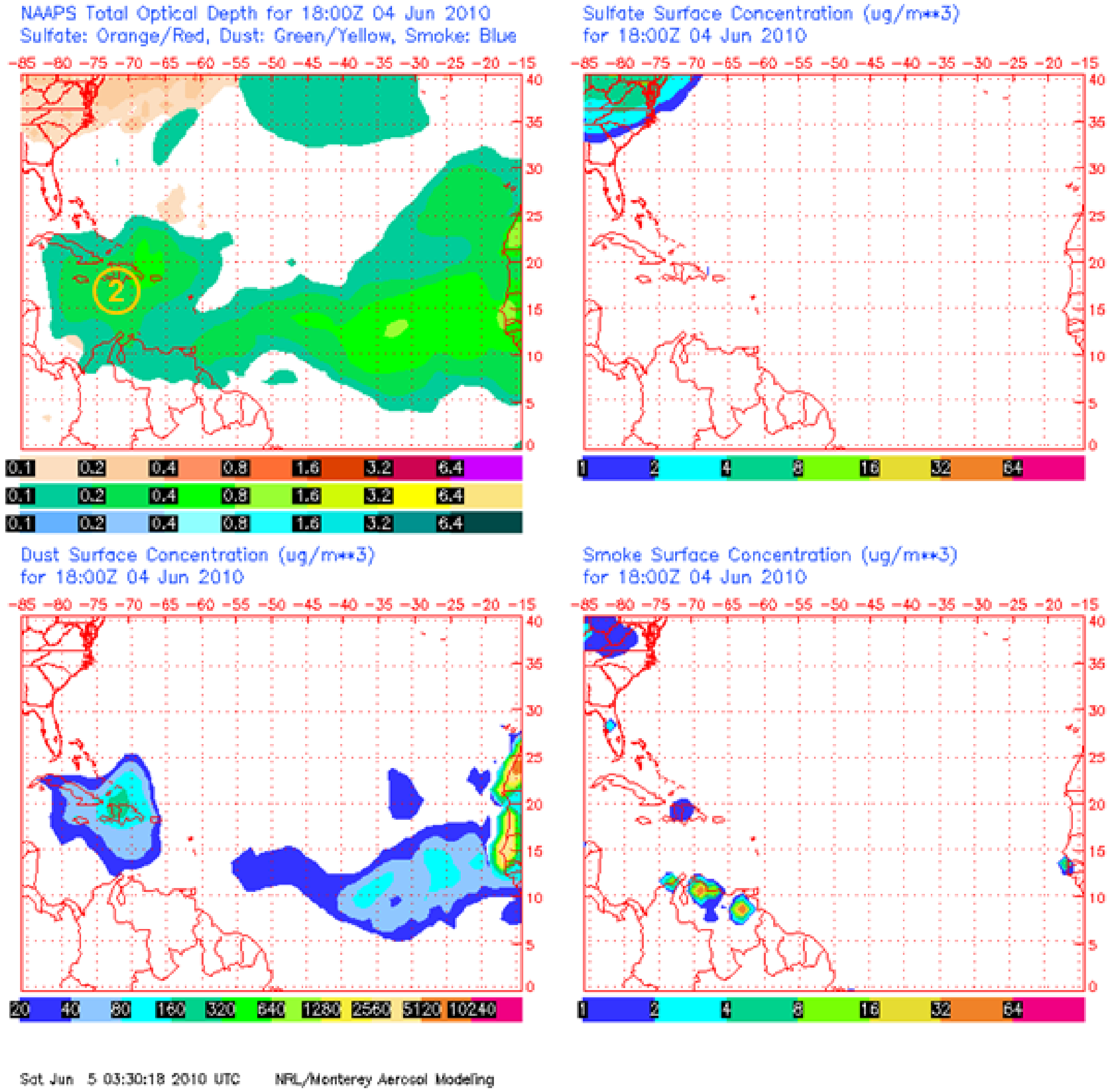

Figure B-31. NRL aerosol analysis 2010 June 4 showing the African dust cloud in the Caribbean Sea.

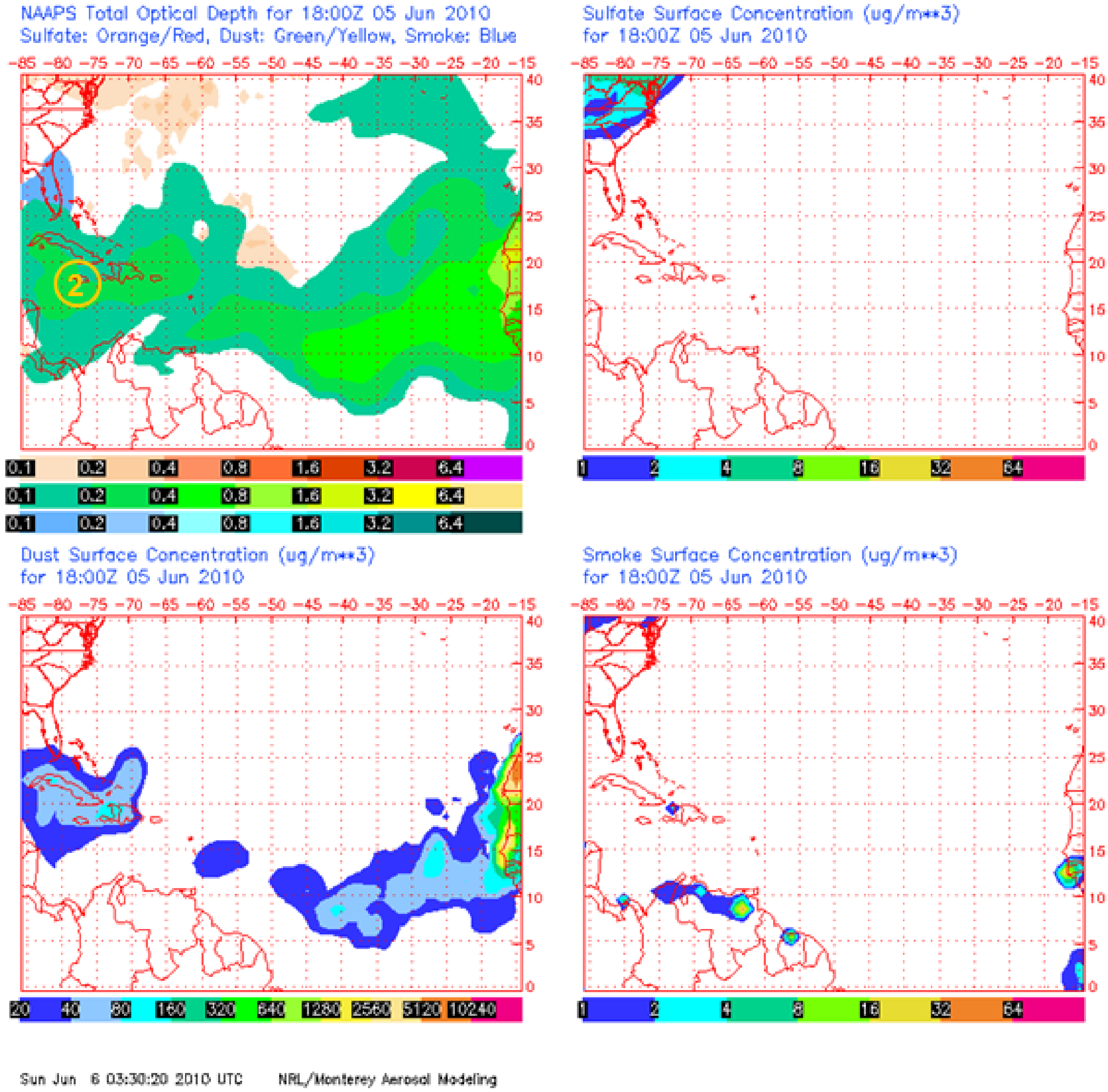

Figure B-32. NRL aerosol analysis 2010 June 5 showing the African dust cloud in the Caribbean Sea.

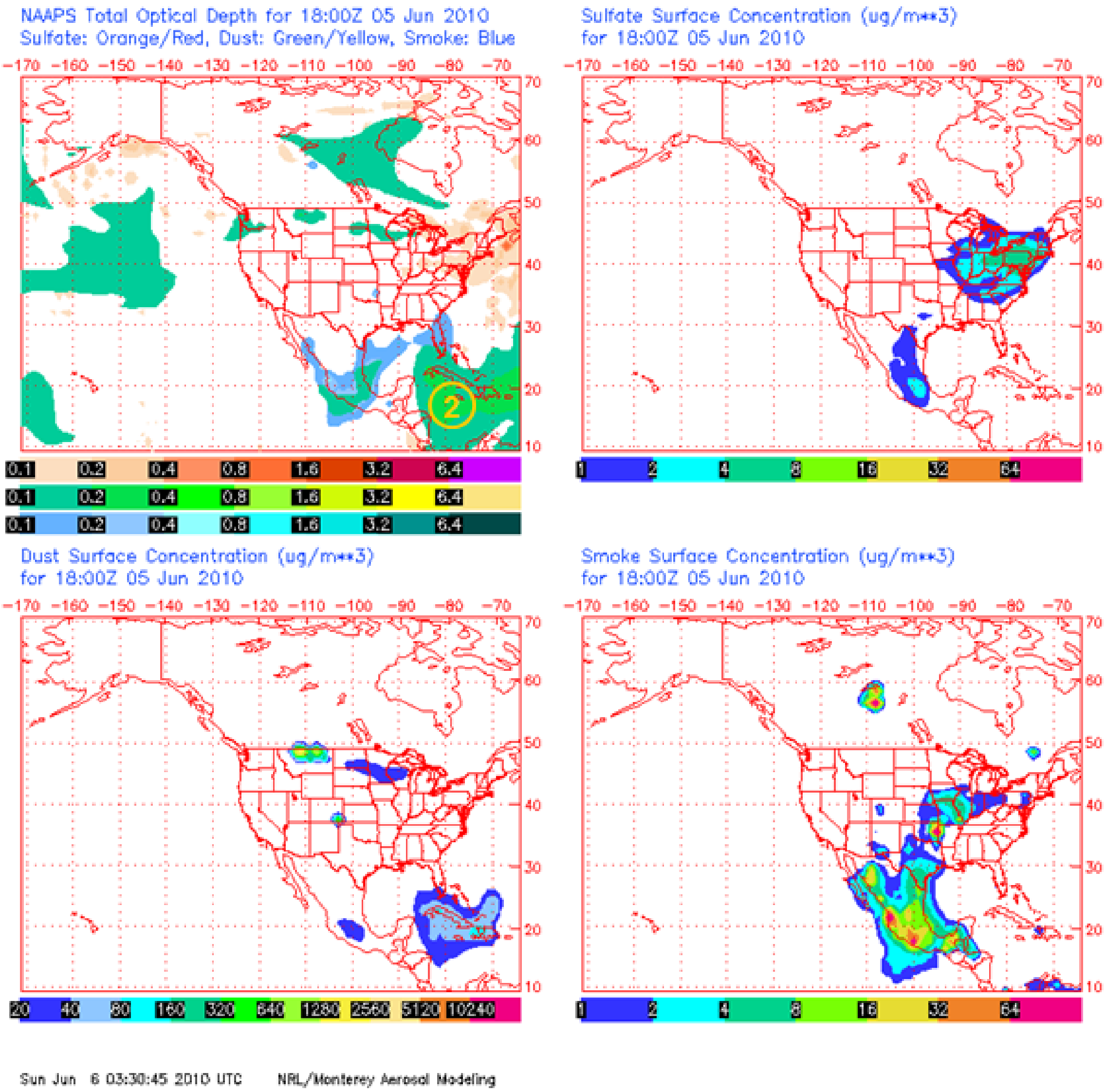

Figure B-33. NRL aerosol analysis 2010 June 5 showing the African dust cloud in the Caribbean Sea.

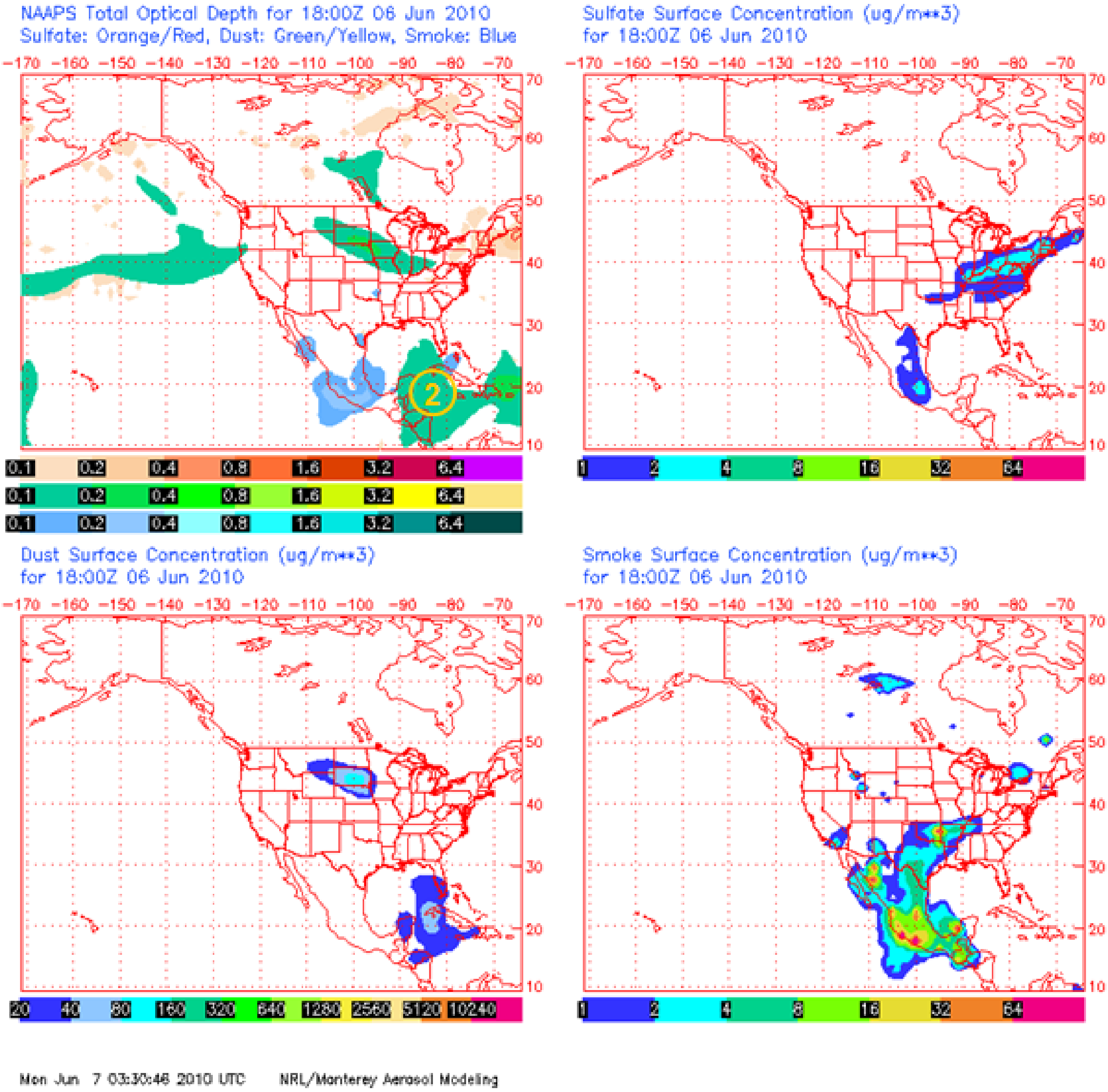

Figure B-34. NRL aerosol analysis 2010 June 6 showing the African dust cloud in the Caribbean Sea.

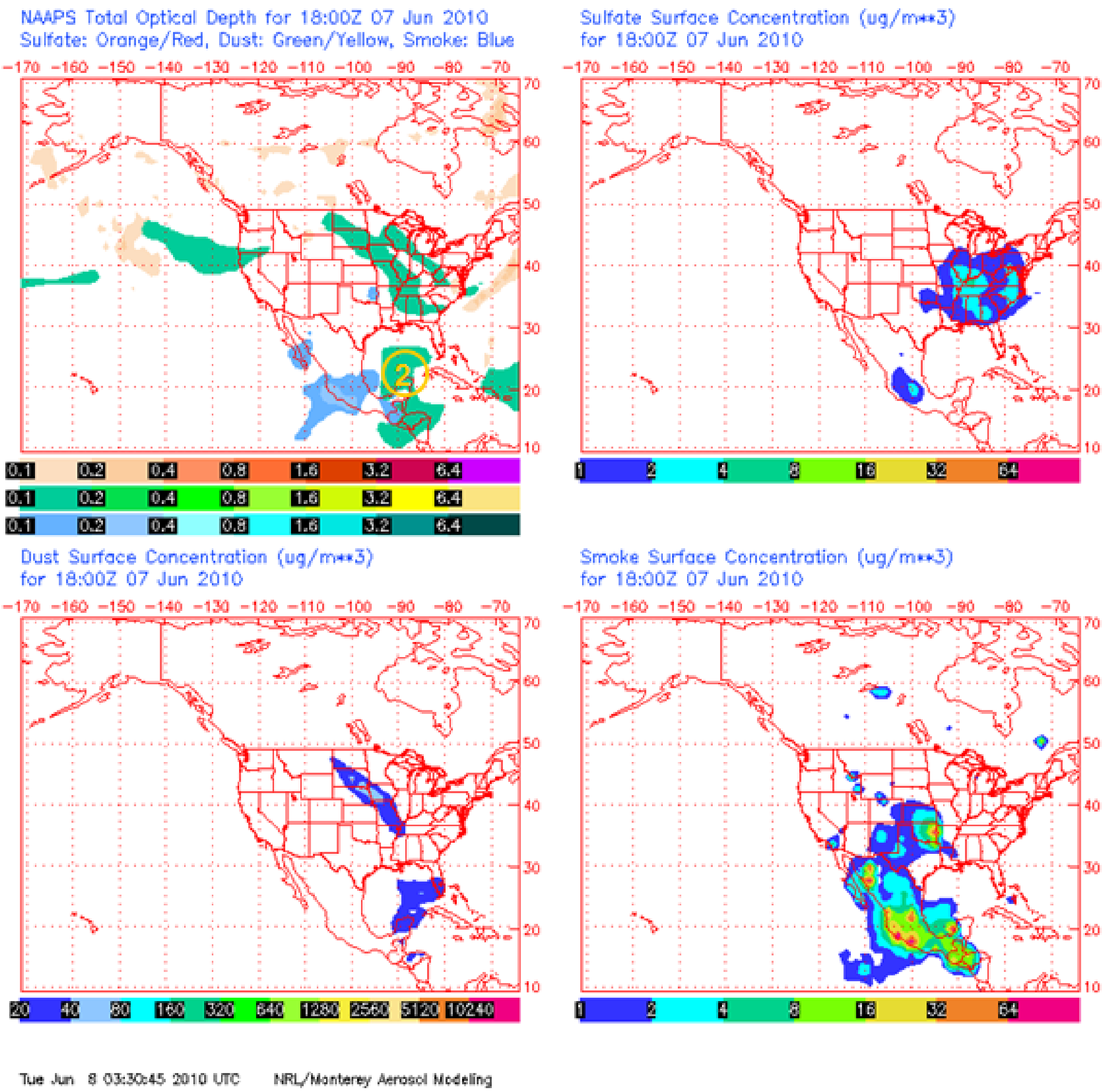

Figure B-35. NRL aerosol analysis 2010 June 7 showing the African dust cloud in the Gulf of Mexico.

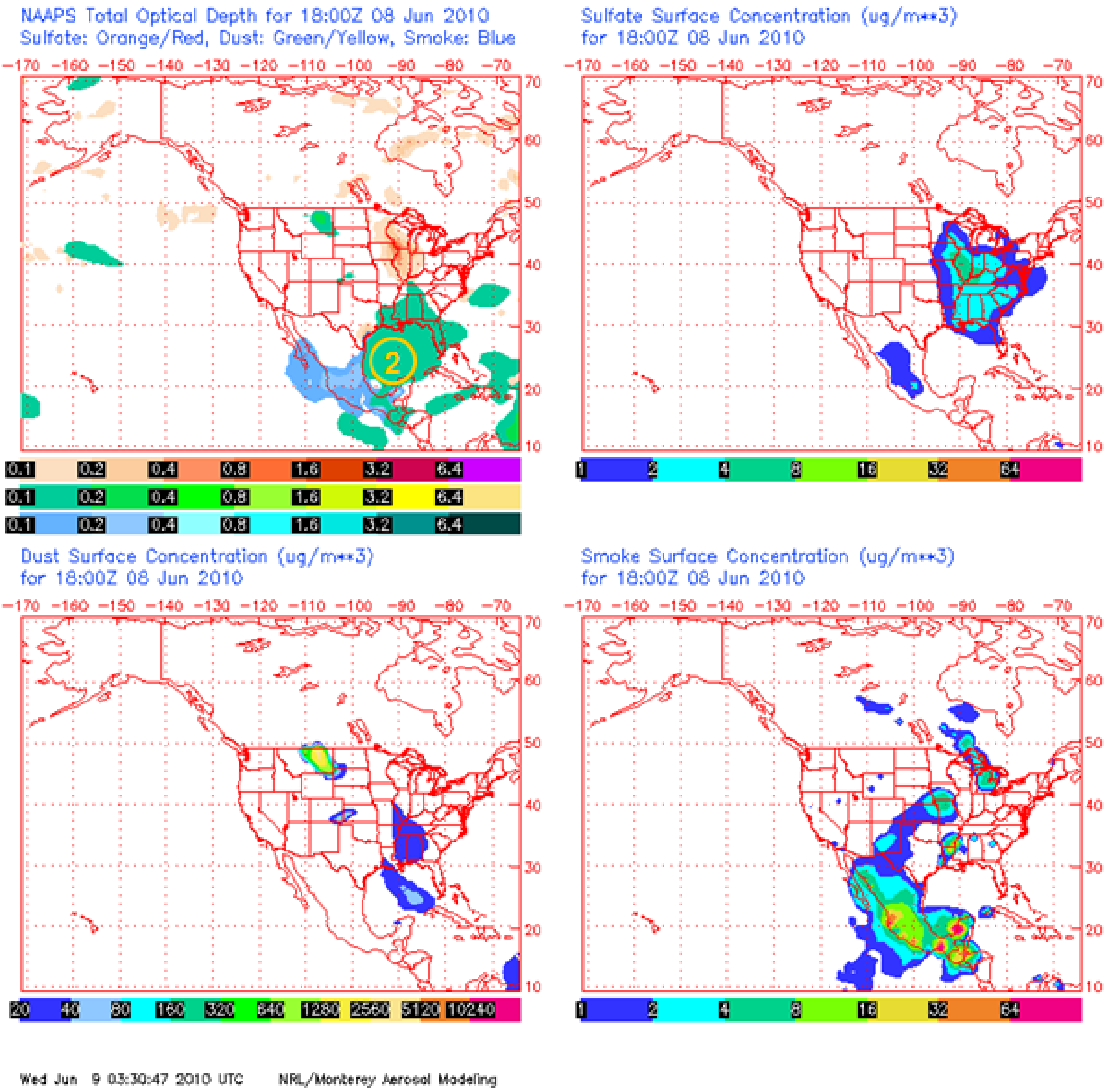

Figure B-36. NRL aerosol analysis 2010 June 8 showing the African dust cloud in the Gulf of Mexico.

