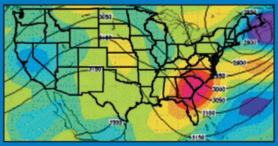
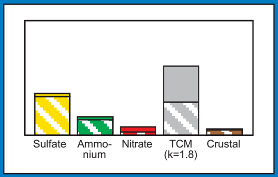
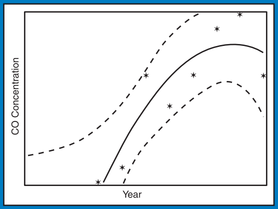
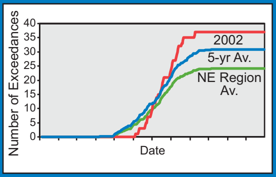
2003 SPECIAL STUDIES









$$CPA=\frac{\sum xy-\frac{\sum x\sum y}{n}}{\frac{\sum (x-y)^2+\sqrt{\left[\sum x^2-\frac{(\sum x)^2}{n}\right]\left[\sum y^2-\frac{(\sum y)^2}{n}\right]}}{n}}$$

Impact of April 2001 Asian Dust Event on Particulate Matter Concentrations in the United States

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Abstract

In April 2001, a large dust storm formed over the Gobi desert in northern China. Satellite remote sensing data and analyses of meteorological conditions were used in this study to follow the dust cloud from China, over the Pacific Ocean, and then coast to coast across the United States over a period of several weeks. Chemical speciation data were used to estimate the $PM_{2.5}$ mass increment associated with the Asian dust, and peak concentrations were plotted to show the progression of elevated concentrations across the contiguous United States. Meteorological analyses, including air parcel trajectories, were used to link the dust cloud overhead to the concentrations below. Also, the contribution of Asian dust to the total mass concentrations measured at the monitors was examined with respect to the U.S. Environmental Protection Agency's (EPA's) health standards and Air Quality Index (AQI) for particulate matter. The findings suggest that this transport event contributed to higher PM concentrations in several areas across the United States, with "average" estimated contributions ranging from 3.1 to 7.4 mg/m^3. Because the event occurred in the springtime when daily concentrations of other PM components are generally low, there were relatively few areas with "unhealthy" AQI days. Nevertheless, this event possibly contributed to "unhealthy" AQI days in three areas. In addition, it raised the 3-year average related to the long-term $PM_{2.5}$ health standard by an estimated 0.1 mg/m^3 in the affected regions. For most sites, this is insignificant, but there are implications for sites with 3-year averages just above the level of the standard.

Introduction

In early April 2001, an unusually large dust storm developed over the Gobi desert in northern China (Figure 1). The generation of dust storms and their impact on islands in the North Pacific have been the focus of research dating back to the late 1960s.[2] However, the focus on the impacts of Asian dust storms did not turn to the western United States until 1998.[3,4] In recent years, the satellite remote sensing data from such instruments as TOMS (Total Ozone Mapping Spectrometer), SeaWIFS (Sea-viewing Wide Field-

Figure 1. Map of Mongolia and northern China, highlighting the Gobi Desert region.[1]

of-view Sensor), MODIS (Moderate Resolution Imaging Spectroradiometer), and AVHRR (Advanced Very High Resolution Radiometer) have added a new dimension to studying such episodic events. These satellite sensors now allow the movement of the dust plume to be captured. In the case of the April 2001 dust storm, the satellites provide an eye-catching image of the dust cloud arriving at the doorstep of the western United States and beyond. But what does such an event, and the compelling satellite images resulting from the event, mean with respect to air quality in the United States and in particular to the levels of health concern for particulate matter?

The purpose of this paper is to provide a meaningful analysis of the impact of the April 2001 Asian dust storm on ground-level particulate matter concentrations within the contiguous United States. In this paper, we explore the formation of the dust storm over the Gobi Desert, the transport of the dust from its origin to the east coast of the United States, the mechanism for transport of dust to the boundary layer, and the ground-level impacts of the dust storm.

Following the Asian Dust Cloud

Formation over the Gobi Desert

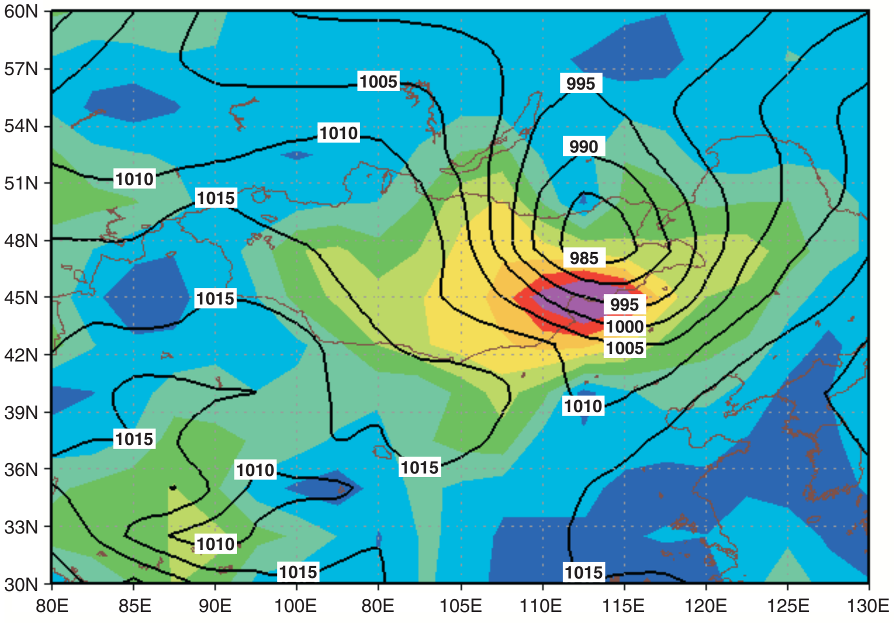
Wind-blown dust in eastern Asia is a locally well-known springtime occurrence. The dust storms tend to originate in the arid deserts of Mongolia and China, particularly the Gobi Desert, and spread eastward with the prevailing winds. The dust cloud itself forms when the friction from high surface winds, with speeds typically in excess of 5 m/s,[5] lifts loose dust particles up into the boundary layer and lofts them into the free troposphere where they can be transported eastward.[3]

An analysis of surface meteorological data for April 6 from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis Project[6] indicates that a strong Siberian low-pressure area (985 mb) was located in northeastern Mongolia (Figure 2). This feature, coupled with relatively higher pressure to the south, produced strong surface winds in excess of 24 m/s in eastern and southern Mongolia. The windspeeds shown are well above the threshold for particle suspension of 5 to 6 m/s[5] and are located over the Gobi Desert region.

The deep low-pressure area evident in Figure 2 continued to propagate eastward on April 7 with the center of maximum winds mirroring the track of the cyclone (low-pressure area). Averaged over a 24-hour period, the maximum surface winds were greater than 20 m/s. The sustained windspeed combined with the upward vertical velocities associated with the low-pressure system were sufficient to elevate the dust above the boundary layer for transport. An analysis of the circulations at 700 and 500 mb showed that the flow was essentially zonal (along the latitude) and toward the east-northeast. The zonal flow allowed the dust cloud a relatively direct pathway to the Pacific Ocean.

Satellites also confirm the formation of the dust cloud. Figure 3 is a composite AVHRR image from the National Oceanographic and Atmospheric Administration (NOAA)-16 satellite centered over Mongolia and northern China on April 6. This image clearly shows the wind-driven dust over southeastern Mongolia becoming entrained in the low-pressure system to the north. The low-pressure area is indicated in the image by the cyclonic cloud formation. The location of the blowing

Figure 2. April 6, 2001, surface windspeeds (color-shaded regions in m/s) overlaid with sea level pressure contours (mb) over the Mongolia and northern China region.



dust, highlighted by the red arrows, correlates well with the center of maximum surface winds shown in Figure 2.

Transport across the Pacific Ocean

Once the dust cloud reached the Pacific Ocean on April 8, it was carried by the northern midlatitude westerly winds (30°–60°N) that are typical during the springtime. Figure 4, created using data from both TOMS and SeaWiFS,[7] shows the daily progression of the dust cloud.[8] The TOMS aerosol index (AI) has been used in the past to show the daily spatial distribution of dust clouds.[9]

As shown in Figure 4, the dust cloud remained fairly compact, with no large sections peeling off northward and no evidence that longitudinal stretching occurred. It is difficult to determine the actual height at which the cloud was transported. Its rapid movement across the Pacific Ocean (5-day average speeds in excess of 20 m/s at 500 mb) and the lack of strong removal processes suggest that the cloud was in the free troposphere and traveling with the strong trans-Pacific westerly flow. The transport speed and zonal flow pattern during this period were verified by an analysis of the circulation at 500 mb.