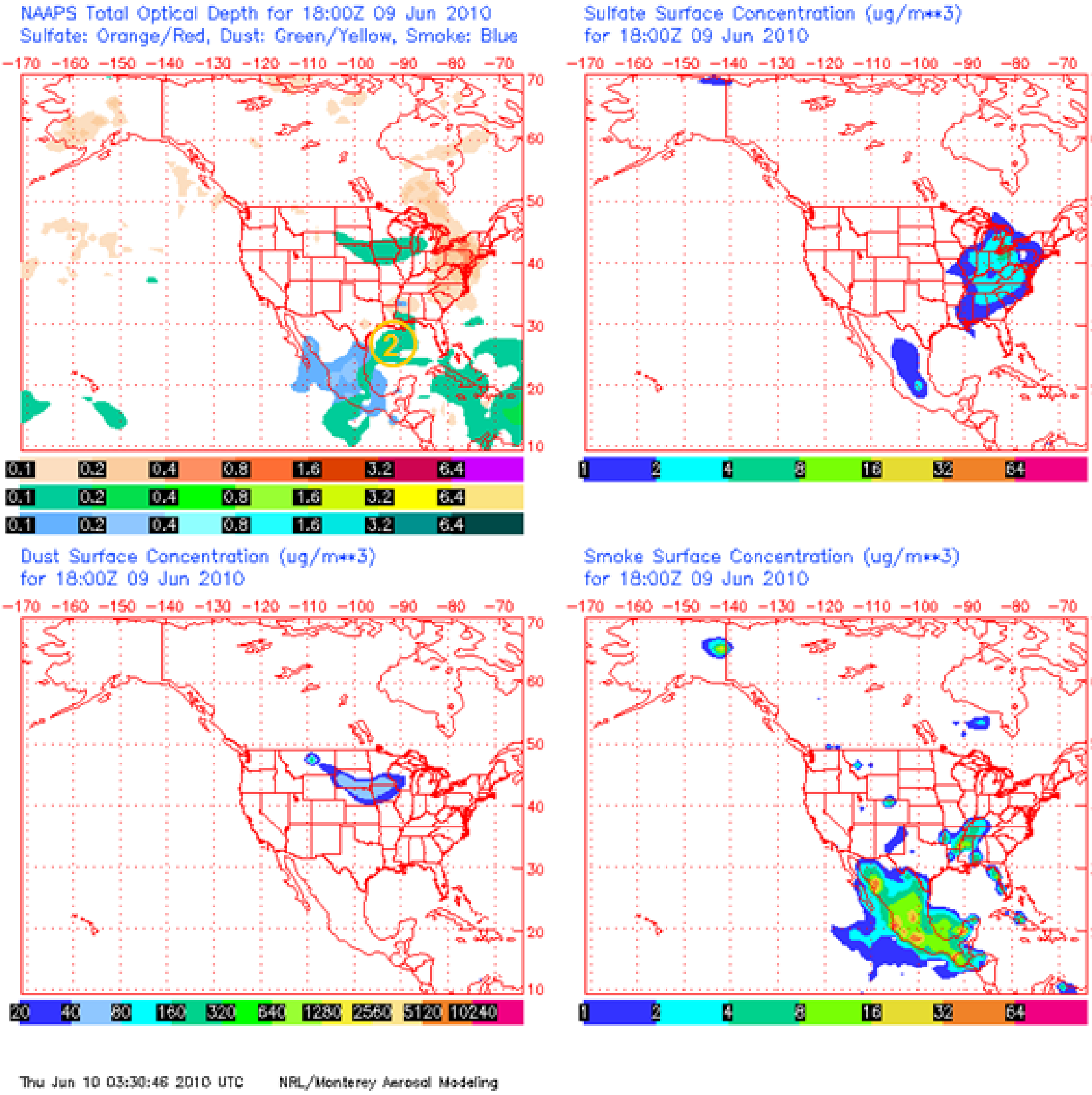

Figure B-37. NRL aerosol analysis 2010 June 9 showing the African dust cloud in the Gulf of Mexico.

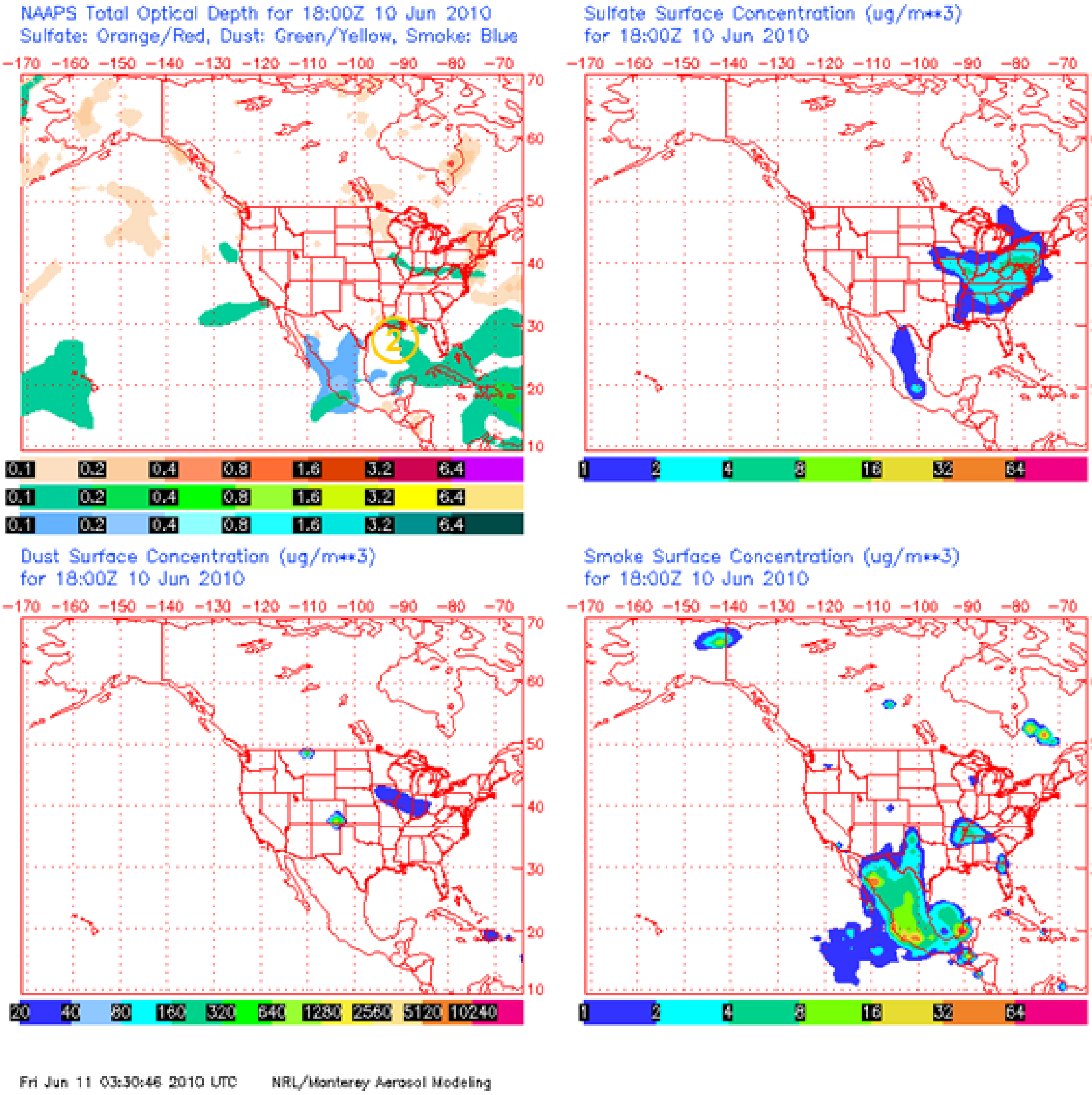

Figure B-38. NRL aerosol analysis 2010 June 10 showing the African dust cloud in the Gulf of Mexico.

Appendix C: Source Analysis for July 13

Back Trajectory

Figure C-1 provides a HYSPLIT back trajectory that shows the approximate path of air arriving in the Houston area at 1200 CST on July 13th and going backward in time 312 hours. The trajectory indicates the air came from Africa. The NOAA web site where the trajectories were produced does not allow them to run past 312 hours. So, it is not possible to follow the air parcel all the way back into Africa.

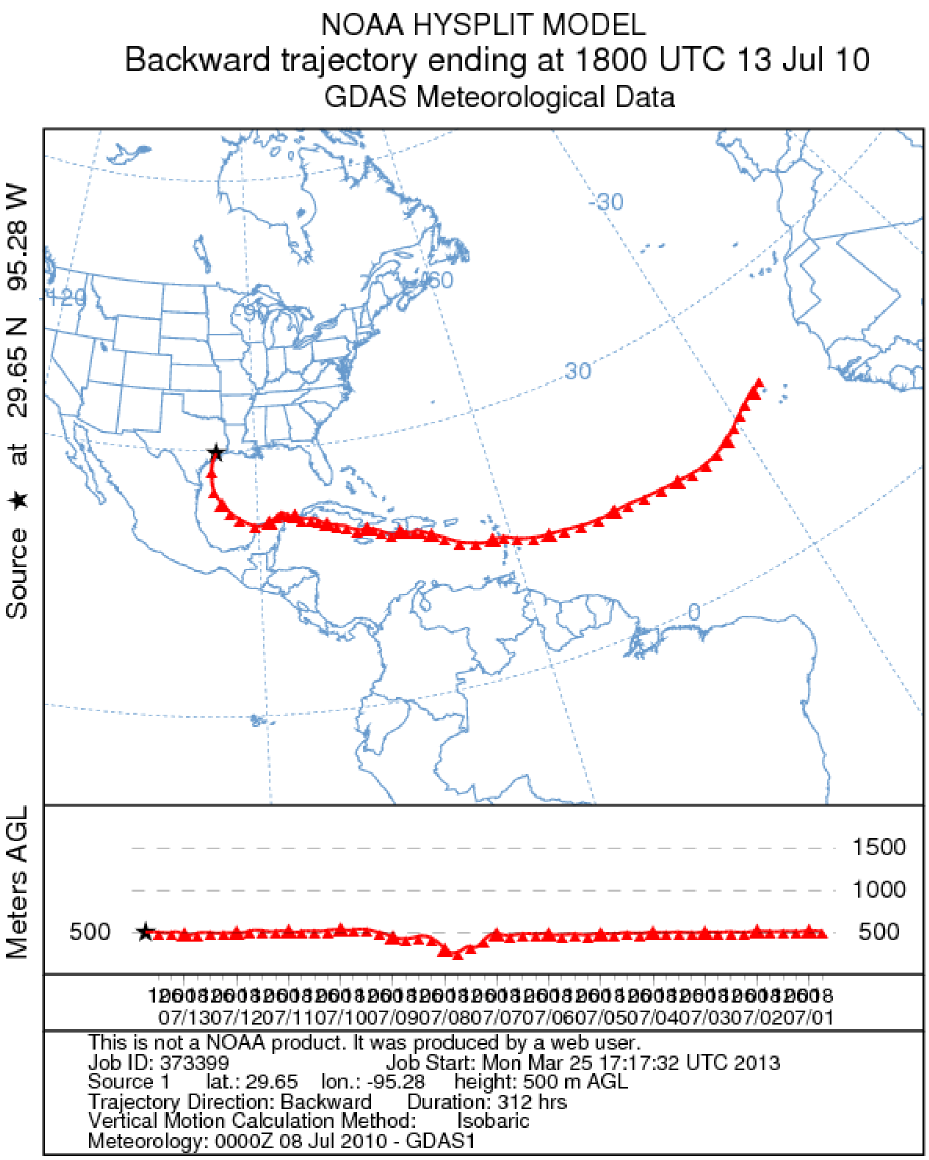

Figure C-1. Backward-in-time air trajectory for July 13, 2010.

Satellite Imagery

Figures C-2 through C-25 provide geostationary satellite images showing a series of three African dust clouds in close succession progressing across the Atlantic, Caribbean Sea, and Gulf of Mexico. The image times are listed in Universal Time Coordinates (UTC) which is five hours ahead of Central Daylight Time. On these images, most clouds are bright white with sharp edges and ocean water is normally very dark away from clouds. Dust in the air makes the ocean look much brighter when present, giving it a milky appearance with soft indistinct edges to the dust cloud.

The first in the series of three African dust clouds had emerged into the eastern Atlantic Ocean from the African coast by June 26, 2010 as shown in Figure C-2. The three dust clouds of interest are labeled with numbers “9”, “10”, and “11” in the satellite images. The first dust cloud 9 tracked across the Atlantic Ocean reaching the Lesser Antilles on June 30th, began moving into the Gulf of Mexico on July 5th, and began moving into the Houston area on July 8th. The second dust cloud 10 departed Africa on July 1st, reached the Lesser Antilles on July 5th, began moving into the Gulf of Mexico on July 11th, and began to move into the Houston area on July 12th. The third dust cloud 11 departed Africa on July 5th, reached the Lesser Antilles on July 10th, began moving into the Gulf of Mexico on July 13th, and began moving into the Houston area on July 15th. These dust clouds were so close to each other that there was little break in the dust between the passage of the centers of the dust clouds.

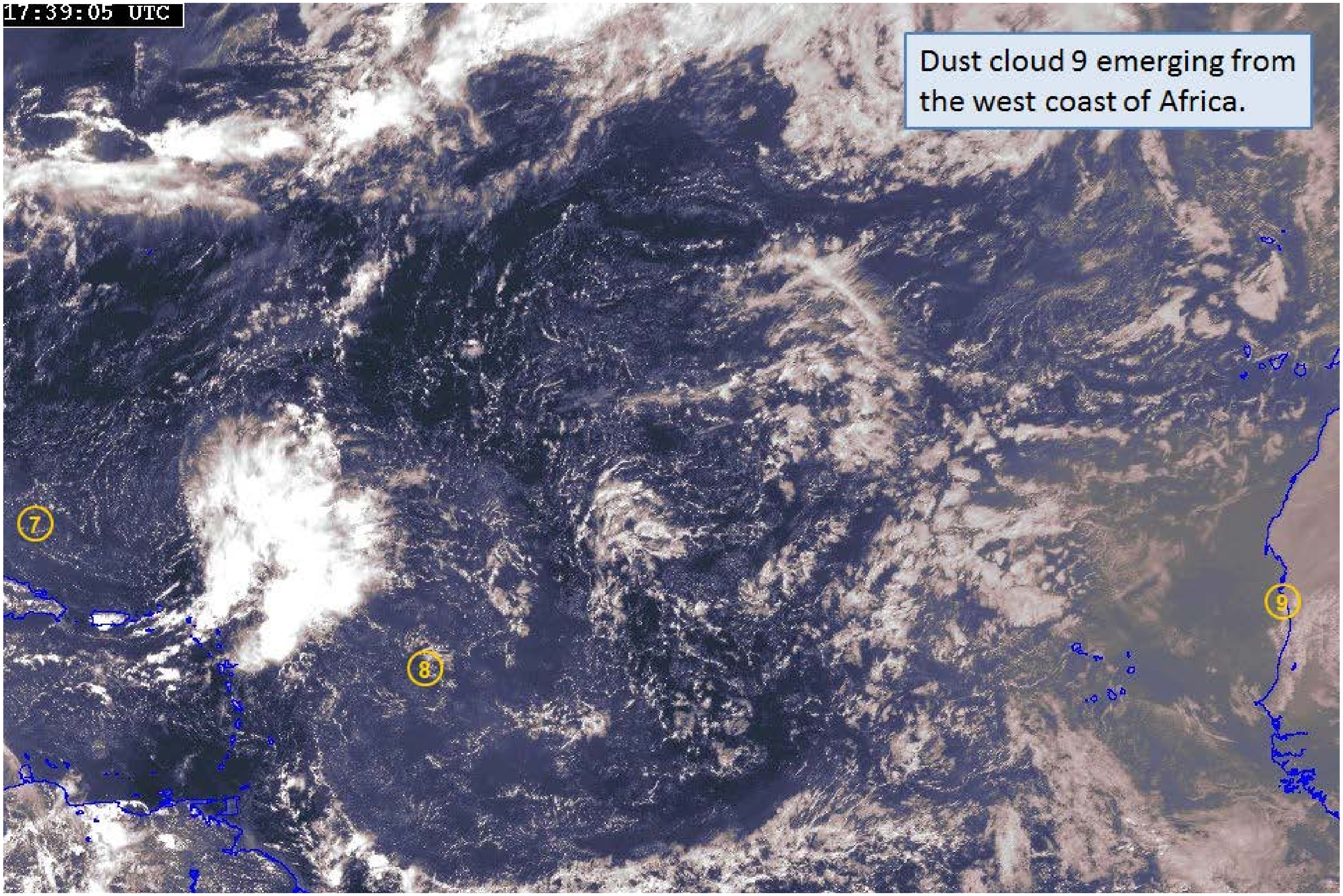

Figure C-2. Visible satellite image for 1745 UTC on June 26, 2010.

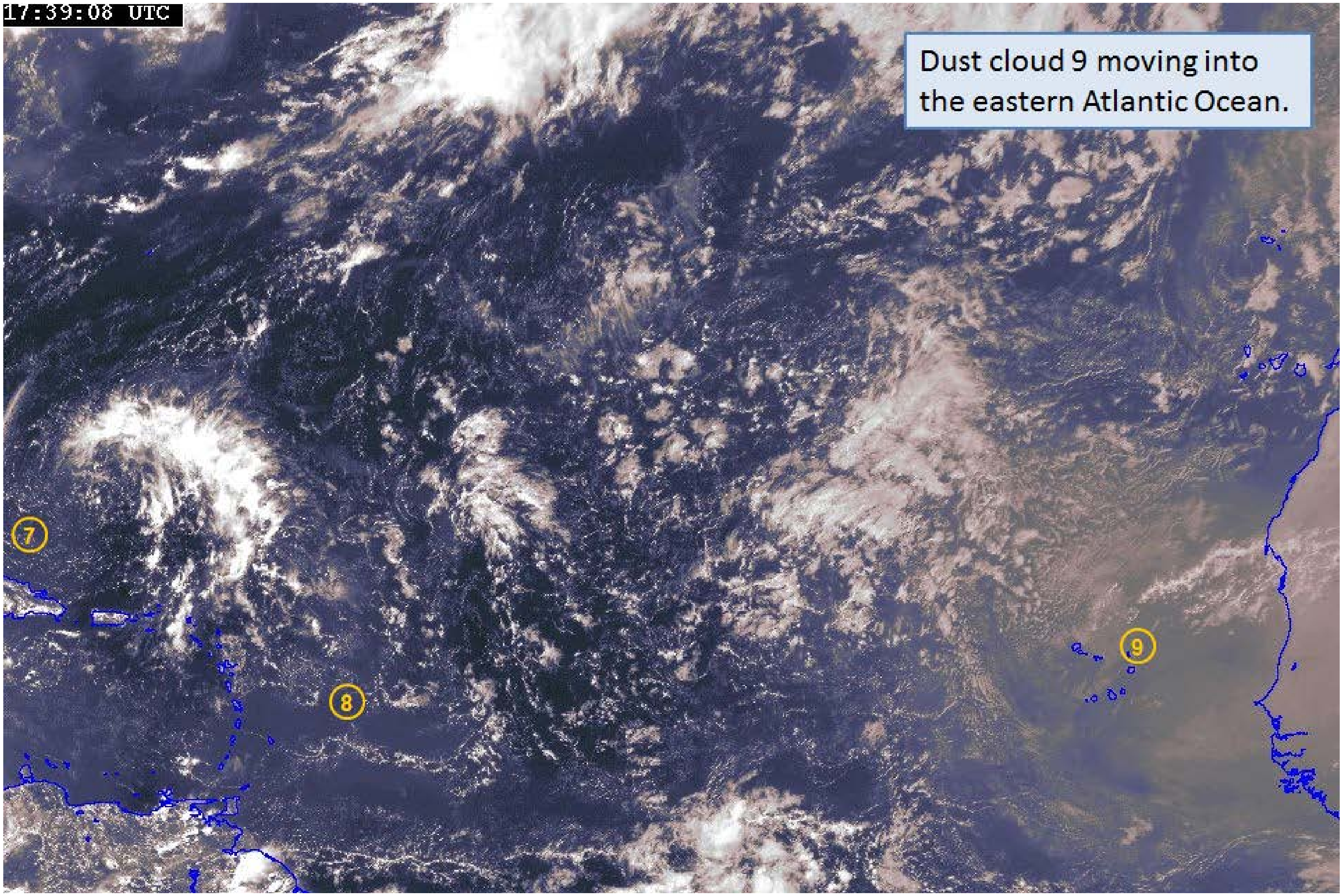

Figure C-3. Visible satellite image for 1745 UTC on June 27, 2010.

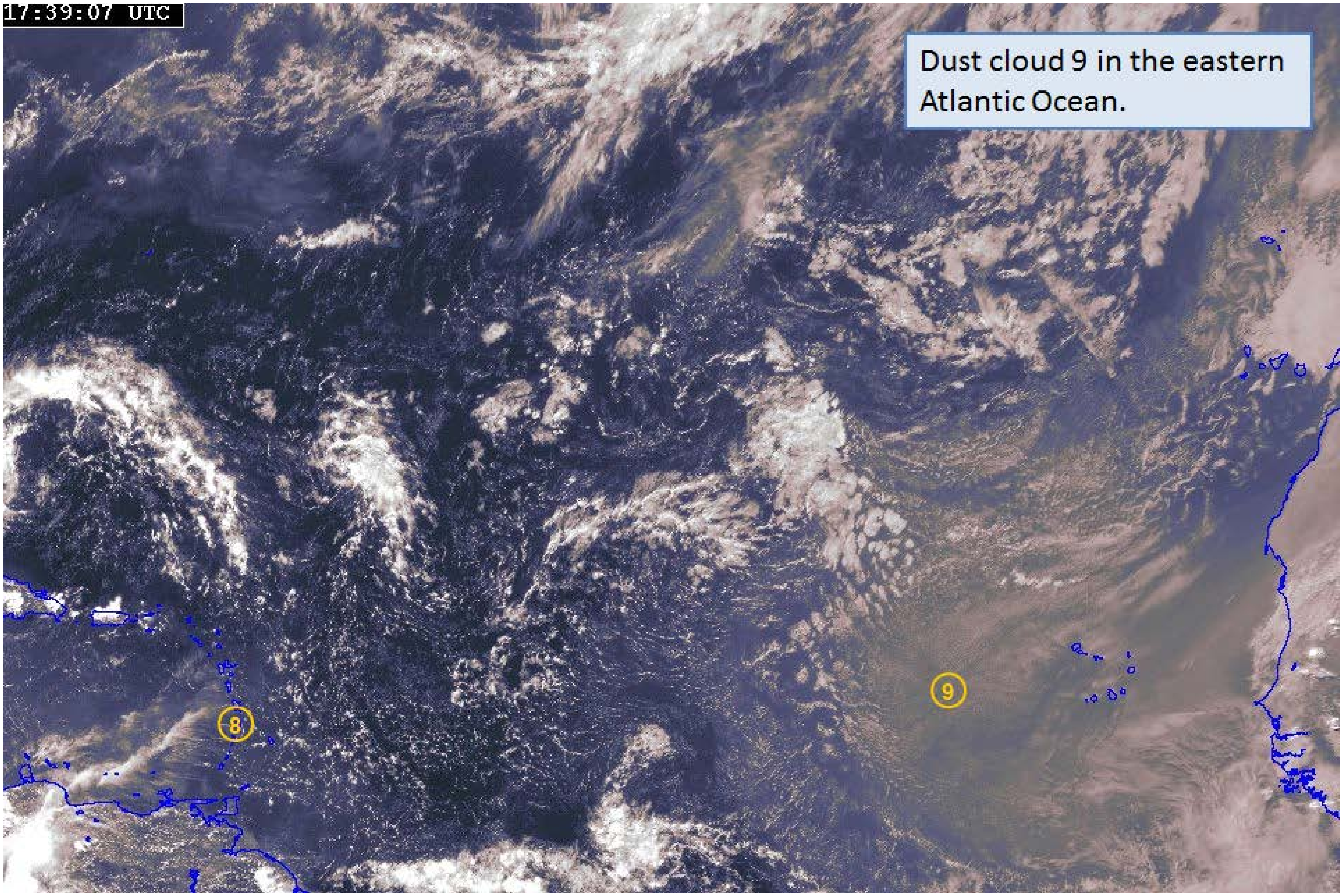

Figure C-4. Visible satellite image for 1745 UTC on June 28, 2010.