Transport across the United States

As Figure 4 shows, the dust cloud first passed over the west coast of North America on April 12 and 13, initially impacting Canada and then the United States. An analysis of meteorological data (Figure 5d–f) shows that the transport of the dust cloud in the free troposphere on April 12 and 13 was from the northwest around the top of a high-pressure ridge that was off the coast of the United States. The pattern then became zonal, which lasted until April 15, when a large high-pressure ridge developed over the Rocky Mountains. The strong ridge moved slowly eastward, carrying the dust cloud with it. Once the ridge moved into the Southeast, it became stalled, allowing the dome of high pressure to increase in size and strengthen, thus trapping the dust cloud within it. The ridge over the Southeast lasted from April 19 to 23, causing southwesterly flow into the Northeast. This flow transported the dust cloud from the Southeast into the mid-Atlantic and Northeast regions on April 22 and 23.

Figure 3. NOAA-16 AVHRR image of the dust storm over Mongolia for April 6, 2001 (Image courtesy of NOAA).

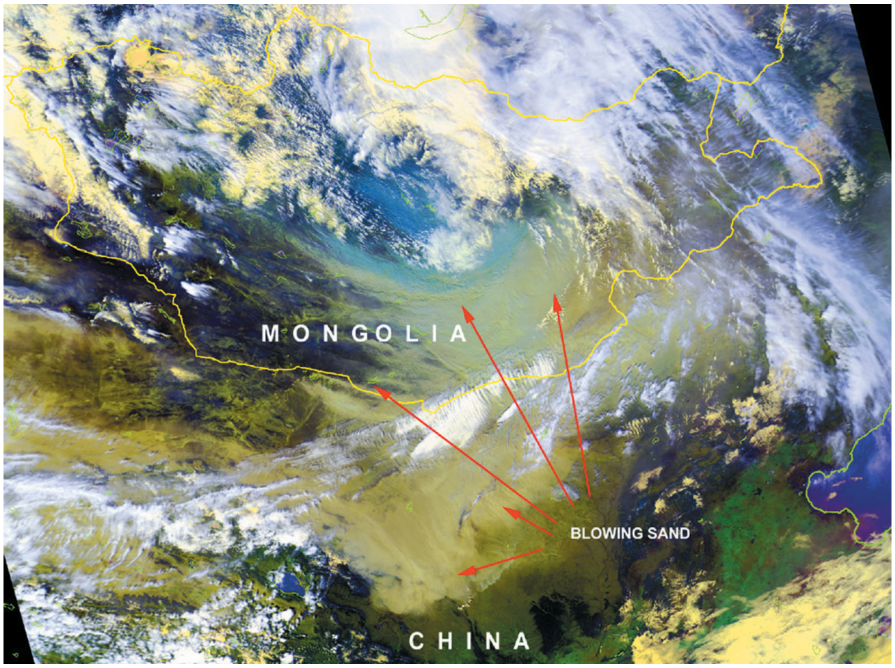
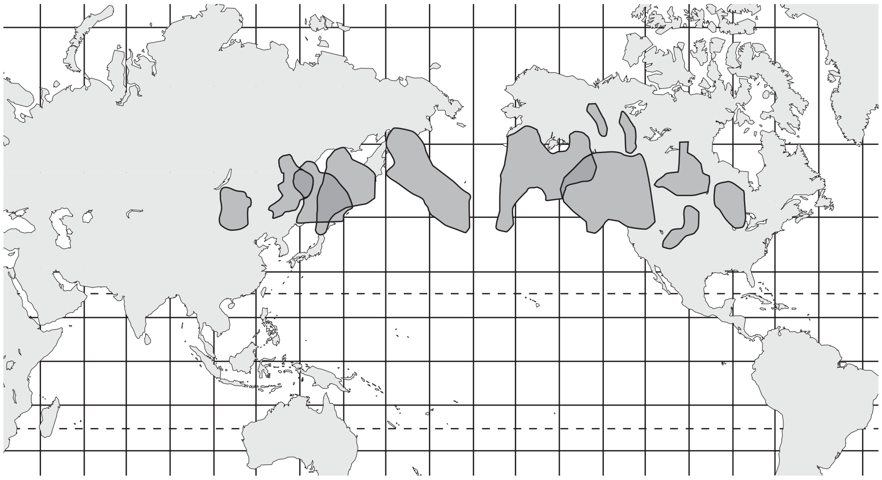


Figure 4. Path of the dust cloud from Asia to the United States, April 6 through April 14, 2001.



A review of TOMS AI and SeaWIFS to assess the temporal and spatial movement of the Asian dust as it crossed over the United States indicates that there were several days that the TOMS AI showed a dust cloud covering much of the United States. An analysis of meteorological conditions in conjunction with the measurements taken at PM monitors indicates that large-scale transport from the free troposphere to the boundary layer did not always occur. In some instances, it appears that the Asian dust was transported over the entire United States with relatively little effect on PM concentrations below (Figure 5).

However, as the dust cloud passed over the United States, monitors in some locations did measure elevated concentrations (>5 µg/m^3) of the soil component of PM$_{2.5}$ at some time during the month of April 2001, as discussed later in this paper. A closer look at the meteorology, including the location and movement of ridges and troughs from west to east, the rising or sinking of large-scale areas of air (negative and positive omega [ω], respectively) at 700 mb,[10] and the calculation of trajectories using the HYbrid Single-Particle Lagrangian Integrated Trajectories (HYSPLIT) program,[11–13] helps to explain the timing and location of the elevated particulate concentrations with respect to the cloud of Asian dust. Three dates are described here, corresponding to three areas of the country that were affected by the dust cloud: the West, the Southeast, and the Mid-Atlantic/Northeast.

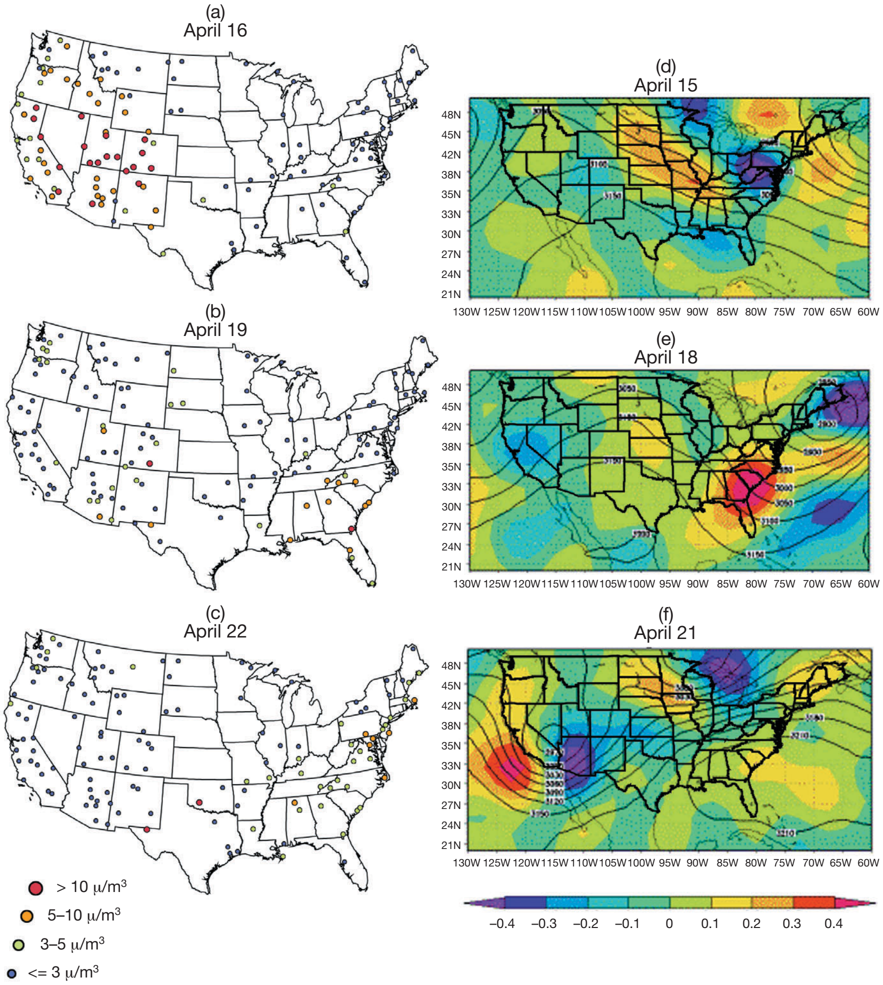
April 16, the West

As shown in Figure 5 (a and d), the peak concentrations seen over the West on this day can be attributed to the synoptic-scale ridging that was in place on April 15. The development of this ridge, coupled with the elevated terrain of the West, caused descending air. This large-scale sinking of air typically occurs under domes of high pressure. Also influencing the concentrations in the West is the likelihood that the dust cloud would have its greatest impact in this region because its first opportunity for measurable deposition was here. The high concentrations in the boundary layer were supported by numerous reports of decreased visibility at many of the national parks (Figure 6) and major cities located in that region, as well as with laser radar (LIDAR) measurements taken in Boulder, CO, on April 15.[14]

April 19, the Southeast