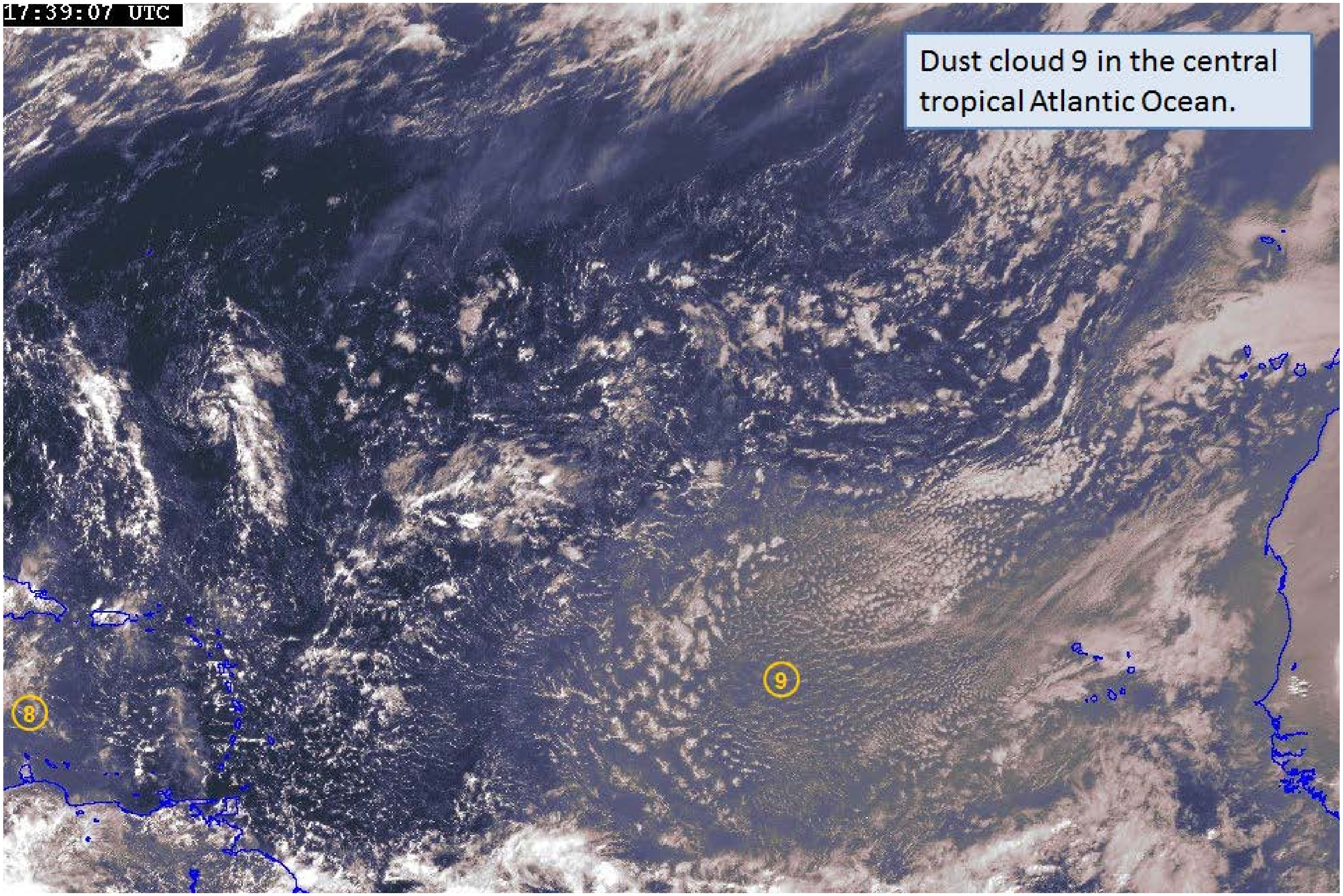

Figure C-5. Visible satellite image for 1745 UTC on June 29, 2010.

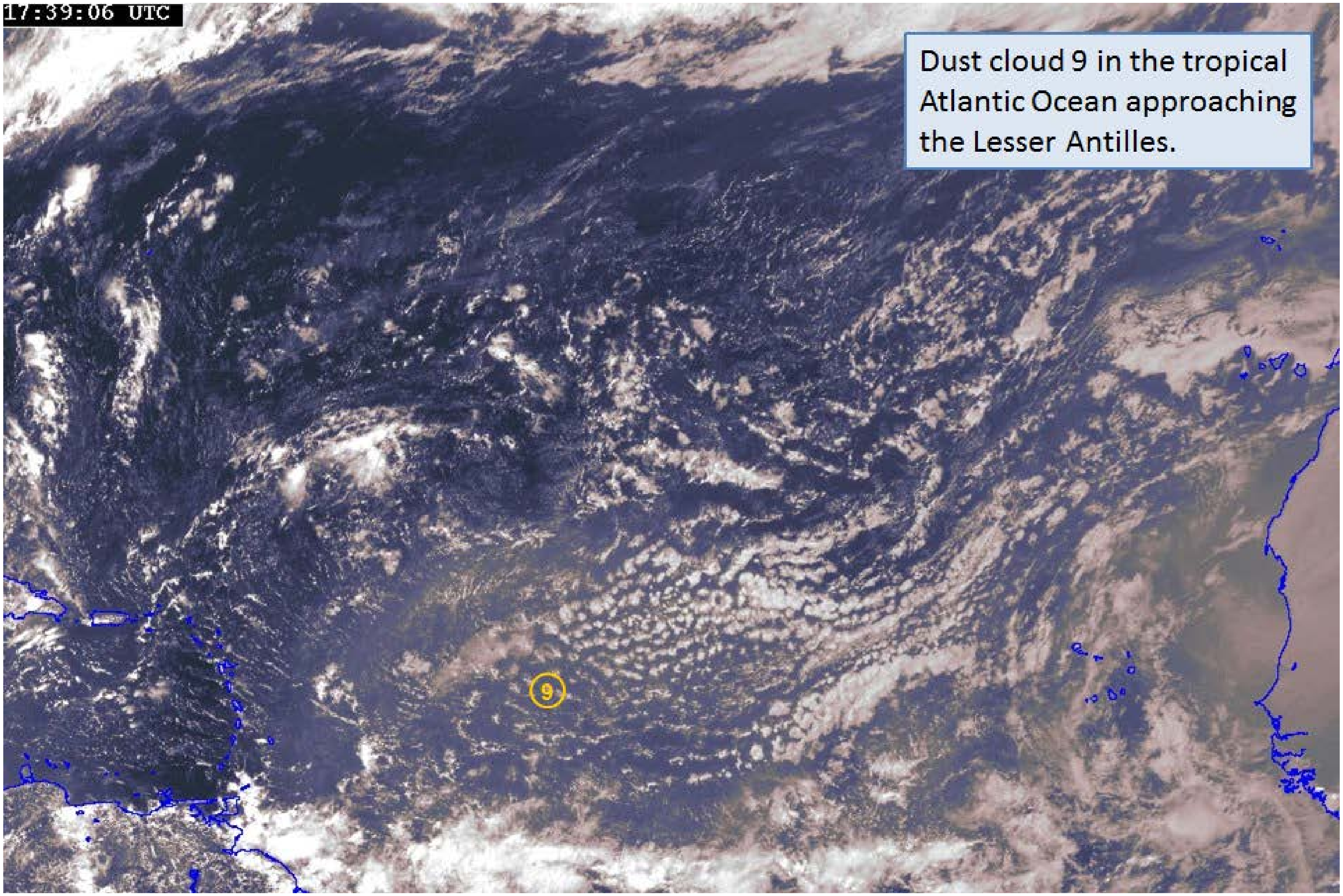

Figure C-6. Visible satellite image for 1745 UTC on June 30, 2010.

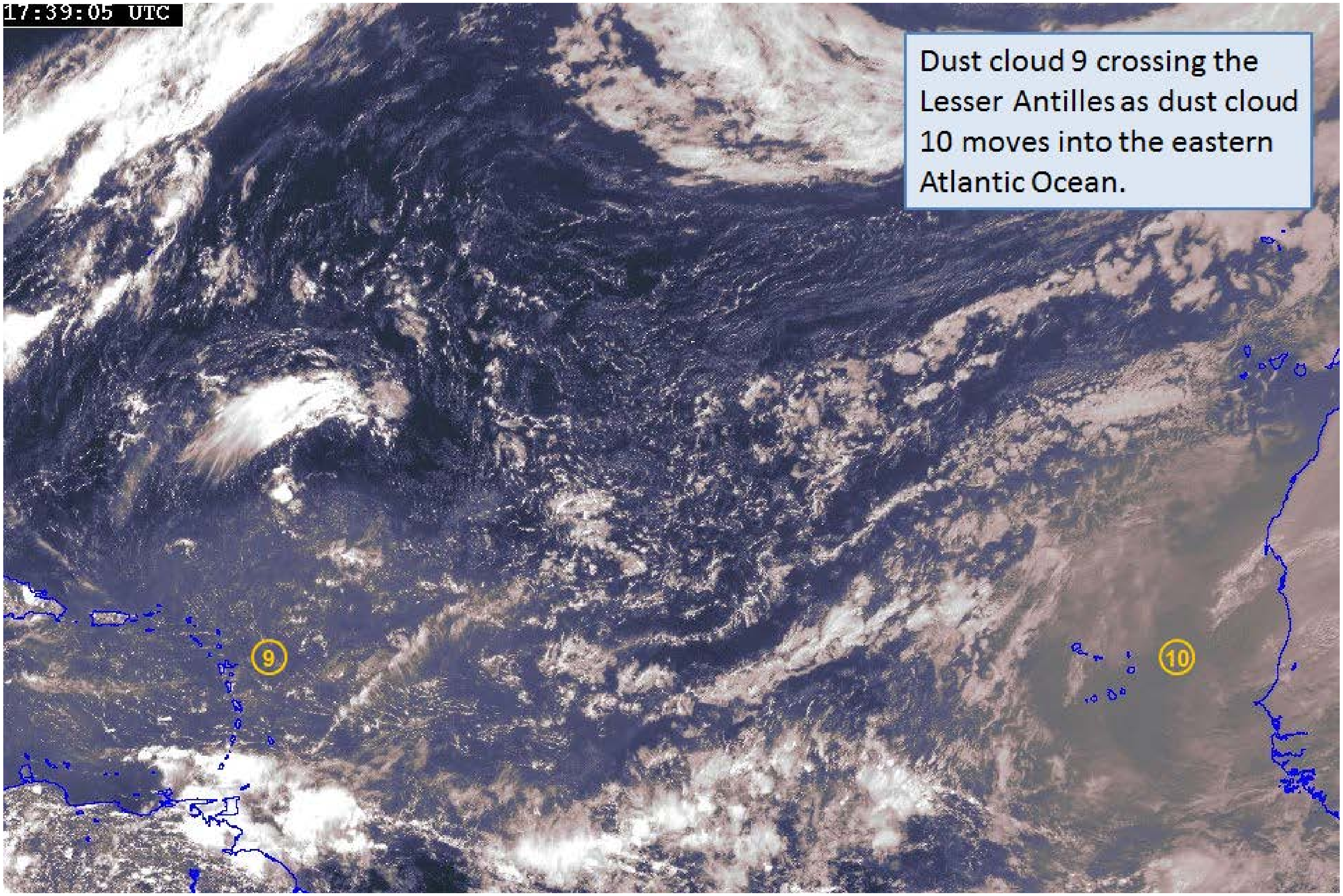

Figure C-7. Visible satellite image for 1745 UTC on July 1, 2010.

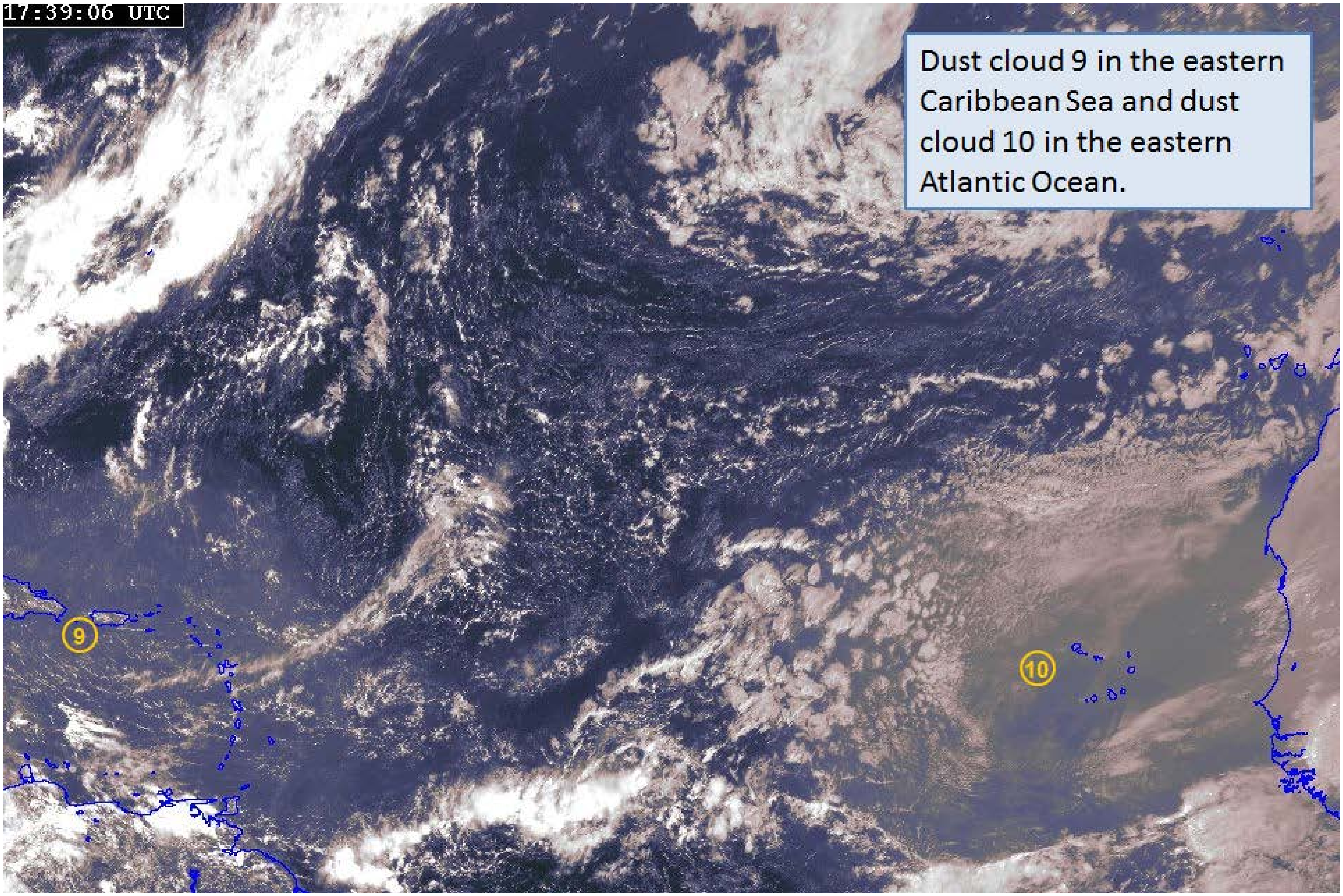

Figure C- 8. Visible satellite image for 1745 UTC on July 2, 2010.

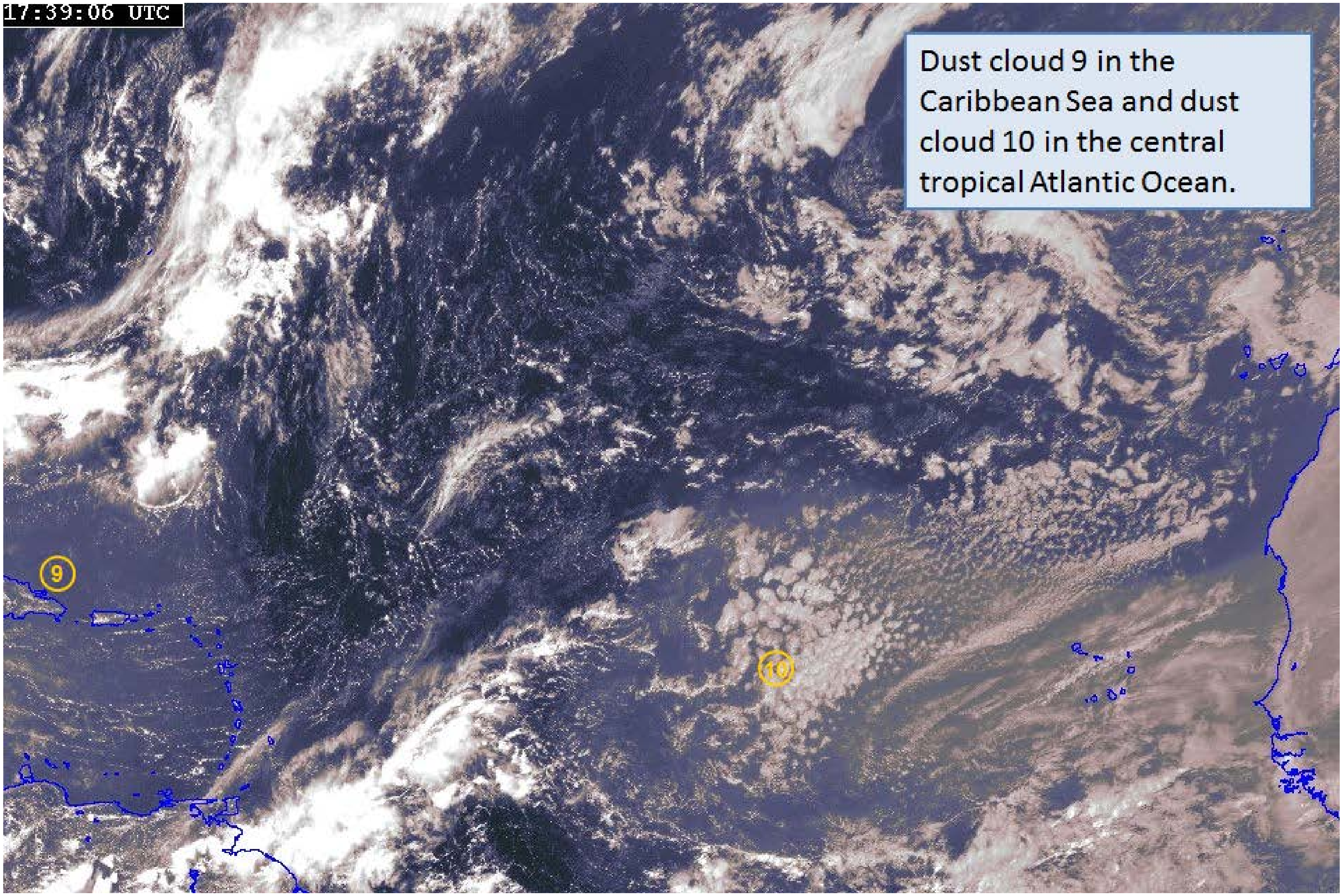

Figure C-9. Visible satellite image for 1745 UTC on July 3, 2010

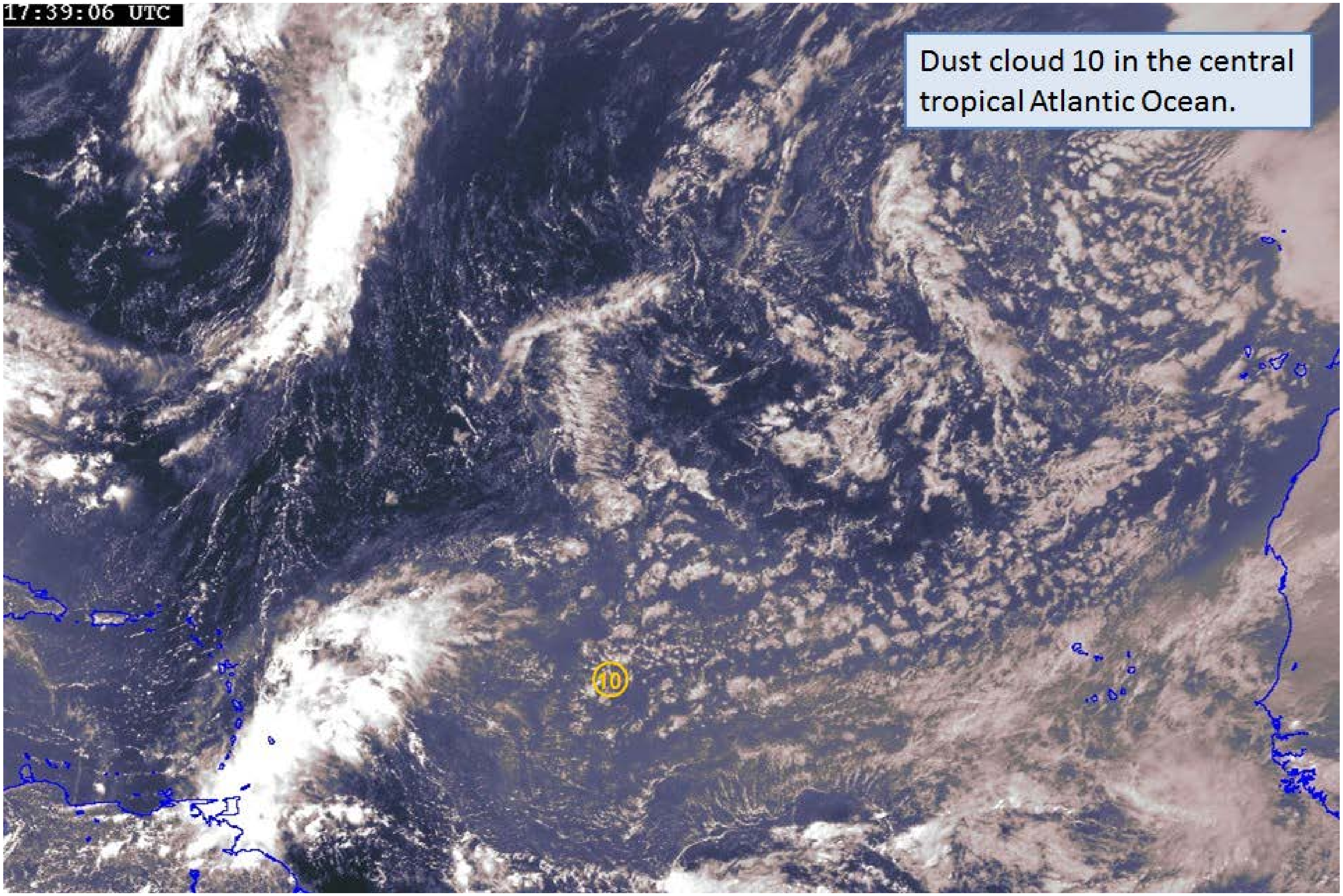

Figure C-10. Visible satellite image for 1745 UTC on July 4, 2010.