The peak concentrations seen in the Southeast on April 19 (Figure 5b) can be attributed to large-scale dynamic forcing that is associated with episodes of strong sinking motion (positive ω). Figure 5e shows the 700-mb height and omega patterns over the Southeast for April 18. A large area of sinking air is shown in red over this region, suggesting that for the Southeast there is a 1-day lag

Figure 5 (a–c). Peak PM$_{2.5}$ estimated soil mass from IMPROVE and STN monitoring networks.
(d–f) NCEP/NCAR reanalysis data for ω (color-shaded regions in pascal/s), overlaid with 700-mb heights.



(a) April 16

(b) April 19

(c) April 22

(d) April 15

(e) April 18

(f) April 21

between the day of peak positive ω (sinking motion) and the peak concentrations measured at the monitors on April 19. The length of the lag appears to depend on the meteorology but may also be exaggerated by the once-every-3-day monitoring schedule, as well as the fact that 24-hour PM concentrations are determined by averaging hourly measurements from midnight to midnight.

Results of a 3-day backward ensemble trajectory (Figure 7) provide insight into the origin of the air mass coming into the Southeast on April 19. The backward ensemble trajectory starts from four separate monitoring locations: Okefenokee, FL, Cape Romain, SC, Great Smoky Mountains, TN, and Gulfport, MS.

The results for the four ensemble trajectories show consistent flow fields with little divergence from the general origin of the air mass, which is the Midwest. The trajectory results were not surprising when compared to the NCEP/NCAR reanalysis data over the same time period. The NCEP/NCAR reanalysis data for the 700-mb heights (Figure 5e) show a northerly flow from the Midwest into the Southeast. A comparison of the vertical motion of the trajectories with ω (Figure 5e) shows good agreement with a large area of sinking air in the Southeast on April 18. When compared with the April 17 TOMS AI and SeaWIFS (Figure 8), this information suggests that the large dust cloud passing over the Great Lakes region is the likely source of the elevated levels of particulate matter.

April 22, Mid-Atlantic/Northeast

The peak concentrations seen in the mid-Atlantic and Northeast on April 22 (Figure 5c) can be attributed to a combination of ridging over the Southeast and a pattern of generally subsiding air over the region. The

Figure 6. Haze over Glen Canyon National Recreation Area (UT, AZ) on April 16, 2001.[4]

Figure 7. Three-day backward ensemble trajectories originating from Okefenokee, FL (30.74 N 82.13 W), Cape Romain, SC (32.94 N 79.66 W), Great Smoky Mountains, TN (35.63 N 83.94 W), and Gulfport, MS (30.39 N 89.05 W) and ending at 15 UTC (11:00 a.m. EDT) on April 19, 2001.