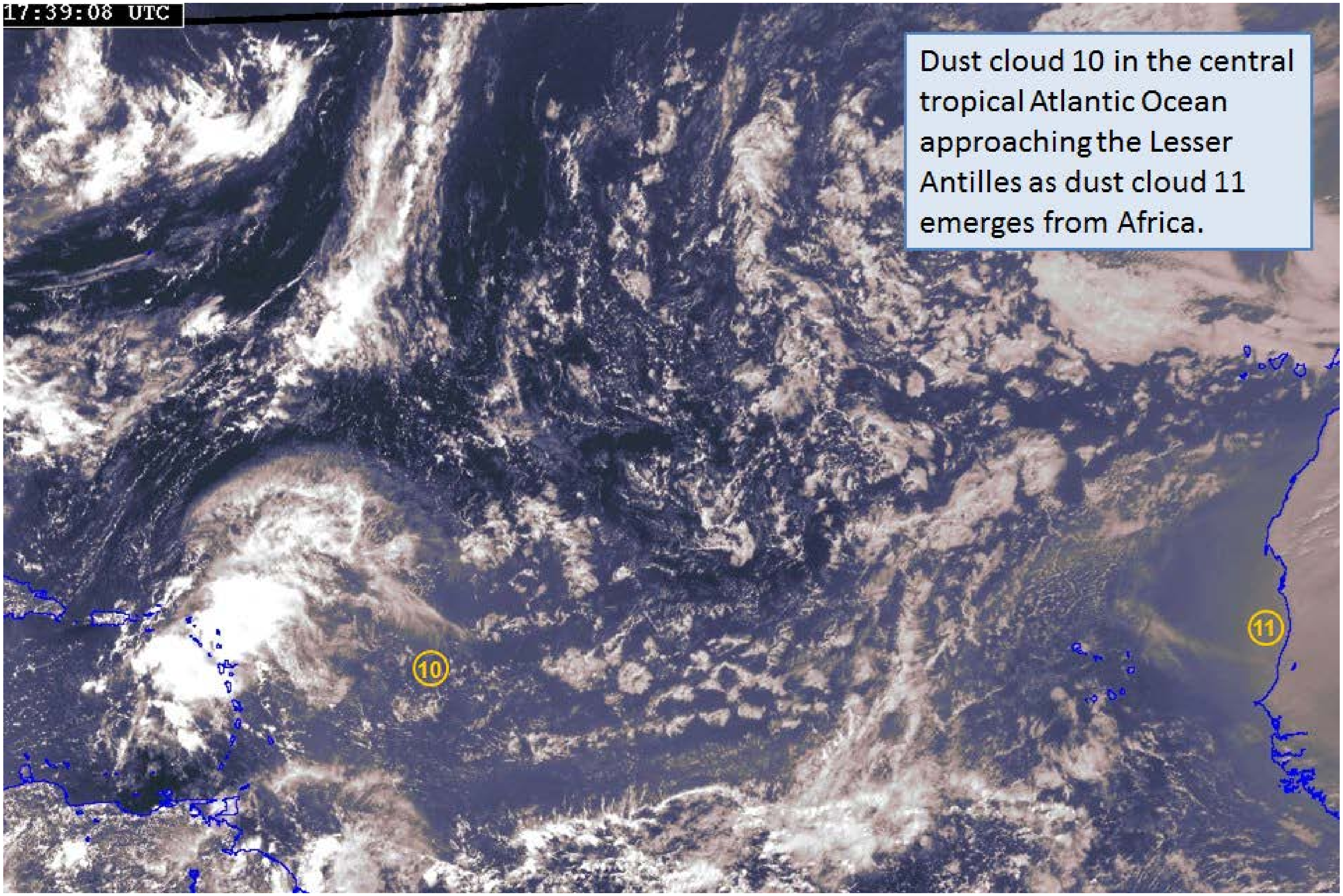

Figure C-11. Visible satellite image for 1745 UTC on July 5, 2010.

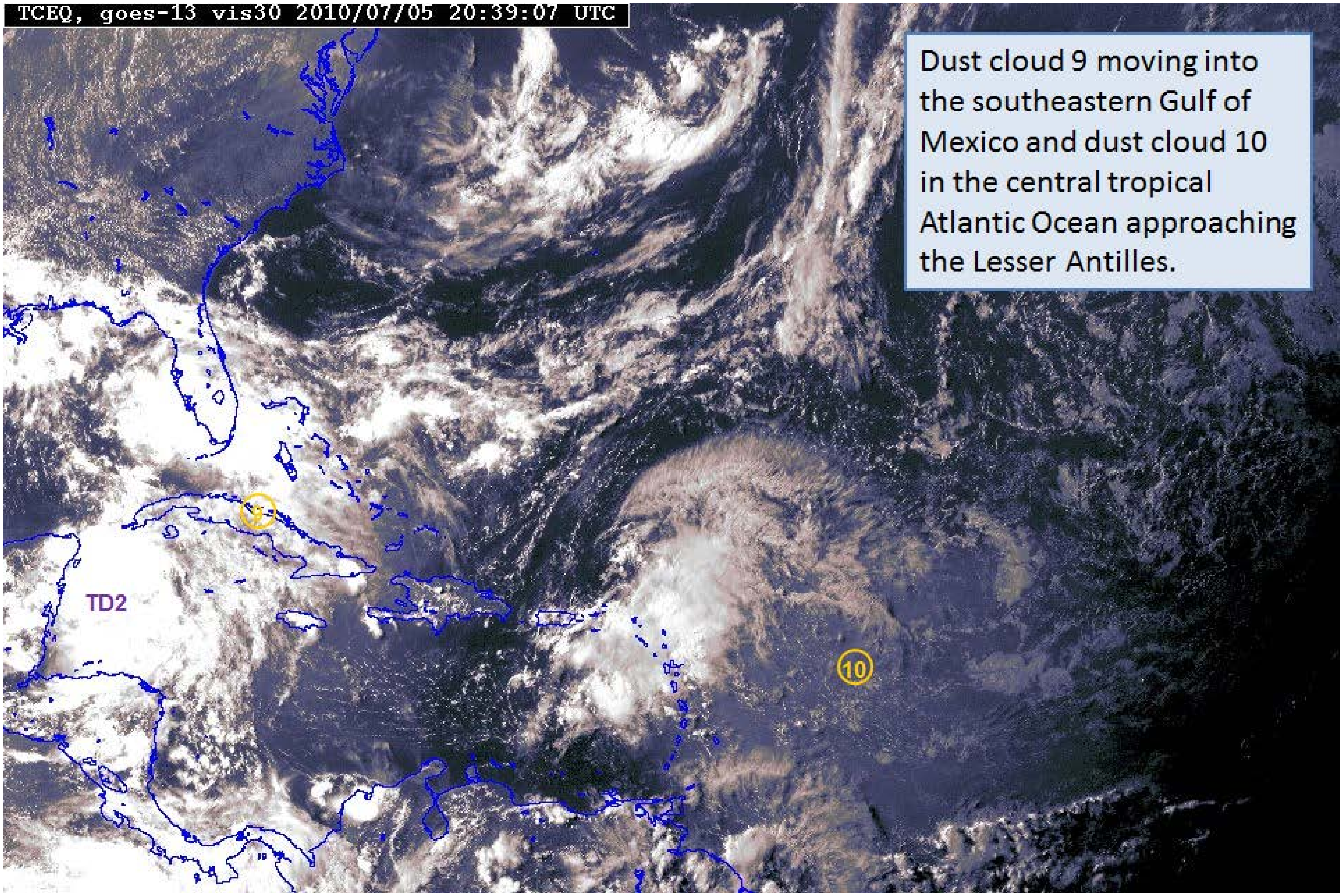

Figure C-12. Visible satellite image for 2045 UTC on July 5, 2010.

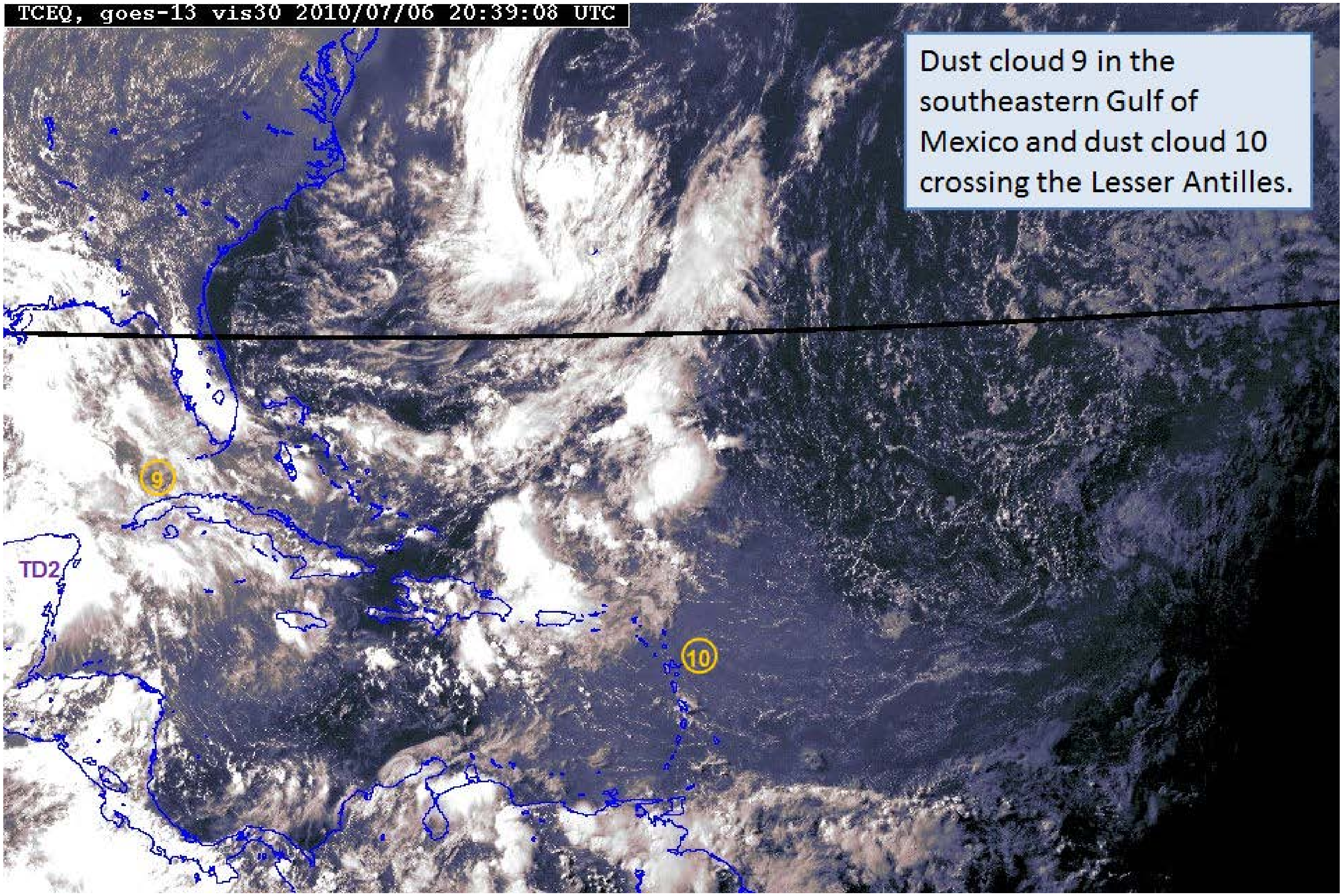

Figure C-13. Visible satellite image for 2045 UTC on July 6, 2010.

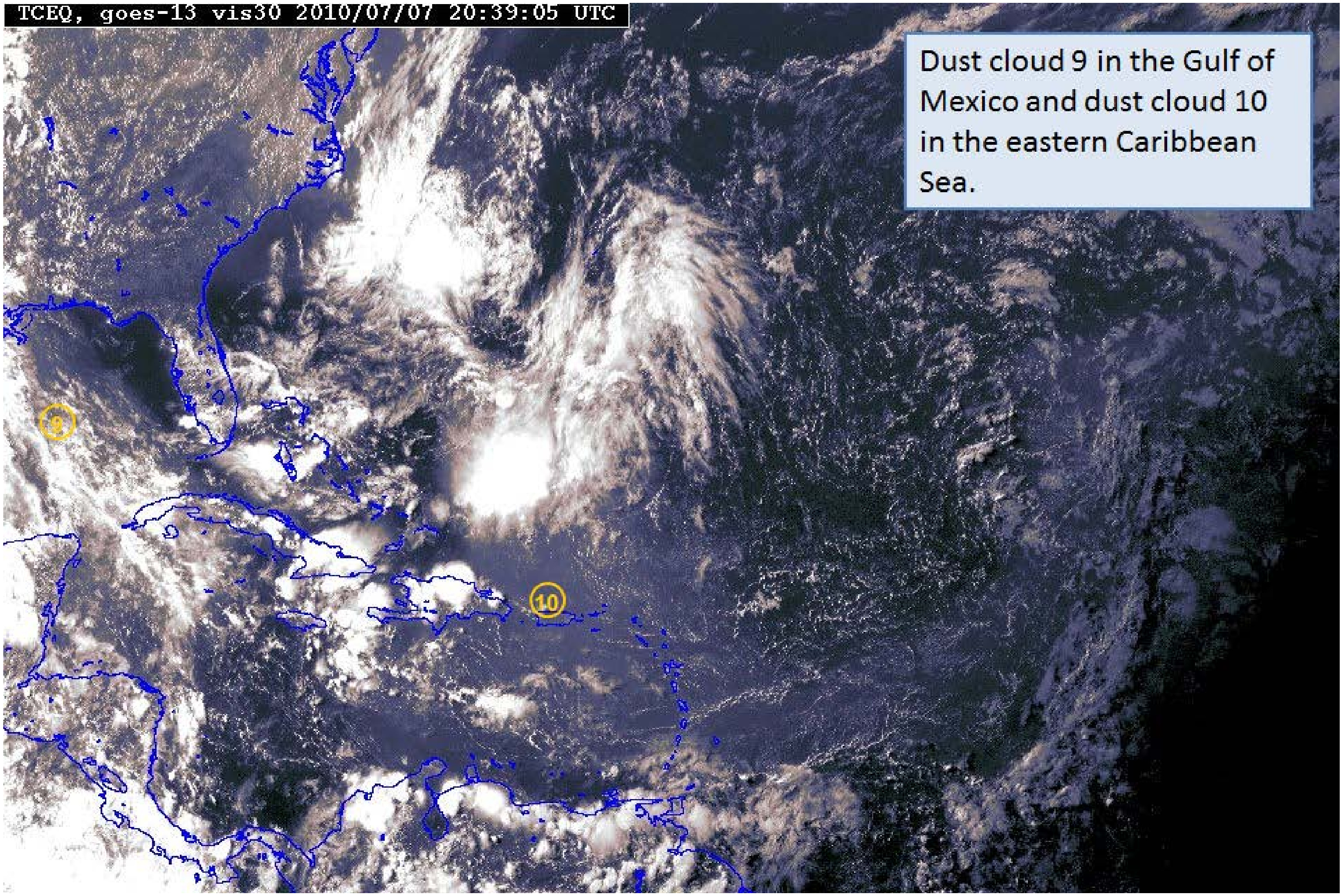

Figure C-14. Visible satellite image for 2045 UTC on July 7, 2010.

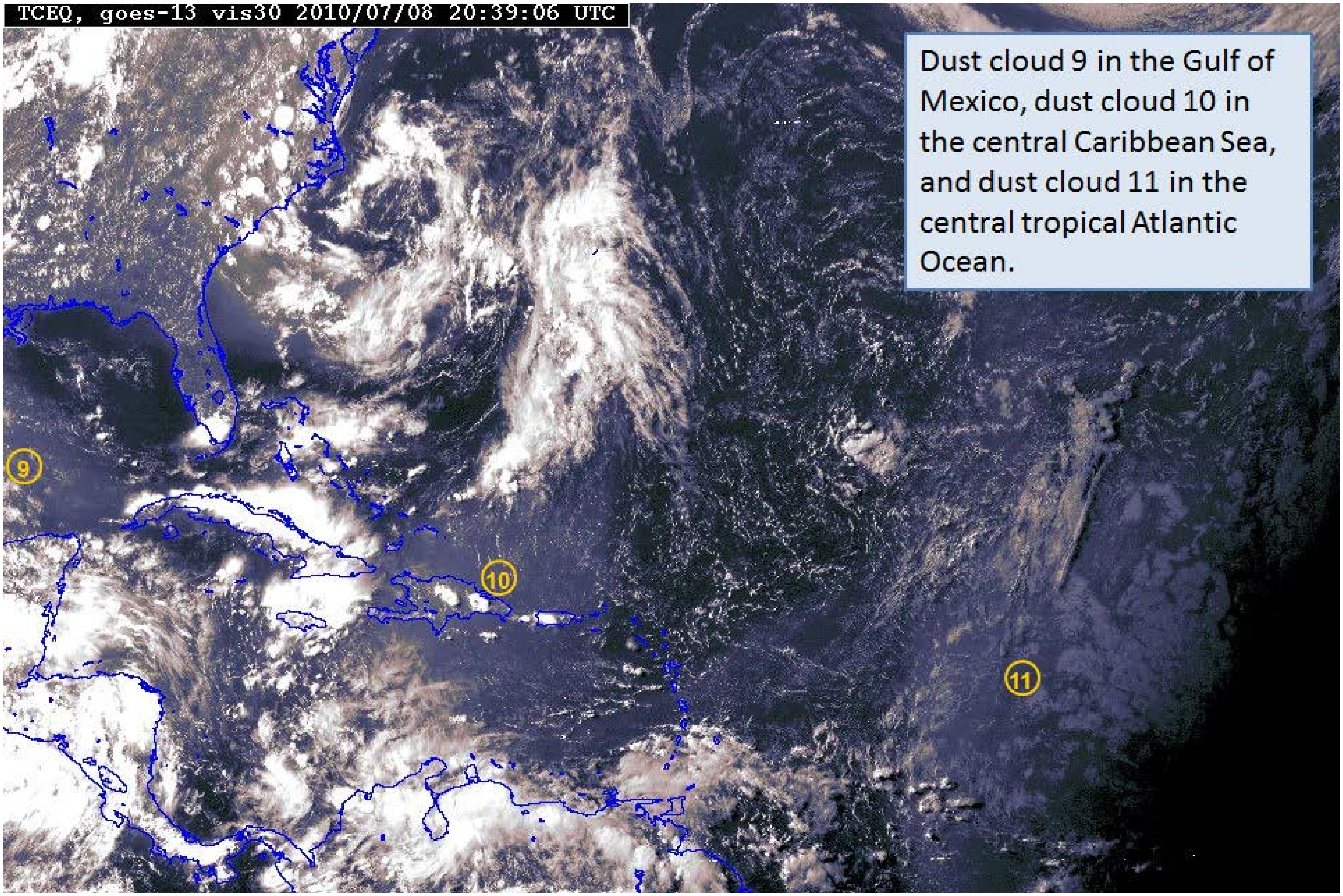

Figure C-15. Visible satellite image for 2045 UTC on July 8, 2010.

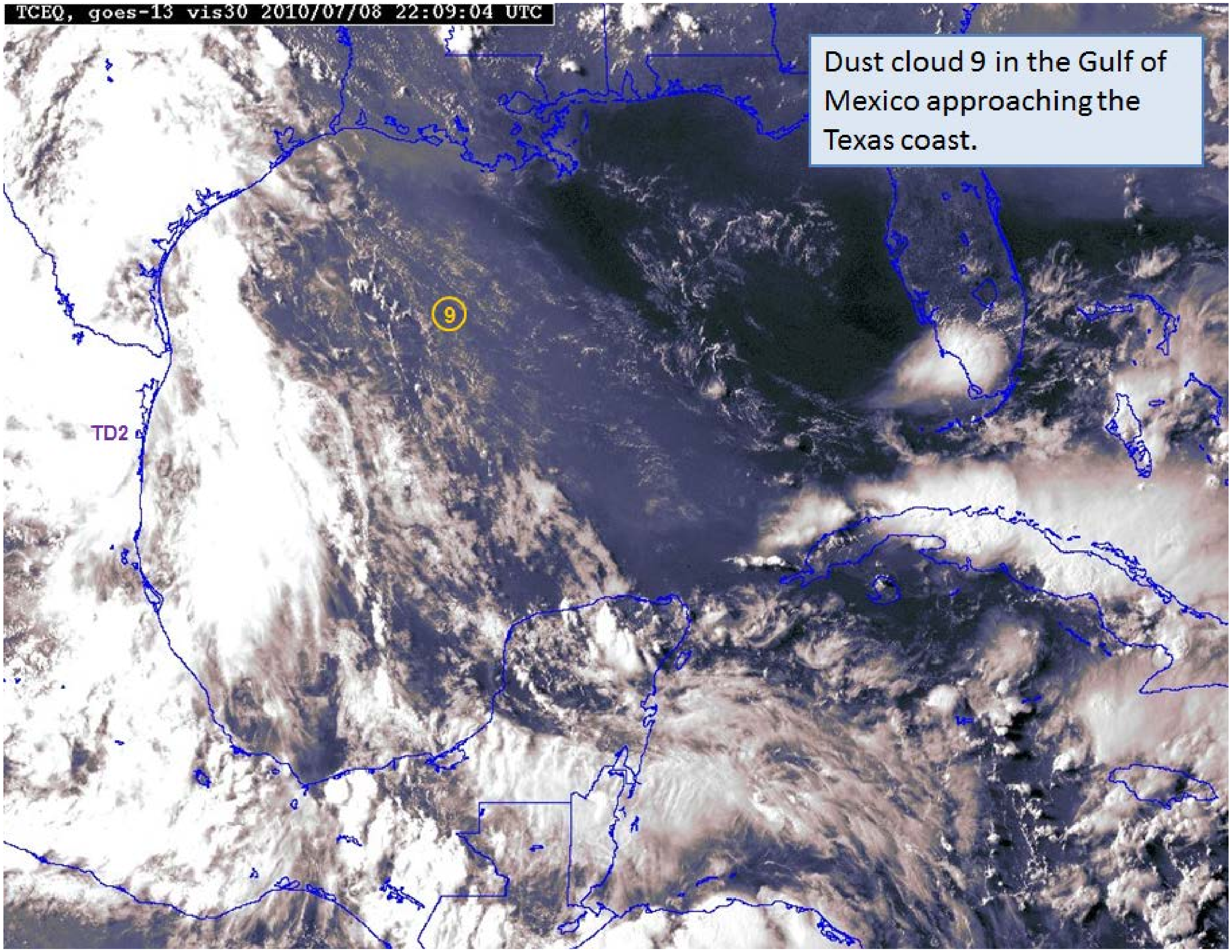

Figure C-16. Visible satellite image for 2215 UTC on July 8, 2010.

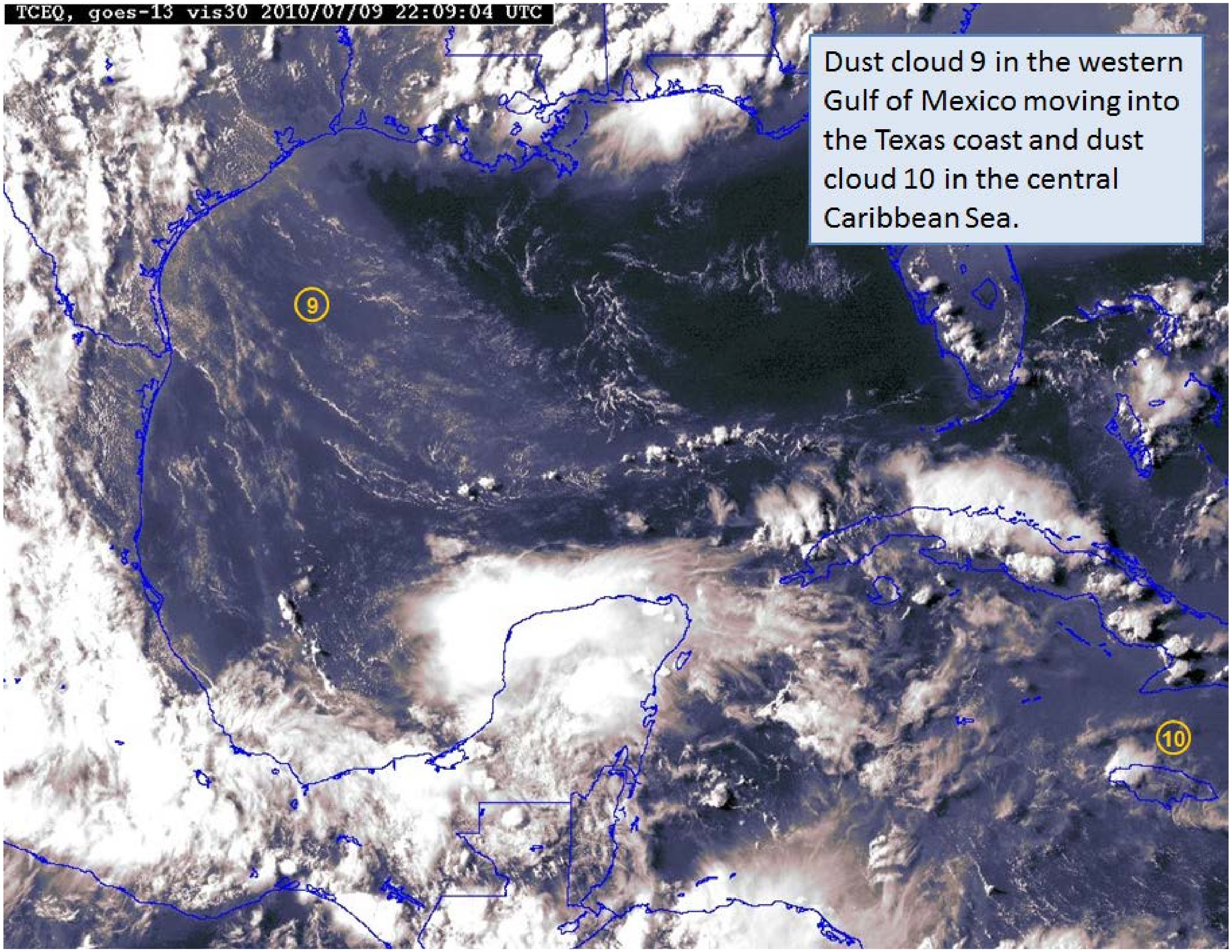

Figure C-17. Visible satellite image for 2215 UTC on July 9, 2010.

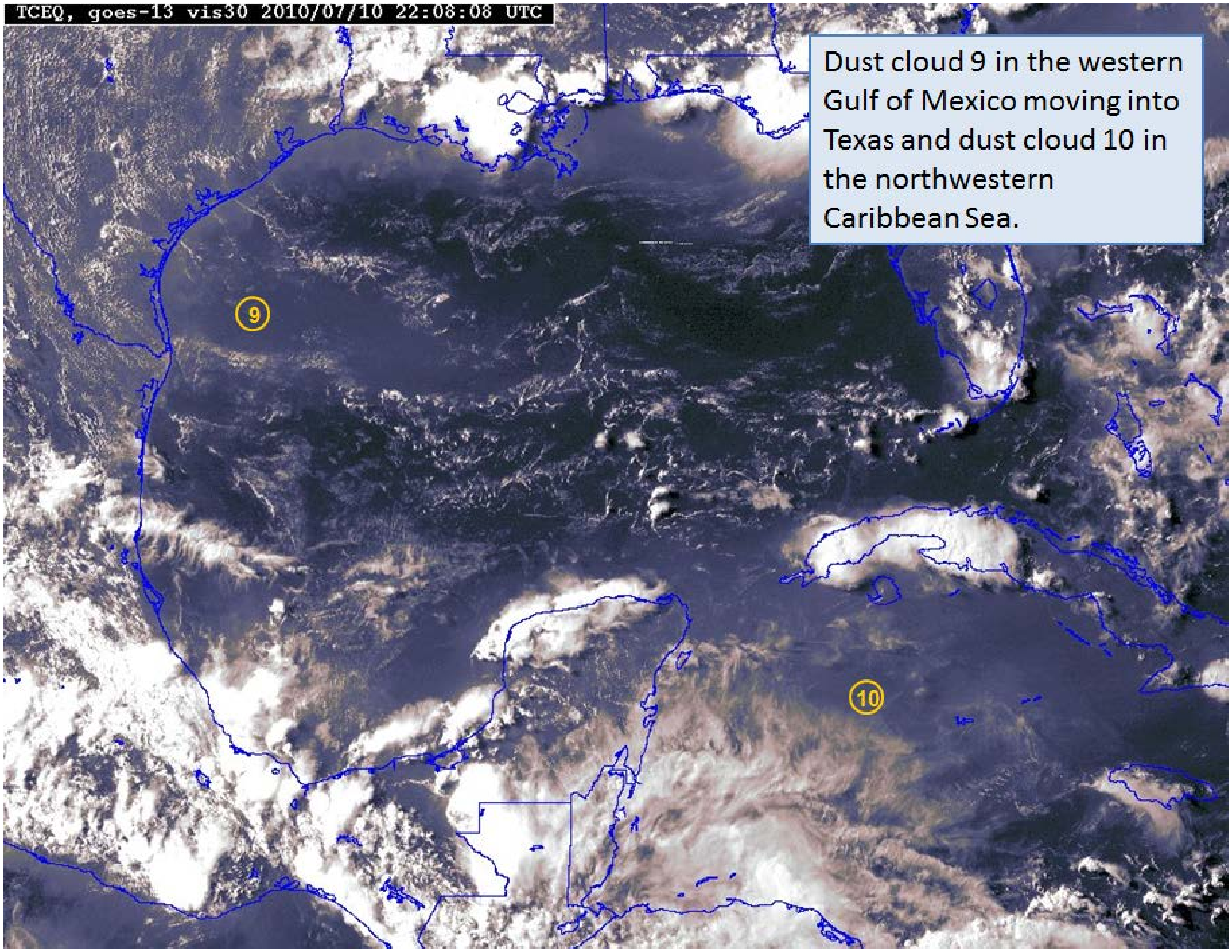

Figure C-18. Visible satellite image for 2215 UTC on July 10, 2010.

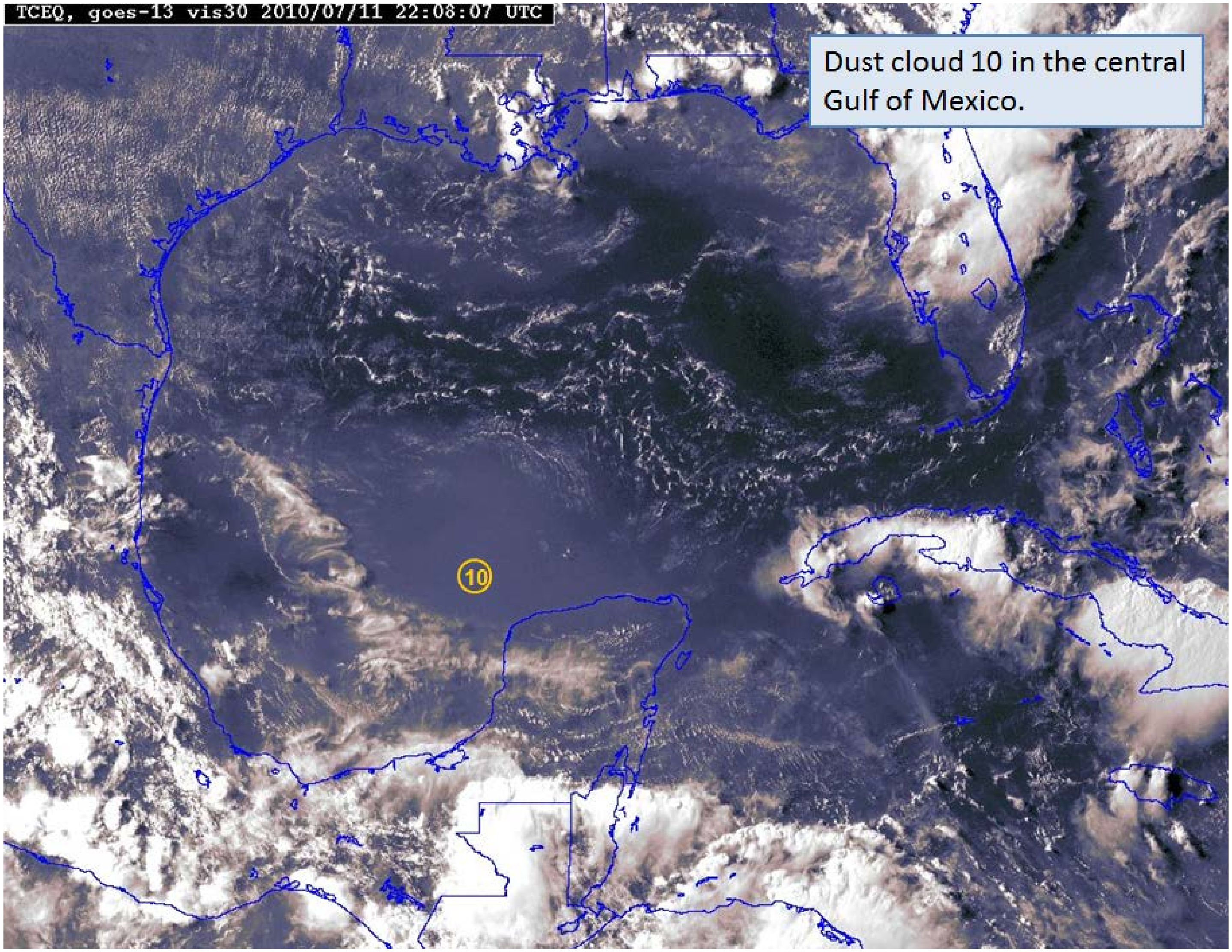

Figure C-19. Visible satellite image for 2215 UTC on July 11, 2010.

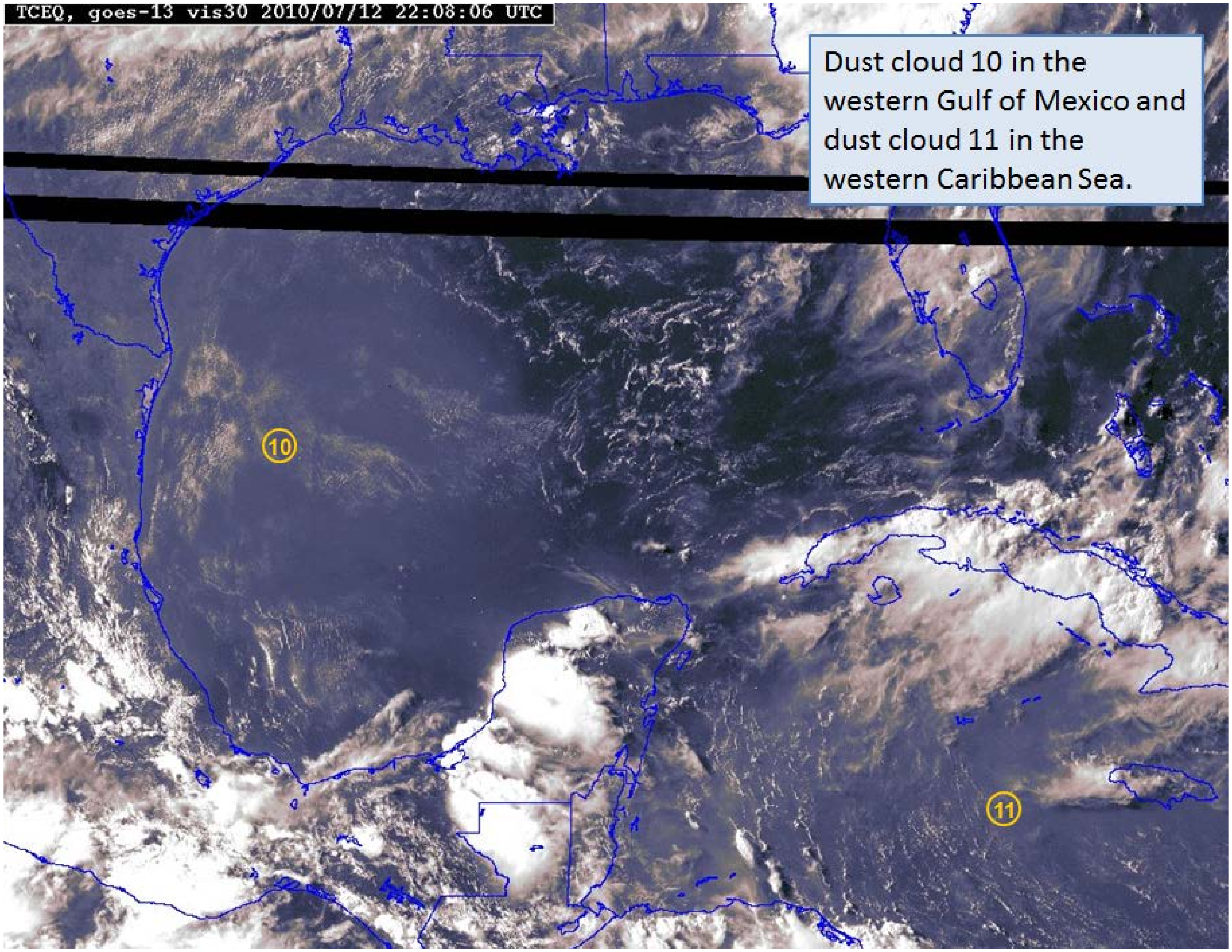

Figure C-20. Visible satellite image for 2215 UTC on July 12, 2010.

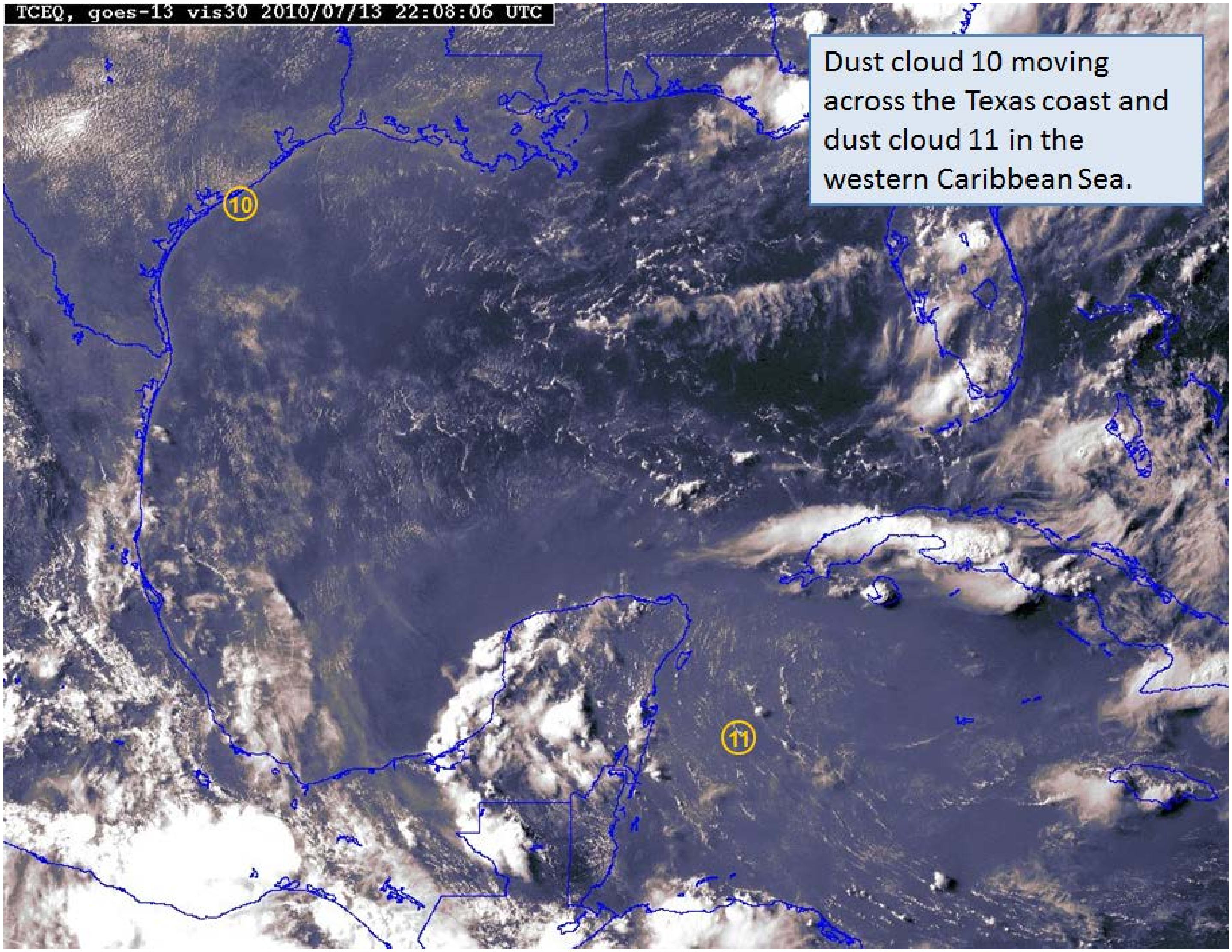

Figure C-21. Visible satellite image for 2215 UTC on July 13, 2010.

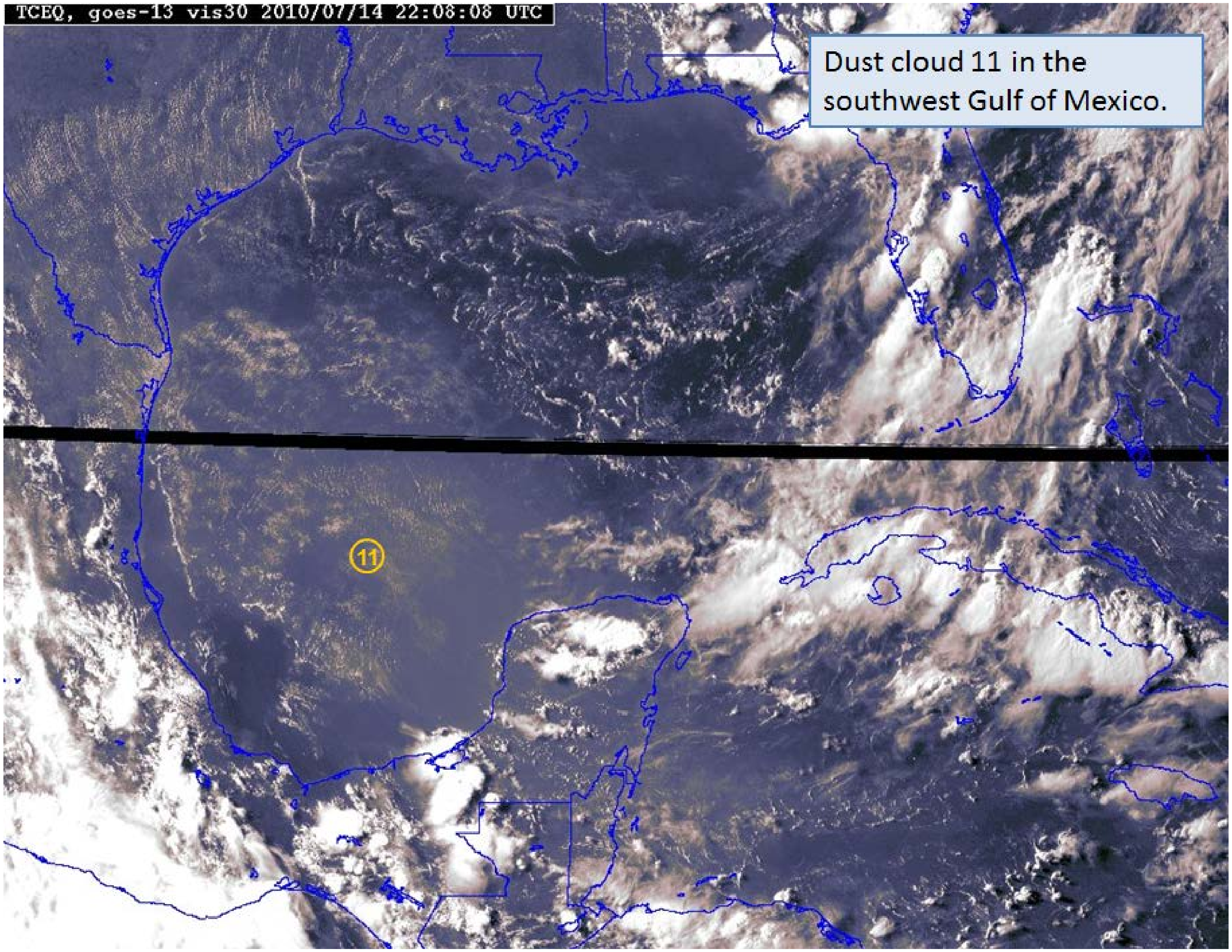

Figure C-22. Visible satellite image for 2215 UTC on July 14, 2010.

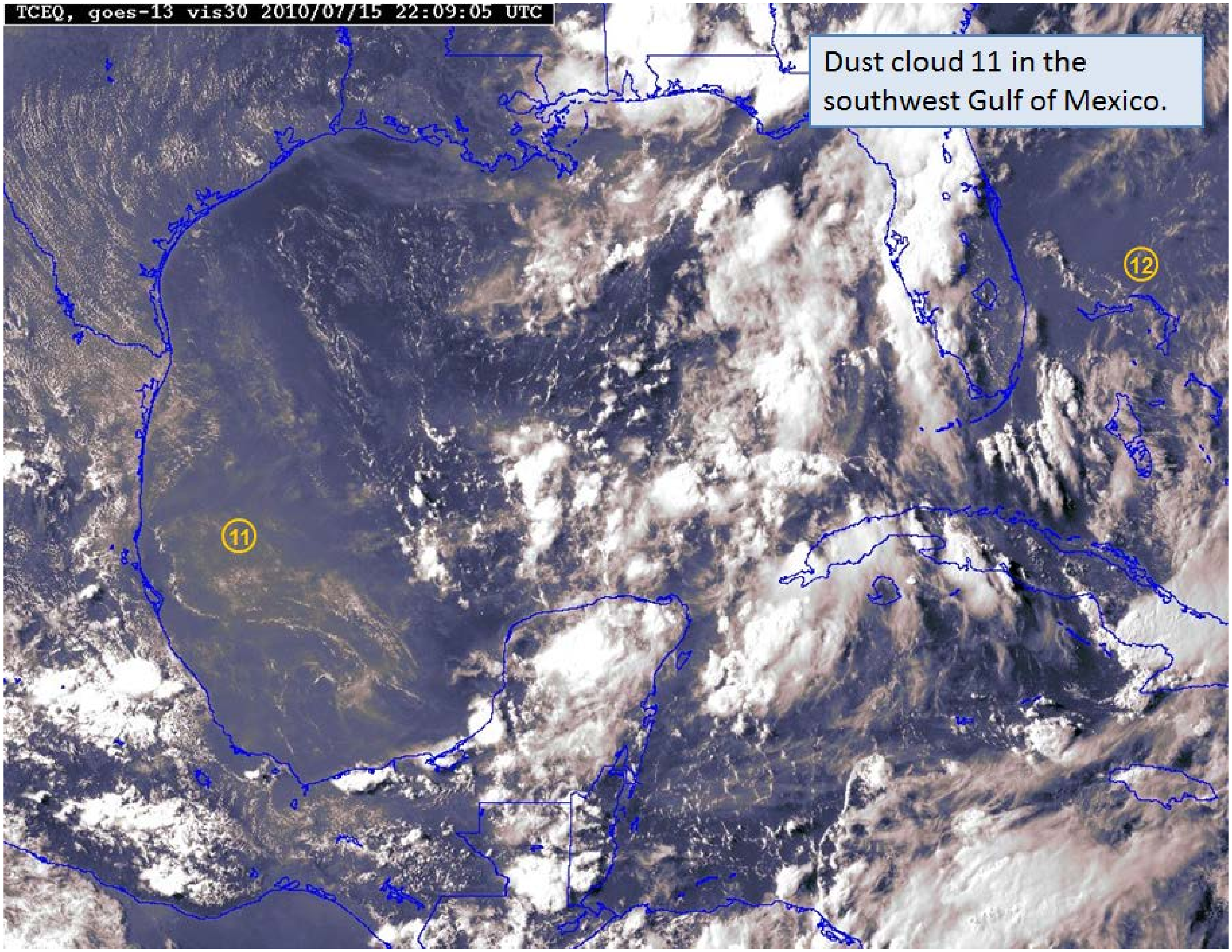

Figure C-23. Visible satellite image for 2215 UTC on July 15, 2010.