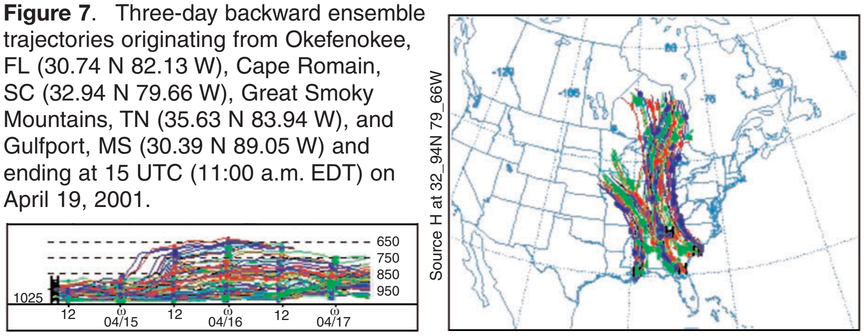
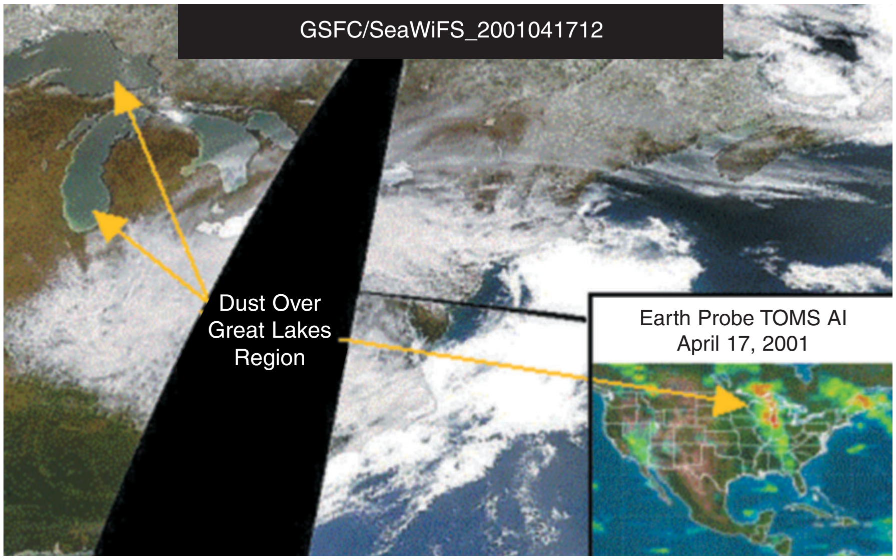


Figure 8. The SeaWiFS image taken on April 17, 2001, shows dust over the Great Lakes region. The eclipsed area in the image is a result of areas not covered during the SeaWiFS overpass on this day. The inset shows that TOMS Aerosol Index for April 17 also captures the dust cloud over the Great Lakes region, extending down into the southeastern United States.



NASA/Goddard Space Flight Center, The SeaWiFs Project, and ORBIMAGE Science Visualization Studio.

ridging over the Southeast seen on April 21 (Figure 5f) is associated with a developing dome of high pressure that generated southwesterly flow toward the Northeast around the periphery of the high. This return flow would have transported any boundary layer pollution (i.e., dust) located over the region into the mid-Atlantic and northeast regions. This synoptic feature, coupled with any sinking air that forced down the remains of the dust cloud, is a likely cause of the increased particulate concentrations seen in the mid-Atlantic/Northeast. A series of backward trajectories from several mid-Atlantic and northeastern monitoring sites with elevated particulate matter concentrations on April 22 indicate that air originated from the southeastern United States 2 days prior to April 22. This result is consistent with the results of the 700-mb analysis.

Assessing the Impact of the Asian Dust Cloud

Characteristics of Particulate Matter

Monitoring data from the $PM_{2.5}$ chemical Speciation Trends Network (STN)[15] and the Interagency Monitoring and Protected Visual Environment (IMPROVE) aerosol monitoring network[16] were used to examine the elemental soil components. In addition, mass measurements from the national PM_{10} and $PM_{2.5}$ Federal Reference Method (FRM) networks were used to assess the health impact of the April 2001 dust event across the United States.

The STN and IMPROVE network use similar sampling and analytical methods to generate similar aerosol composition data. The soil component of $PM_{2.5}$ can be determined from the measurements made by these networks using the following formula:

$$PM_{2.5}\ \text{dust} = 2.2[\text{Al}] + 2.49[\text{Si}] + 1.63[\text{Ca}] + 2.42\,[\text{Fe}] + 1.94[\text{Ti}].^{17}$$