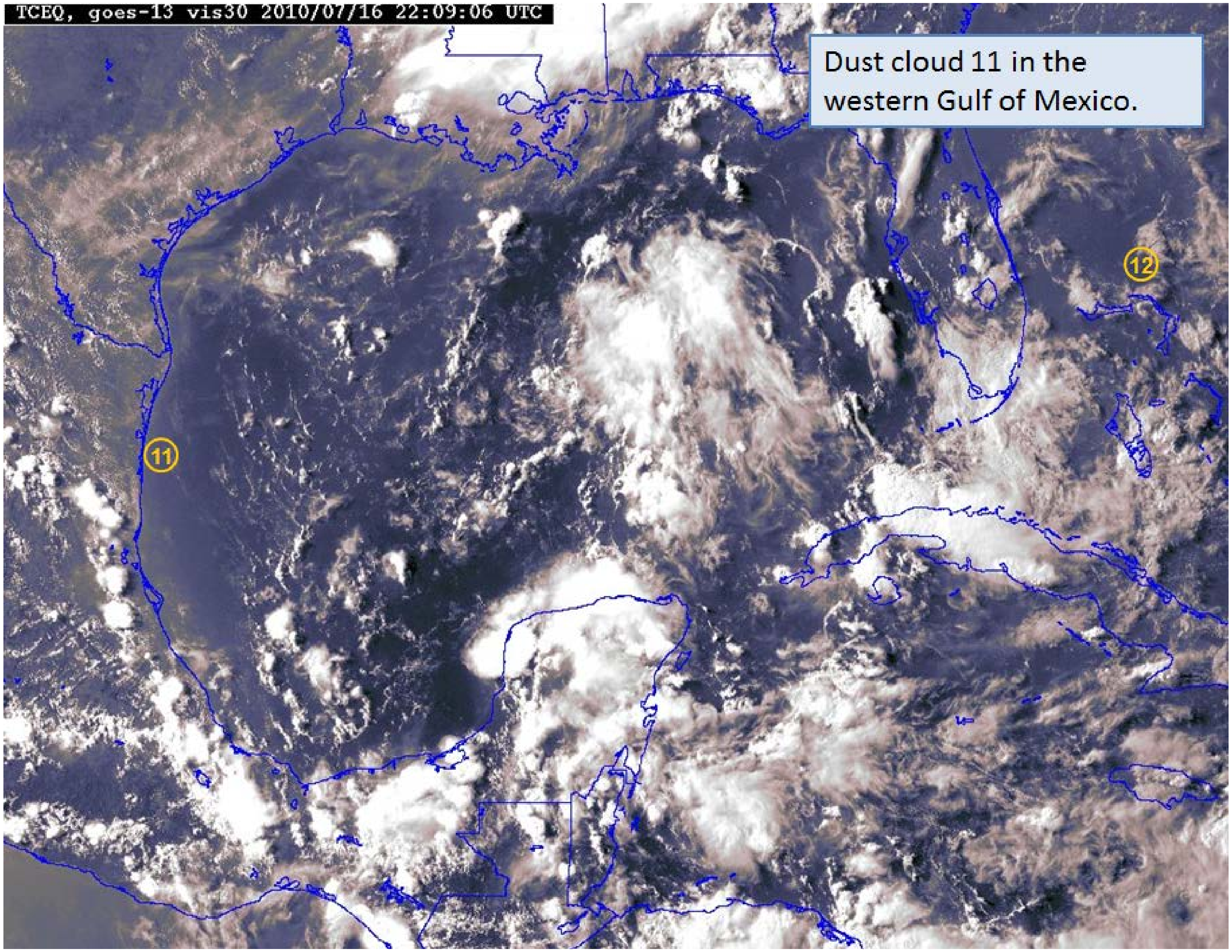

Figure C-24. Visible satellite image for 2215 UTC on July 16, 2010.

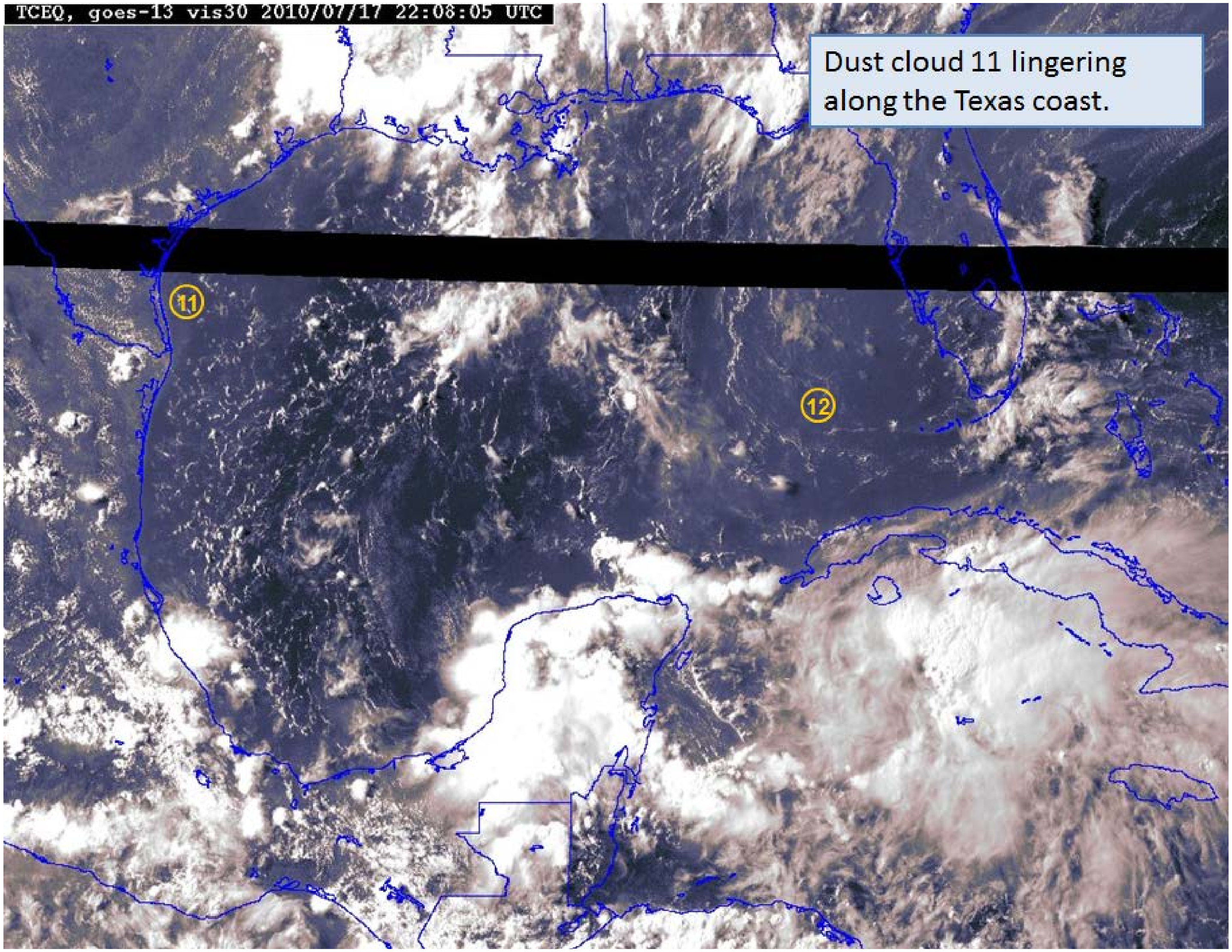

Figure C-25. Visible satellite image for 2215 UTC on July 17, 2010.

Aerosol Analyses

Figures C-26 through C-41 provide aerosol analyses from the Naval Research Laboratory (NRL) showing the African dust cloud that arrived in the Houston area on July 13 as it progressed across the Atlantic, Caribbean Sea, and Gulf of Mexico. The satellite derived optical depth from dust is shown in shades of green and yellow in the upper left panel of each figure. The same numbering system used to identify dust clouds on the previous satellite imagery is used in these figures for comparison. These aerosol analyses corroborate well with the satellite imagery and back trajectories shown previously.

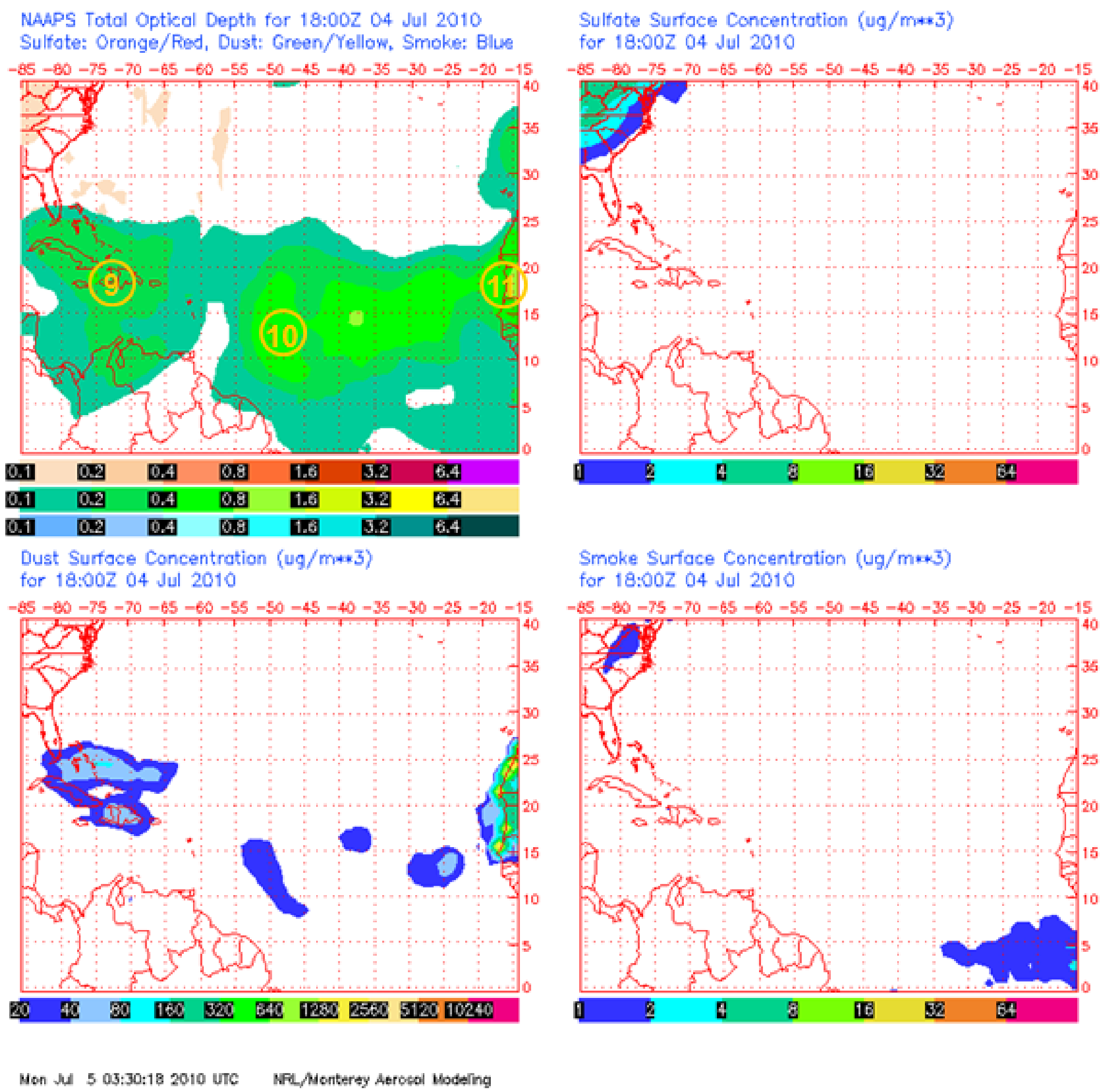

Figure C-26. NRL aerosol analysis 2010 July 4 showing dust clouds 9, 10, and 11 stretching across the Atlantic Ocean from the African coast.

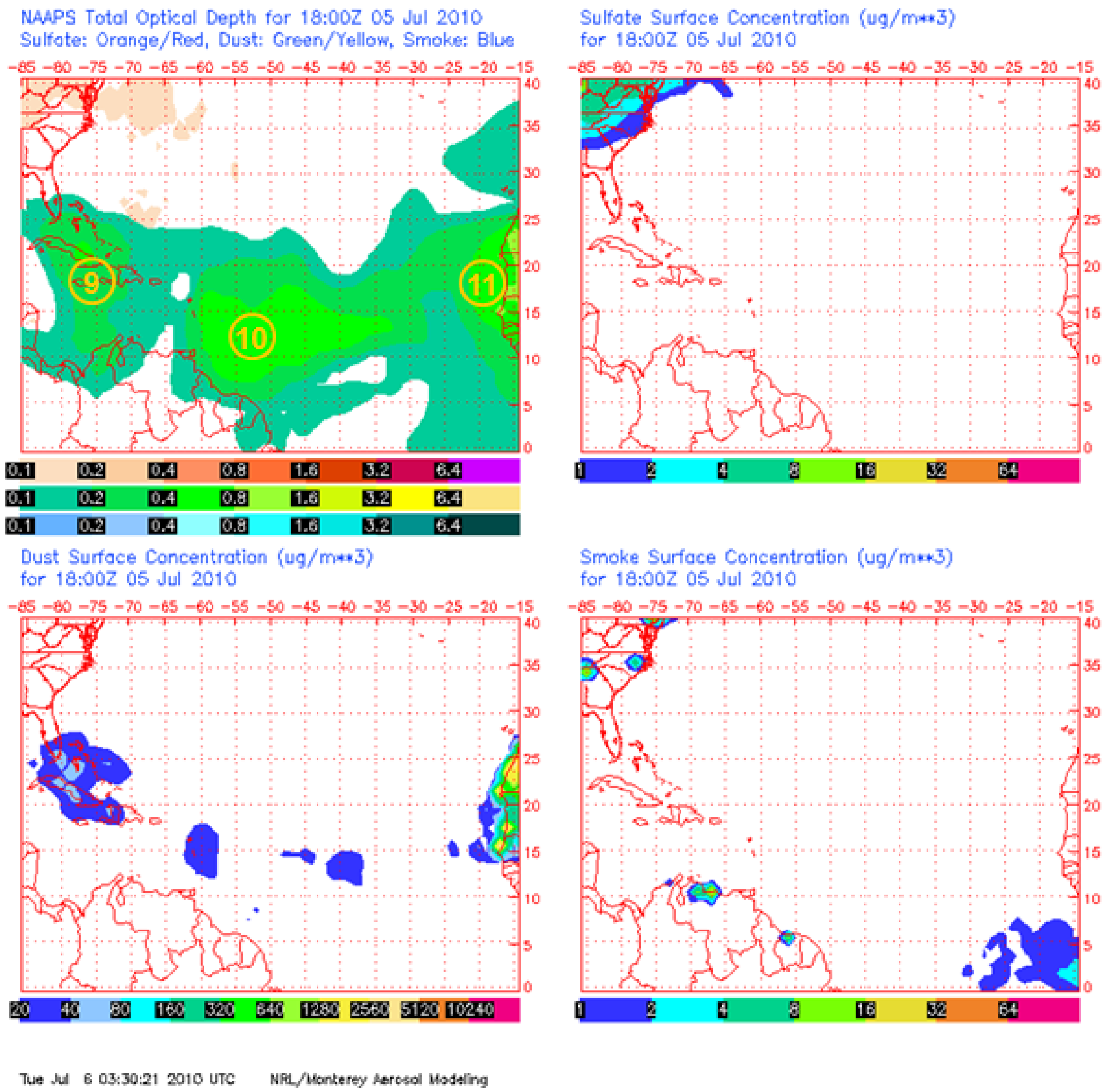

Figure C-27. NRL aerosol analysis 2010 July 5 showing dust clouds 9, 10, and 11 stretching across the Atlantic Ocean from the African coast.

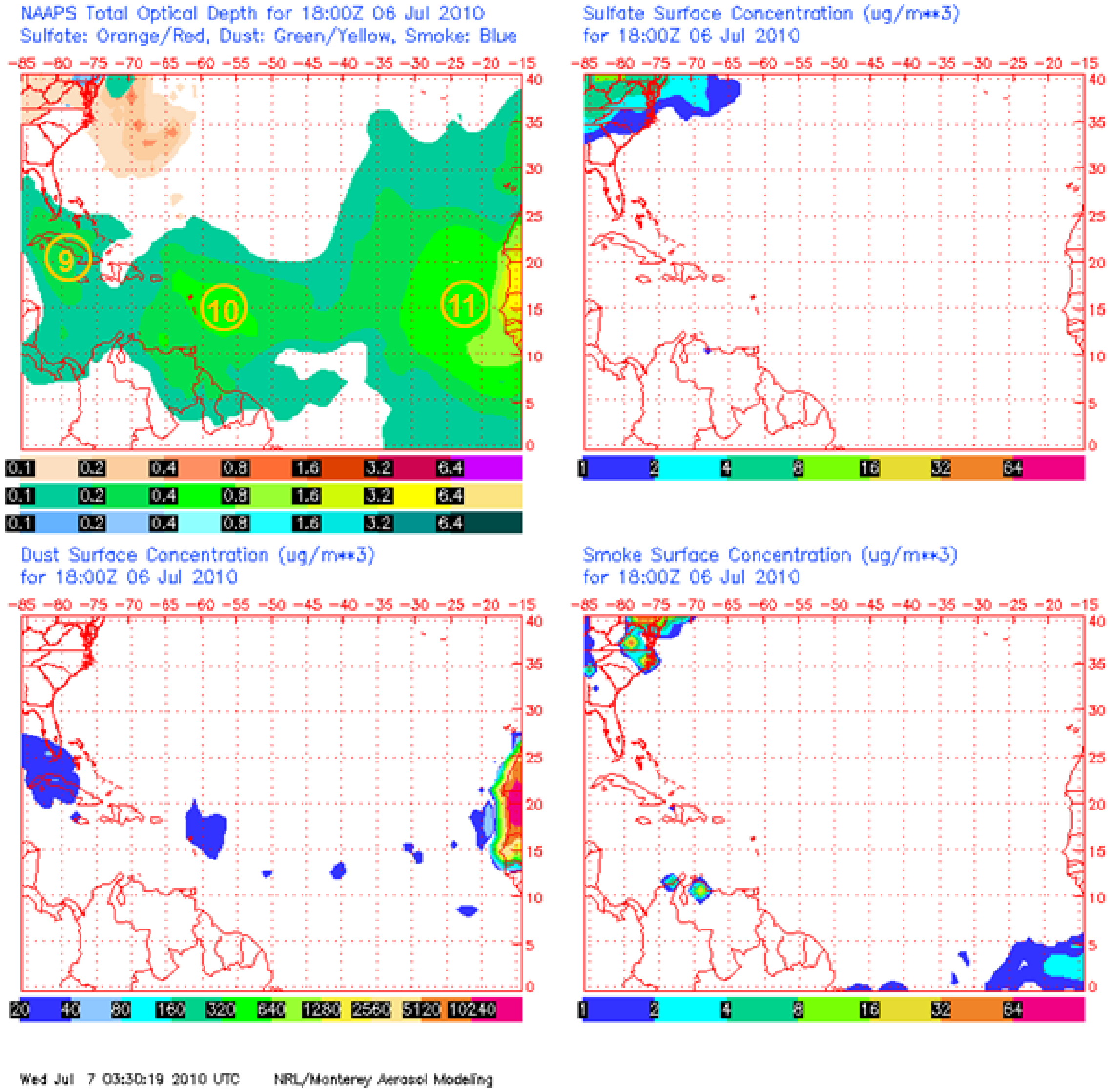

Figure C-28. NRL aerosol analysis 2010 July 6 showing dust clouds 9, 10, and 11 stretching from the western Caribbean Sea across the Atlantic Ocean to the African coast.

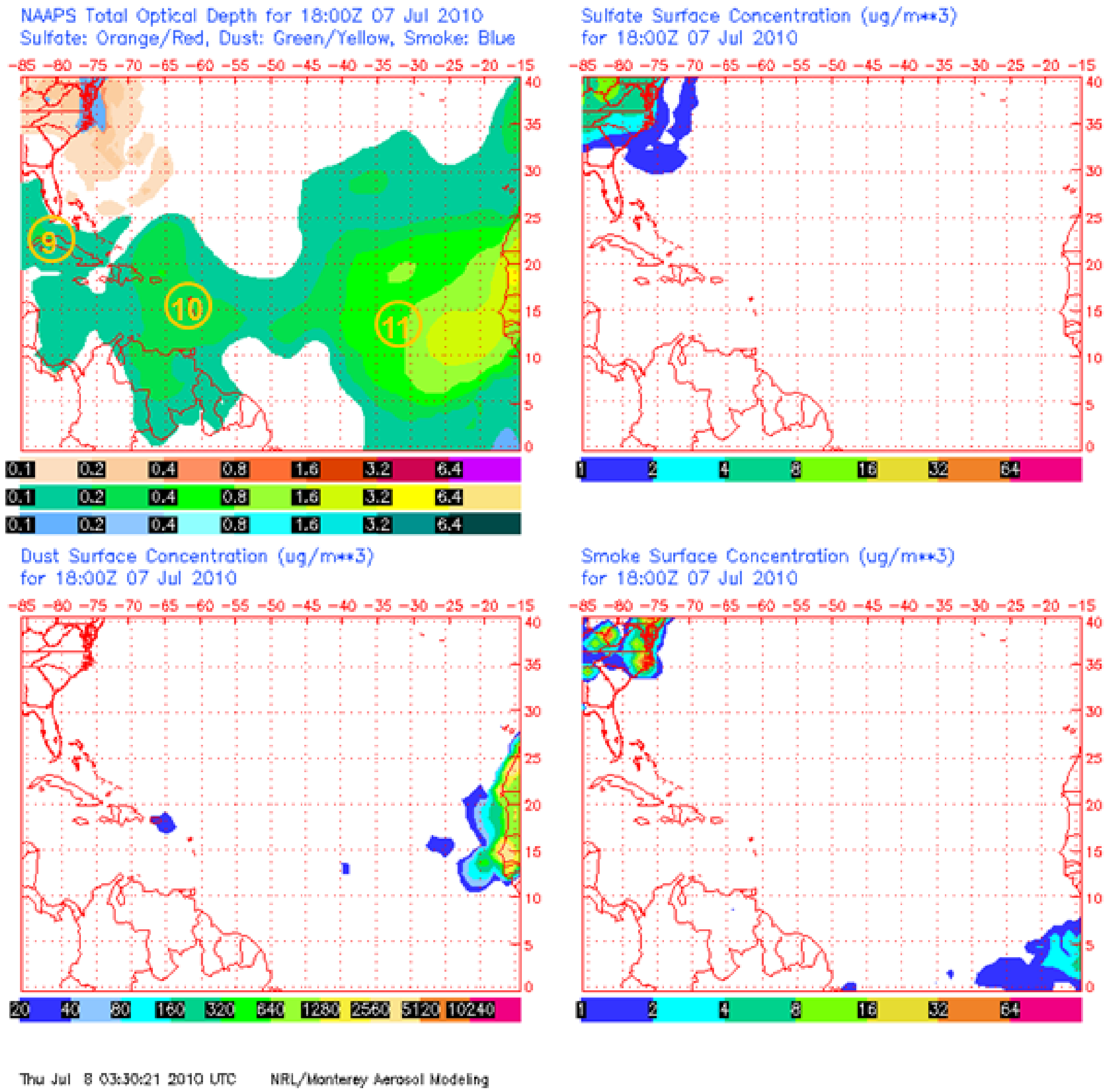

Figure C-29. NRL aerosol analysis 2010 July 7 showing dust 9 entering the Gulf of Mexico, dust cloud 10 entering the Caribbean Sea, and dust cloud 10 in the eastern Tropical Atlantic Ocean.

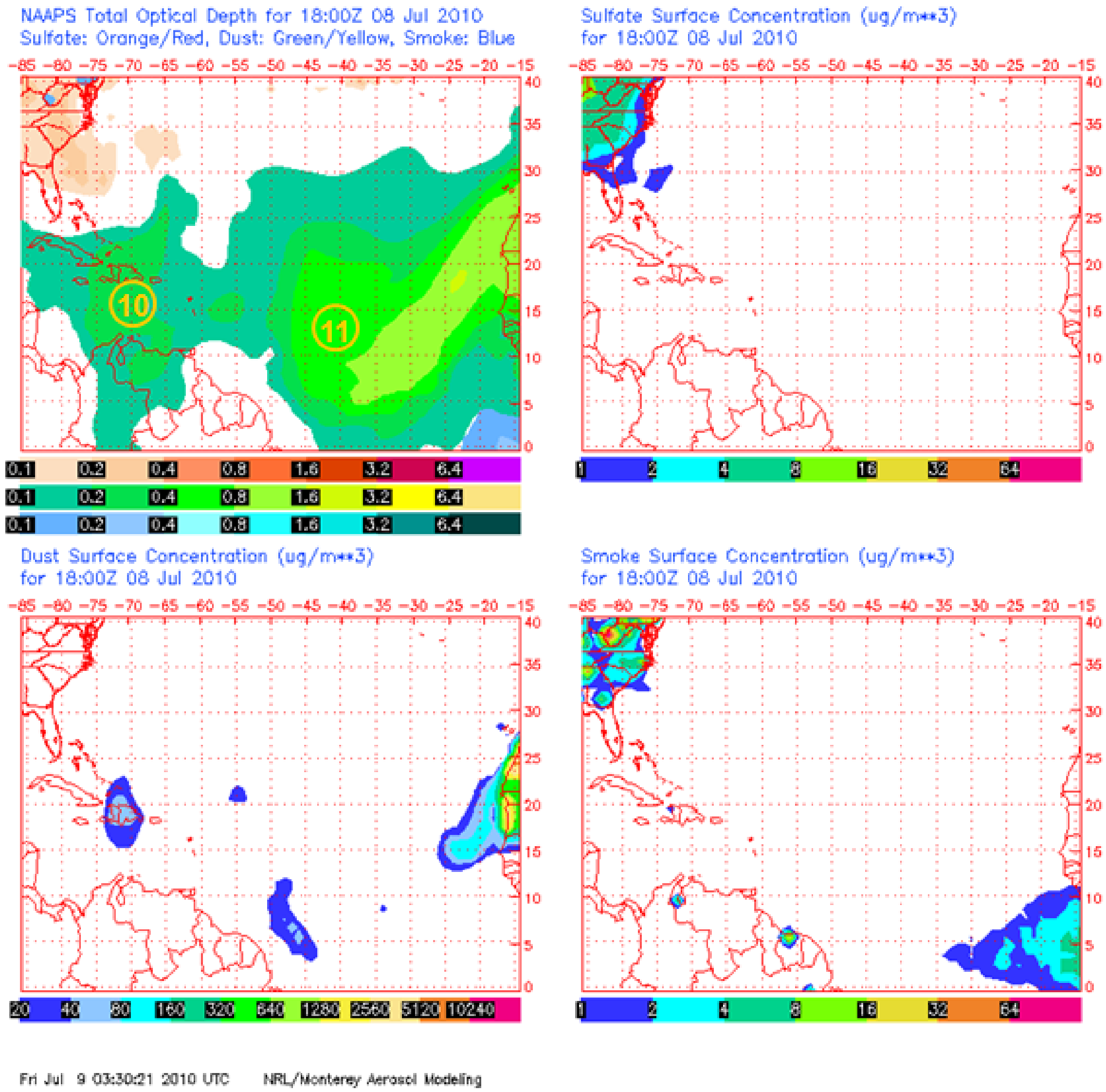

Figure C-30. NRL aerosol analysis 2010 July 8 showing dust cloud 10 in the eastern Caribbean Sea as dust cloud 11 crosses the central portion of the Tropical Atlantic Ocean.

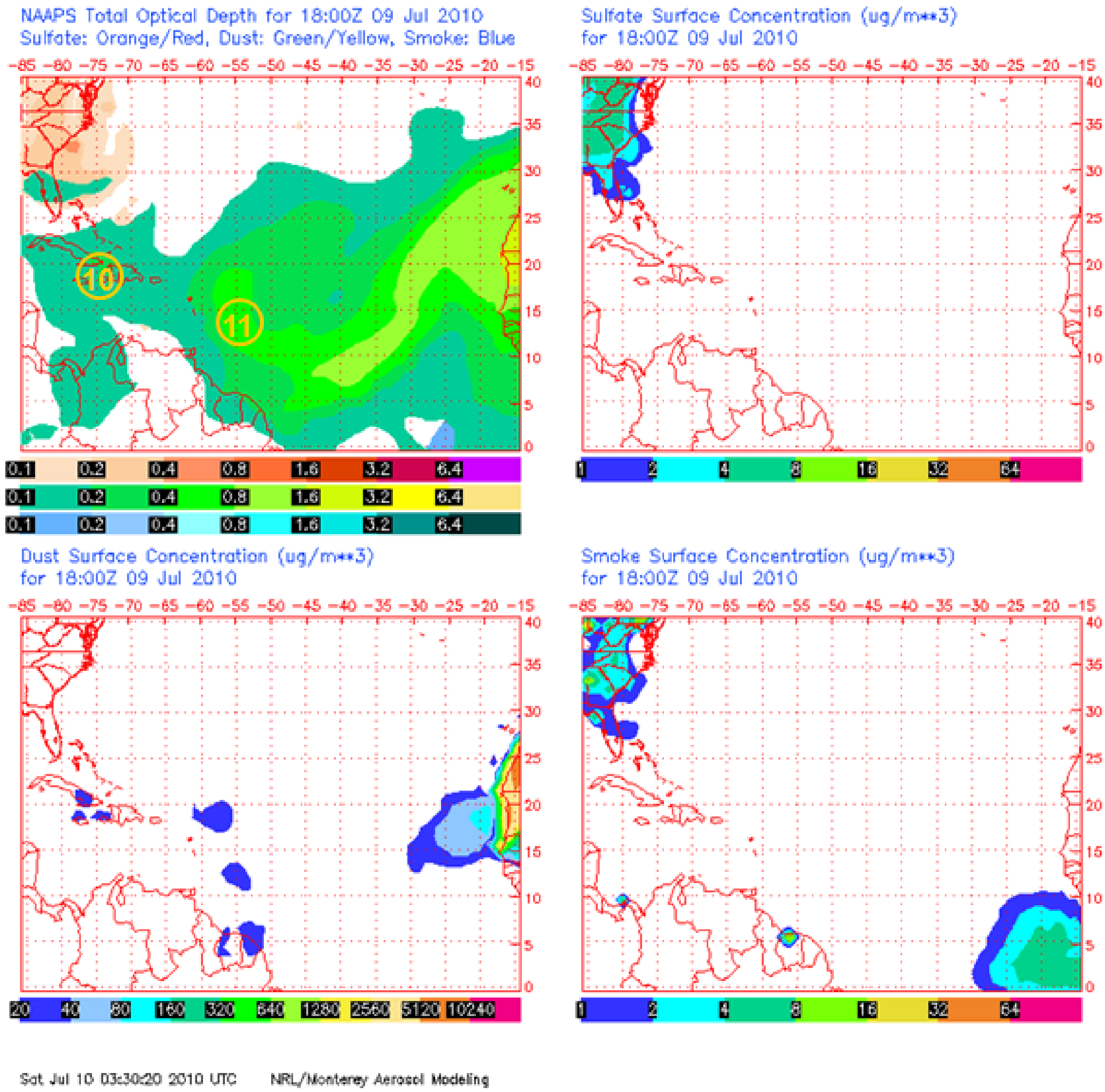

Figure C-31. NRL aerosol analysis 2010 July 9 showing dust cloud 10 moving into the western Caribbean Sea and dust cloud 11 approaching the Lesser Antilles.

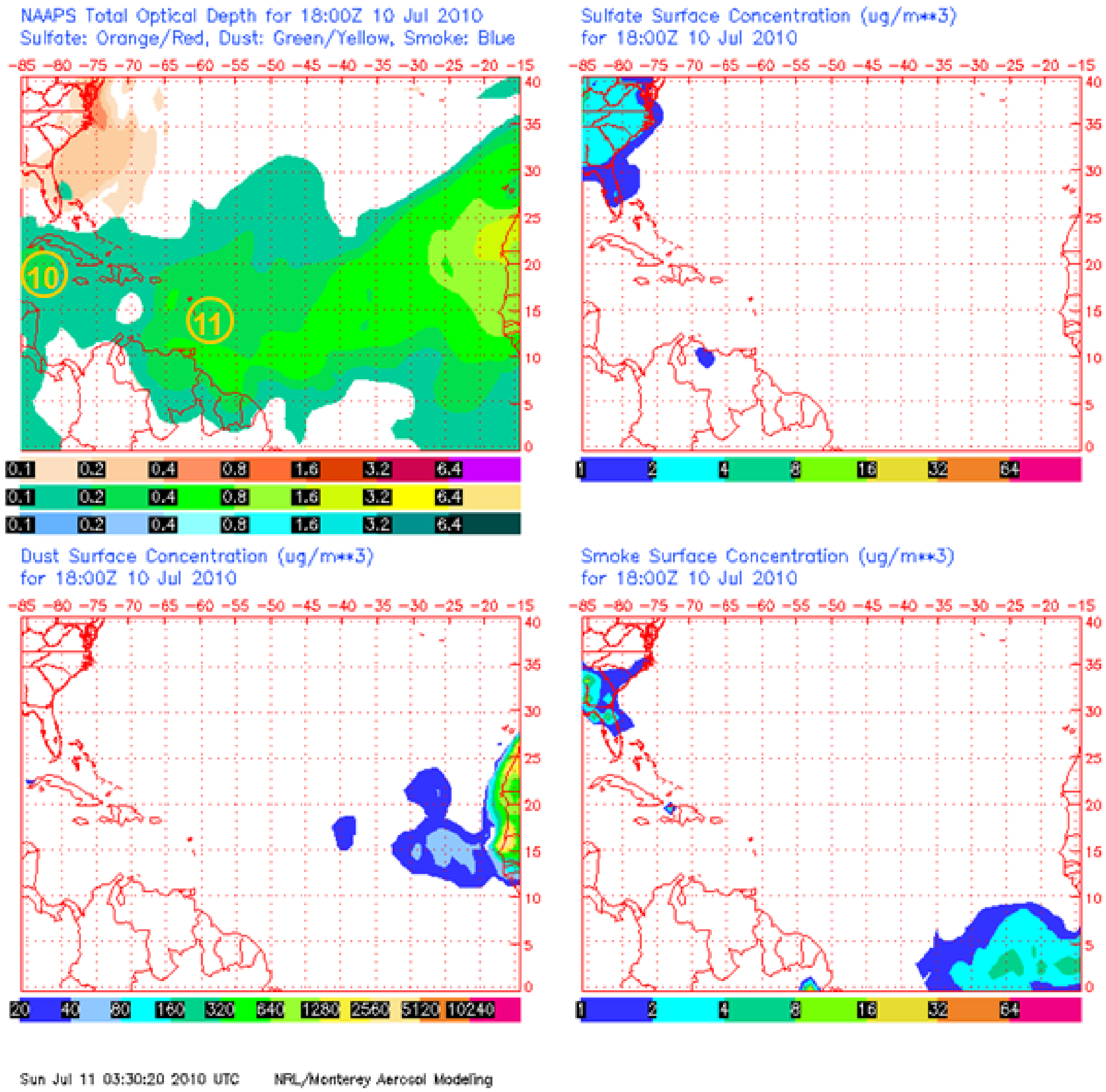

Figure C-32. NRL aerosol analysis 2010 July 10 showing dust cloud 10 in the western Caribbean Sea as dust cloud 11 moves into the eastern Caribbean Sea.

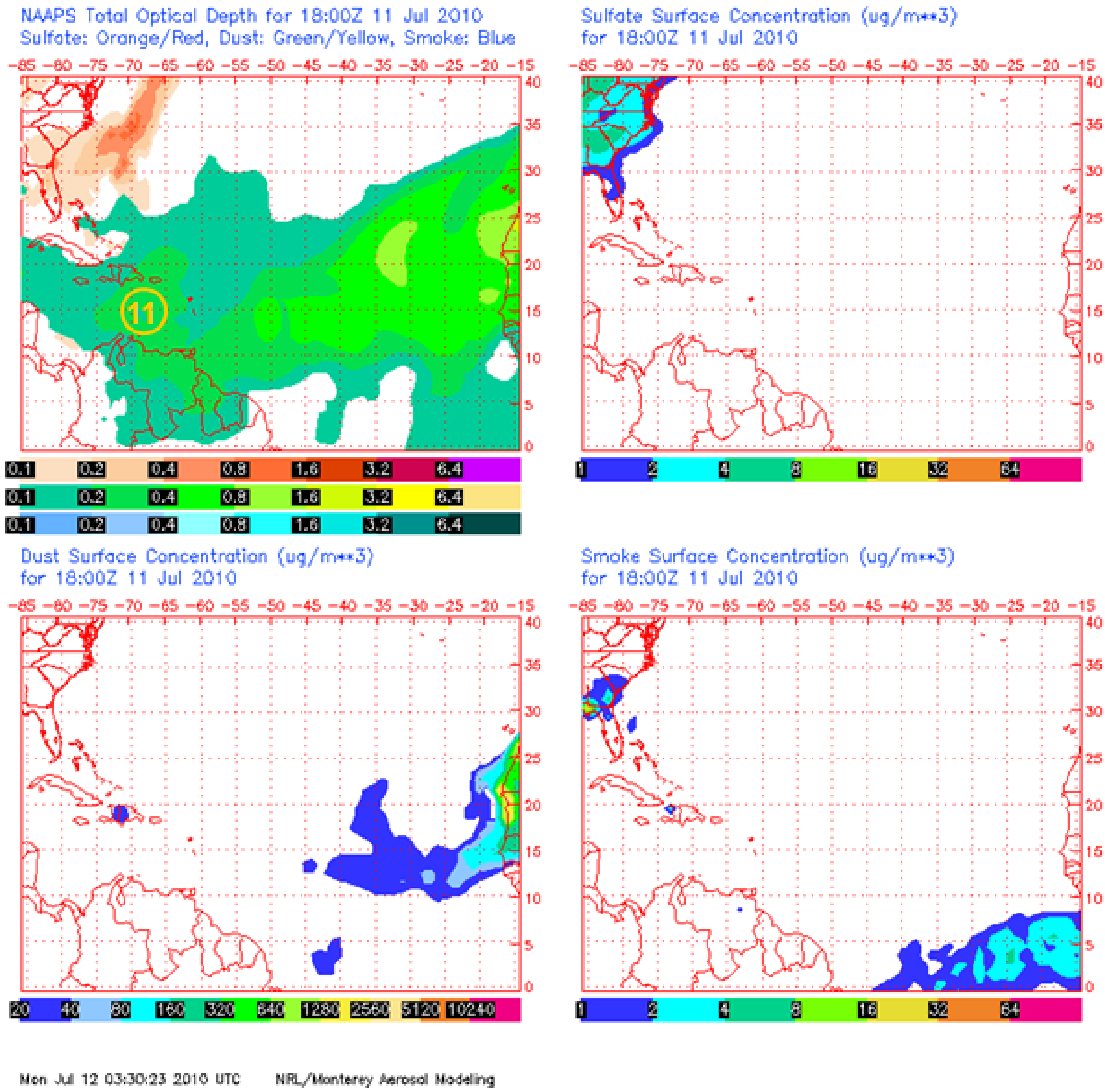

Figure C-33. NRL aerosol analysis 2010 July 11 showing dust cloud 11 in the Caribbean Sea.

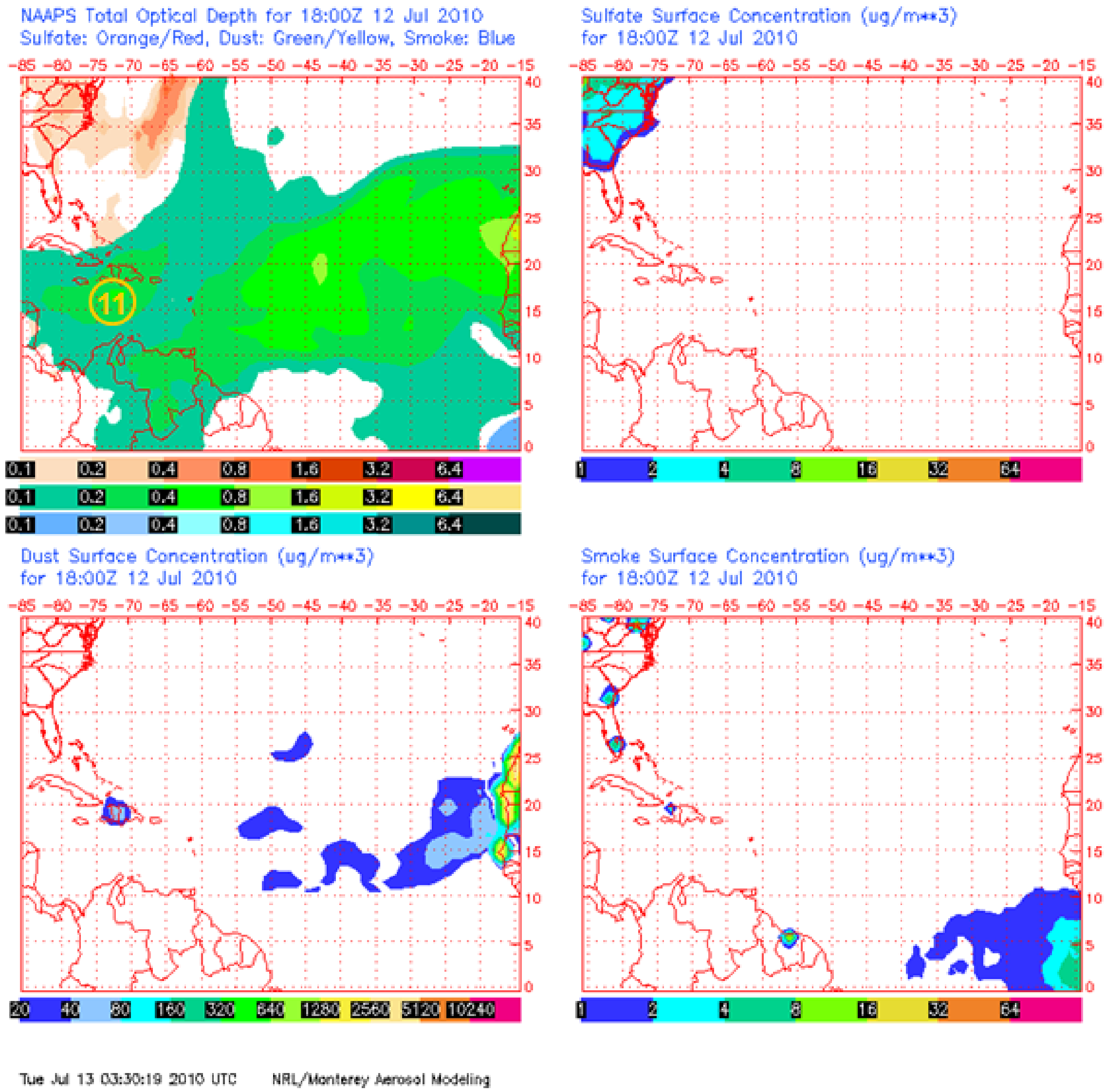

Figure C-34. NRL aerosol analysis 2010 July 12 showing dust cloud 11 in the Caribbean Sea.

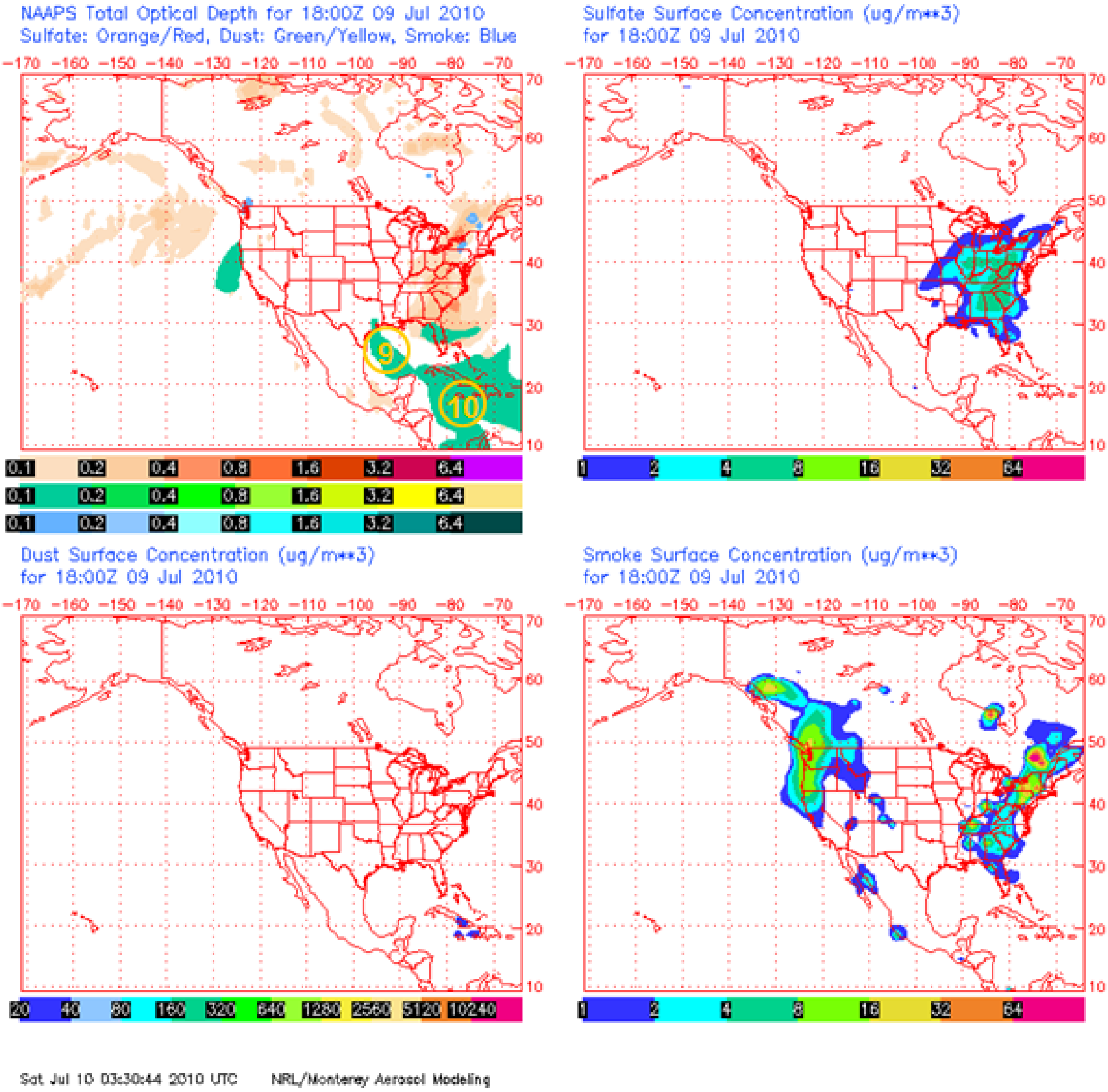

Figure C-35. NRL aerosol analysis 2010 July 9 showing dust cloud 9 in the western Gulf of Mexico and dust cloud 10 in the western Caribbean Sea.