In the United States, dust (also called crustal material or soil) in the ambient air typically originates from wind-blown dust, road surface materials, construction activity, and certain agricultural activities.[18] Dust particles are typically less than 10 µm in diameter. Those particles nominally less than 2.5 µm in diameter are typically measured as part of the fine ($PM_{2.5}$) mass. Those between 2.5 and 10 µm are typically measured as part of the coarse (PM_{10}–$PM_{2.5}$) mass. Because monitors do not have a perfectly sharp size separator at the 2.5-µm cutpoint, some of the particles greater than 2.5 µm can be captured as $PM_{2.5}$ mass, and some of the particles measuring less than 2.5 µm can be captured as coarse mass.[19] The degree to which this occurs varies, depending on the monitoring device and particle separator. During the April 1998 Asian dust event, the mass mean diameter of the dust was observed to be 2 to 3 µm, overlapping the 2.5-µm cutpoint.[3]

Soil concentrations make up only a small fraction of $PM_{2.5}$ in the East and most areas of the West. Other components such as sulfates, nitrates, and carbon make up the majority of the $PM_{2.5}$ mass. Concentrations of these components are influenced by meteorology and emission sources and, therefore, vary by season and region of the country.

Because very few speciation data are available for the coarse mass, and there is a growing network of $PM_{2.5}$ speciation data, the analyses in this paper focus on $PM_{2.5}$ soil components. Results relevant to EPA's particulate matter health standards are shown in terms of $PM_{2.5}$ and PM_{10} mass.

Examining Historical Trends

Although 24-hour $PM_{2.5}$ soil concentrations are typically low (<3 µg/m^3),[20] unusual events such as dust storms can cause short-term peaks. Local dust storms in the desert Southwest are relatively common. However, long-term transport of dust from Asia to North America is not, although there is evidence suggesting that Asian dust storms have become more intense in the past decade. Recent studies have linked the increased intensity to climate change, drought conditions, and land use practices in China.

The dust transported from Asia in April 2001 caused the soil component of $PM_{2.5}$ to rise dramatically at certain locations in the United States, with some monitoring sites seeing record-high levels. The $PM_{2.5}$ soil concentration at Canyonlands National Park in southeast Utah (Figure 9), for example, measured 16.6 µg/m^3, twice as high as any previous measurement on record. However, other sites have measured higher levels in previous years. Sula, MT (Figure 10), for example, recorded a higher concentration during the April 1998 Asian dust event.[3] At sites in the Southeast, such as Okefenokee National Wildlife Refuge in Georgia (Figure 11), the peaks in previous years are consistent with seasonal Sahara dust transport.

April 2001 is the first time that East Coast soil peaks have been associated with dust transport from Asia. The site at Brigantine National Wildlife Refuge in New Jersey (Figure 12), for example, had a peak soil concentration of 7.8 µg/m^3 on

Figure 9. Historical $PM_{2.5}$ soil concentrations at Canyonlands National Park.

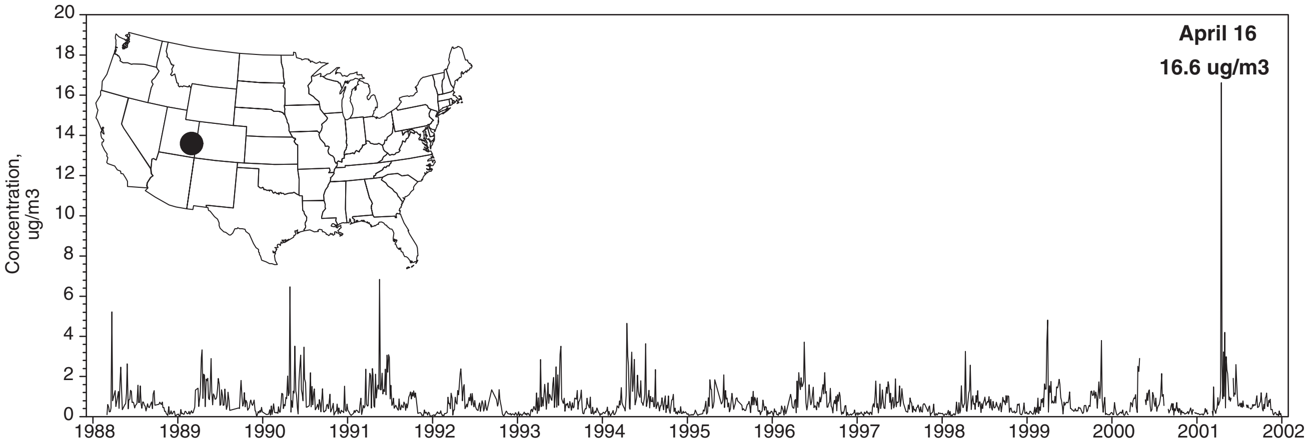


Figure 10. Historical $PM_{2.5}$ soil concentrations at Sula Wilderness Area.