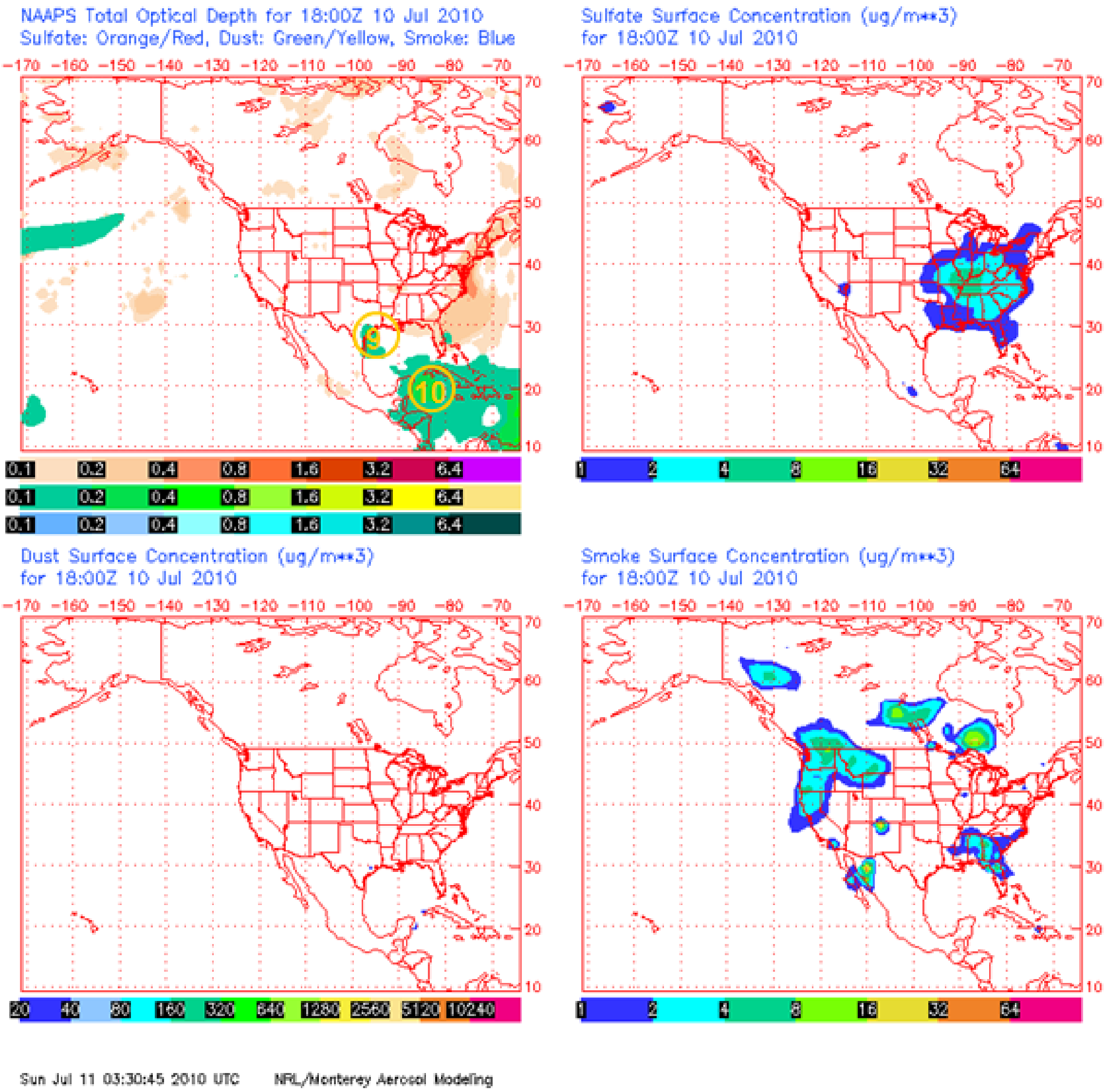

Figure C-36. NRL aerosol analysis 2010 July 10 showing dust cloud 9 moving into Texas and dust cloud 10 in the northwestern Caribbean Sea.

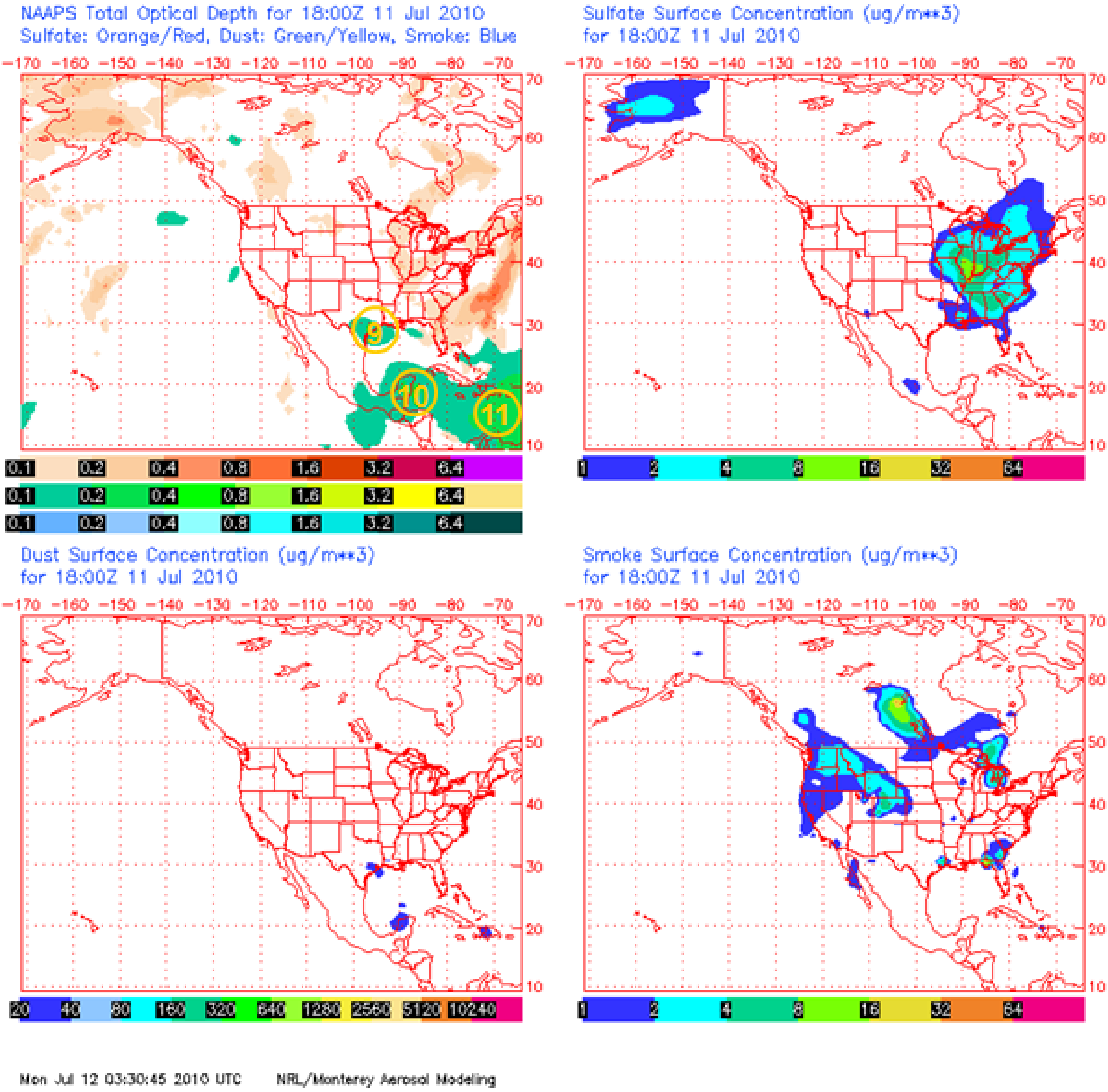

Figure C-37. NRL aerosol analysis 2010 July 11 showing dust cloud 9 in Texas, dust cloud 10 moving into the South Central Gulf of Mexico, and dust cloud 11 in the Central Caribbean Sea.

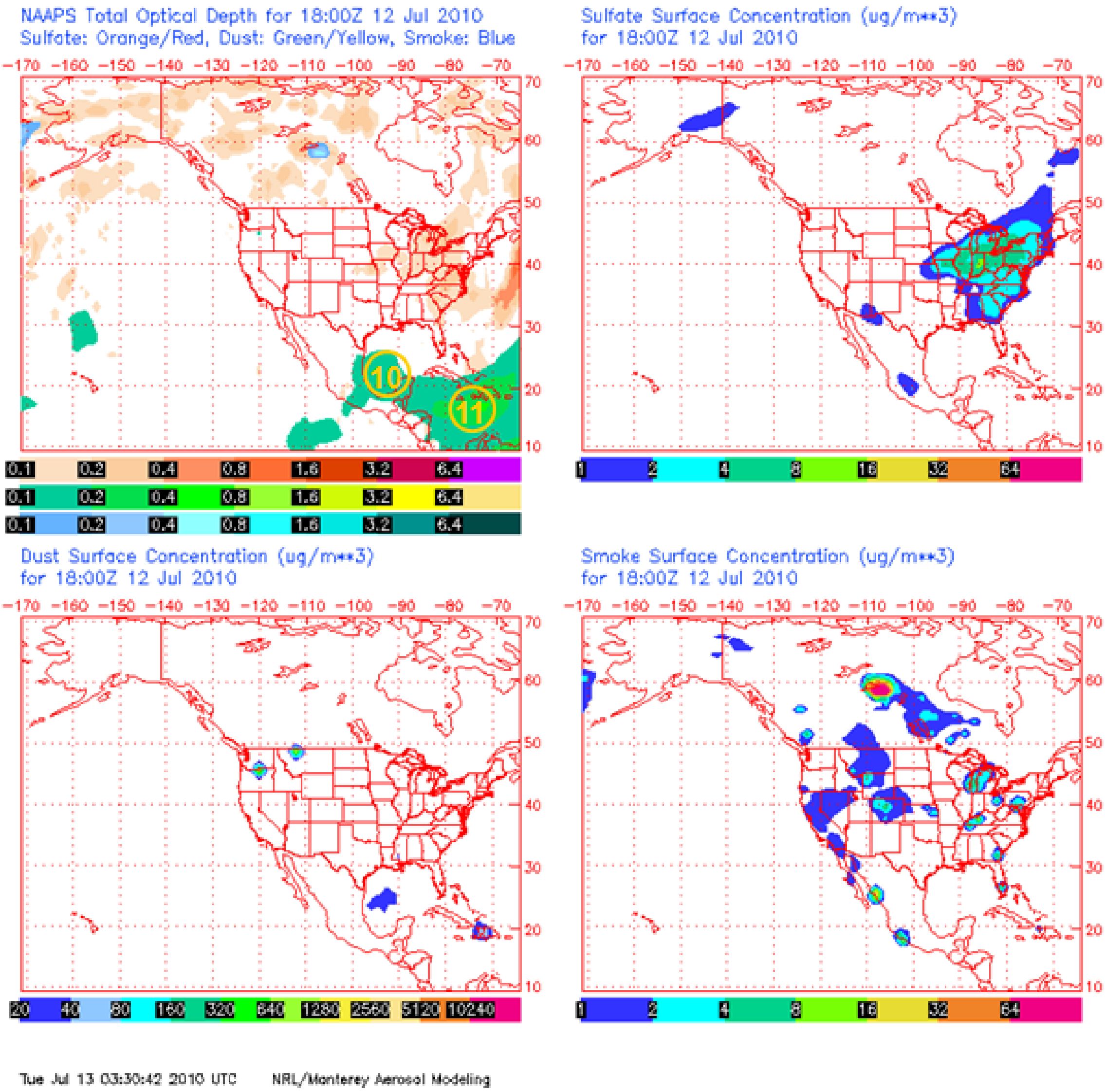

Figure C-38. NRL aerosol analysis 2010 July 12 showing dust cloud 10 in the southwestern Gulf of Mexico and dust cloud 11 in the Caribbean Sea.

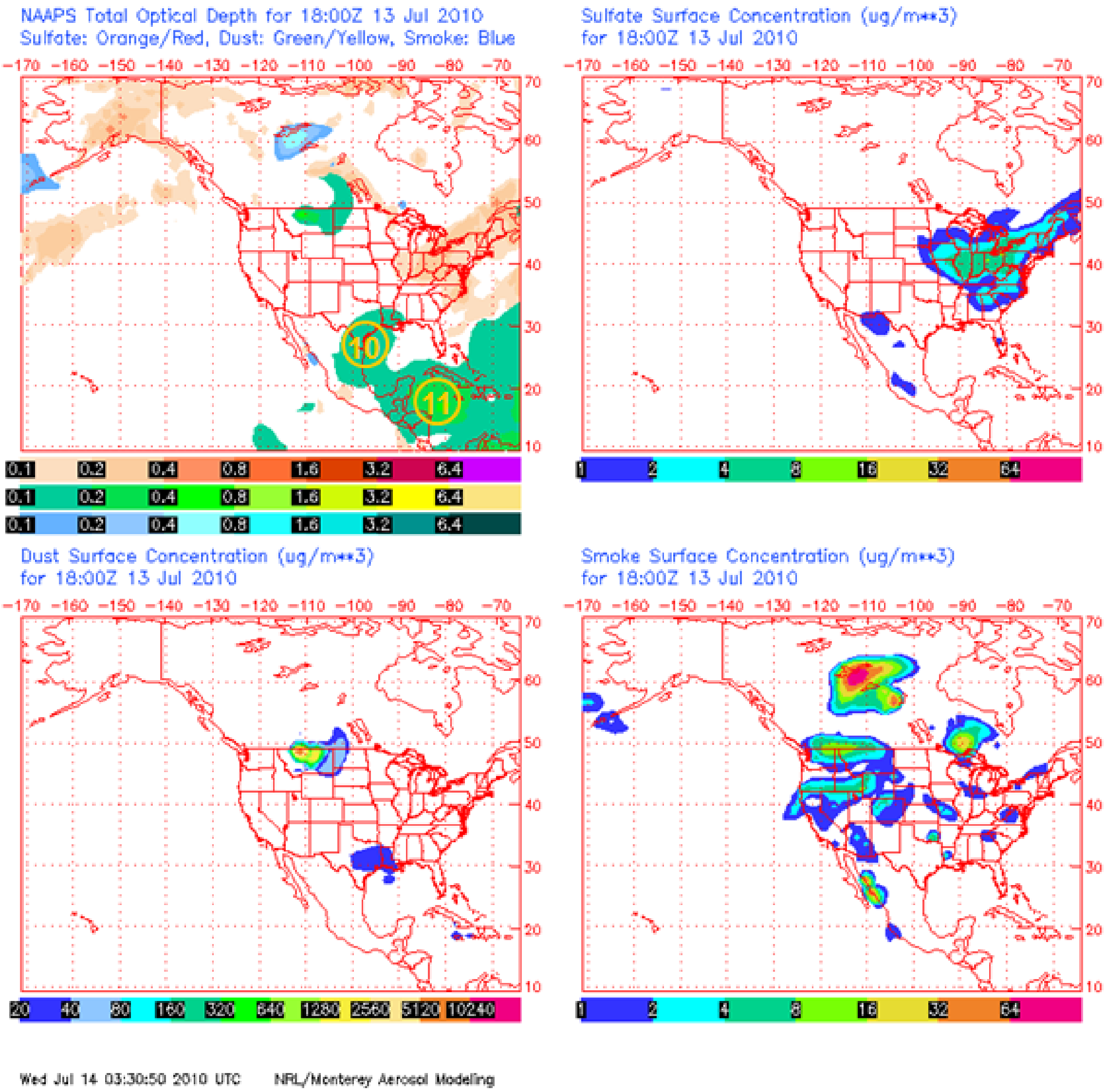

Figure C-39. NRL aerosol analysis 2010 July 13 showing dust cloud 10 moving into Texas and dust cloud 11 in the northwestern Caribbean Sea.

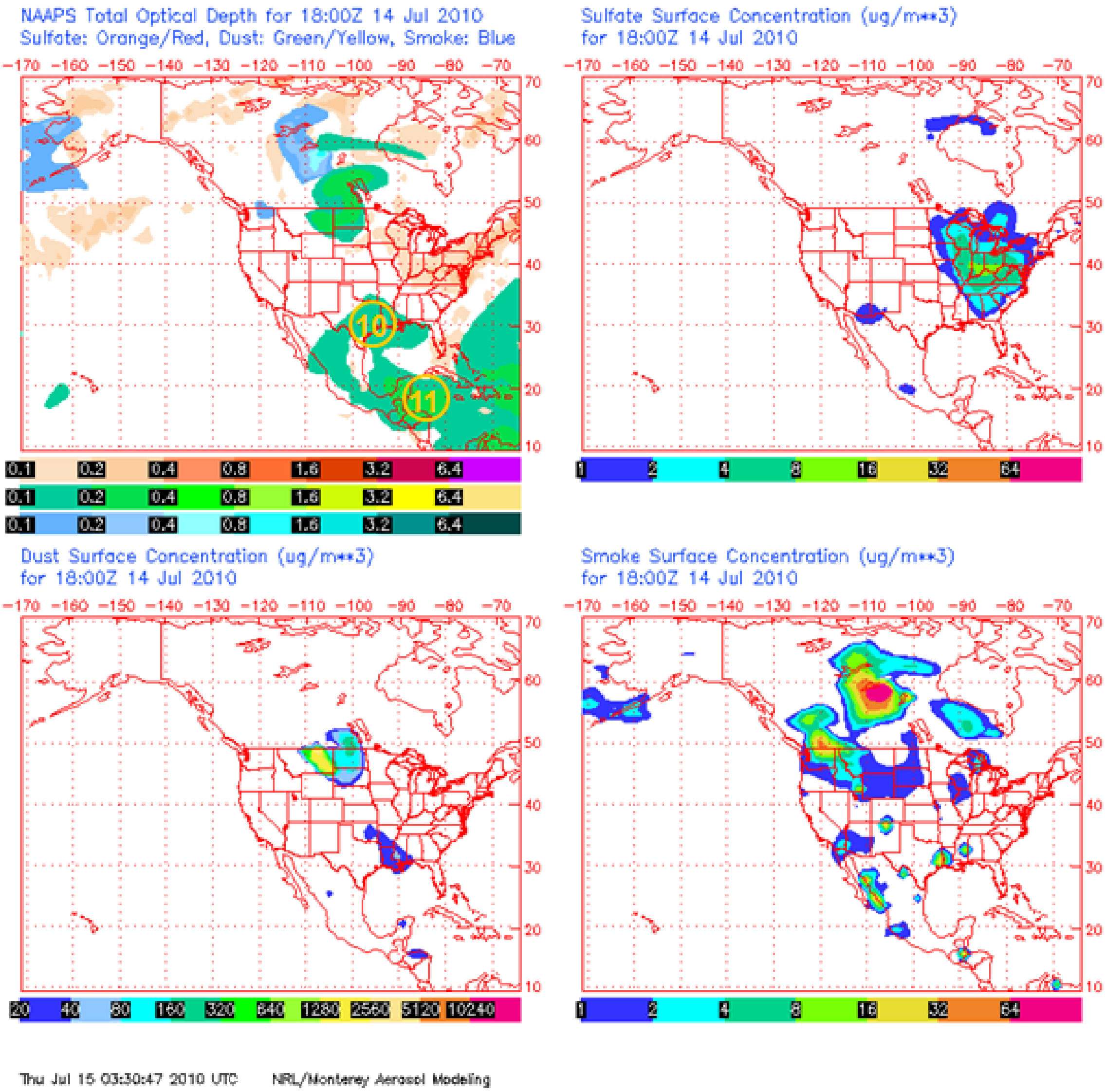

Figure C-40. NRL aerosol analysis 2010 July 14 showing dust cloud 10 in Texas and dust cloud 11 near the Yucatan Peninsula of Mexico.

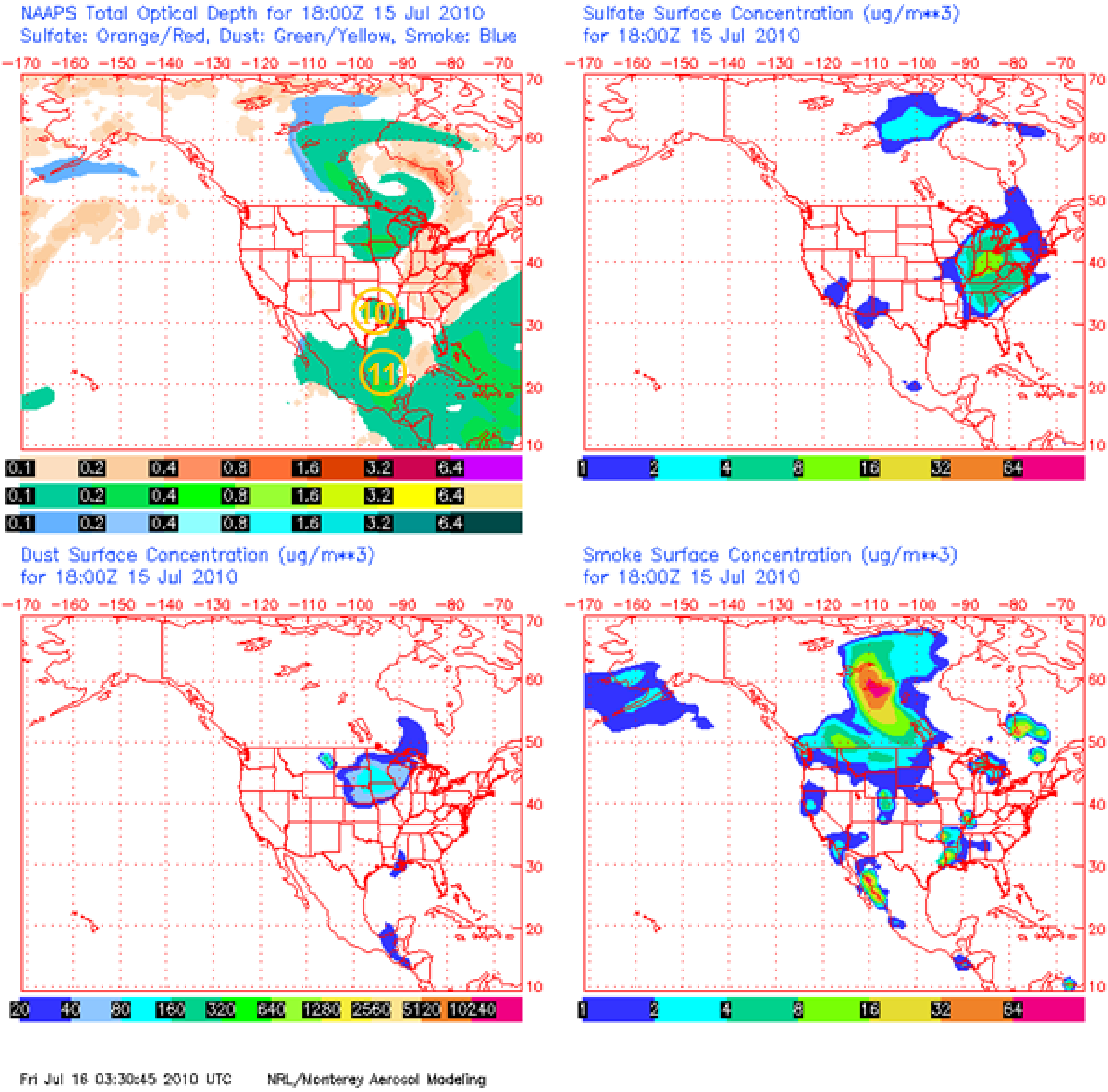

Figure C- 41. NRL aerosol analysis 2010 July 15 showing dust cloud 10 in Texas and dust cloud 11 in the southwestern Gulf of Mexico.