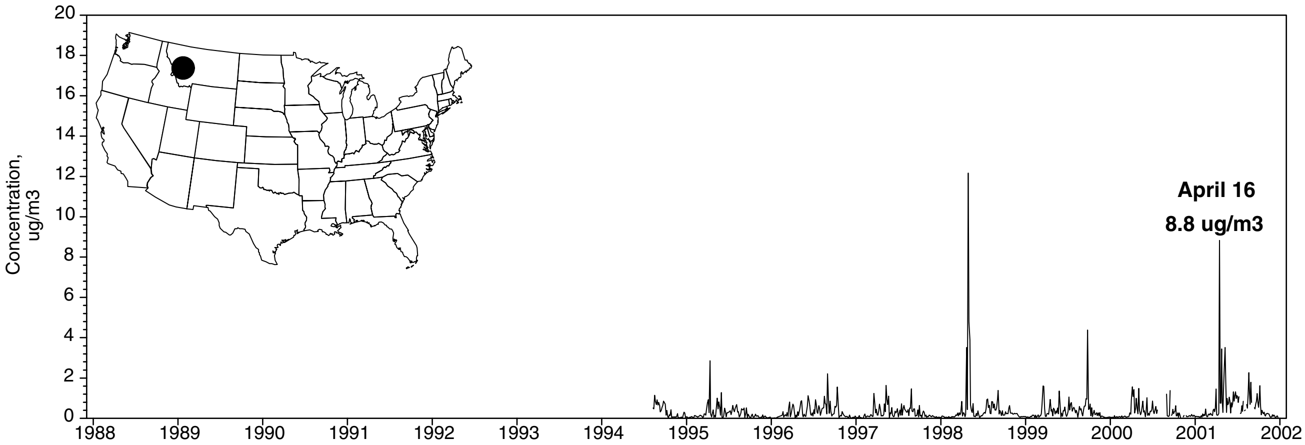


Figure 11. Historical $PM_{2.5}$ soil concentrations at Okefenokee National Wildlife Refuge.

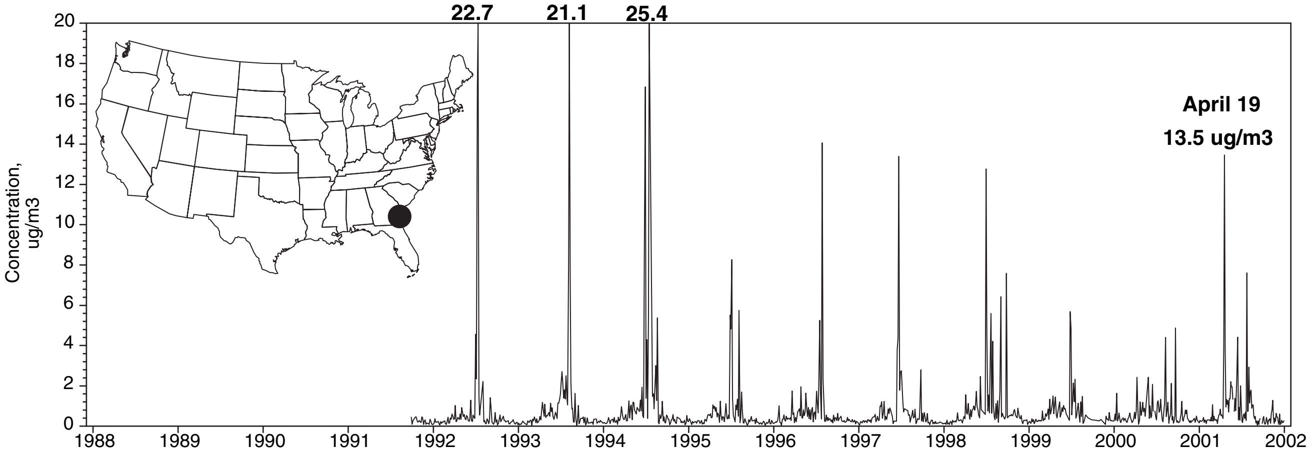
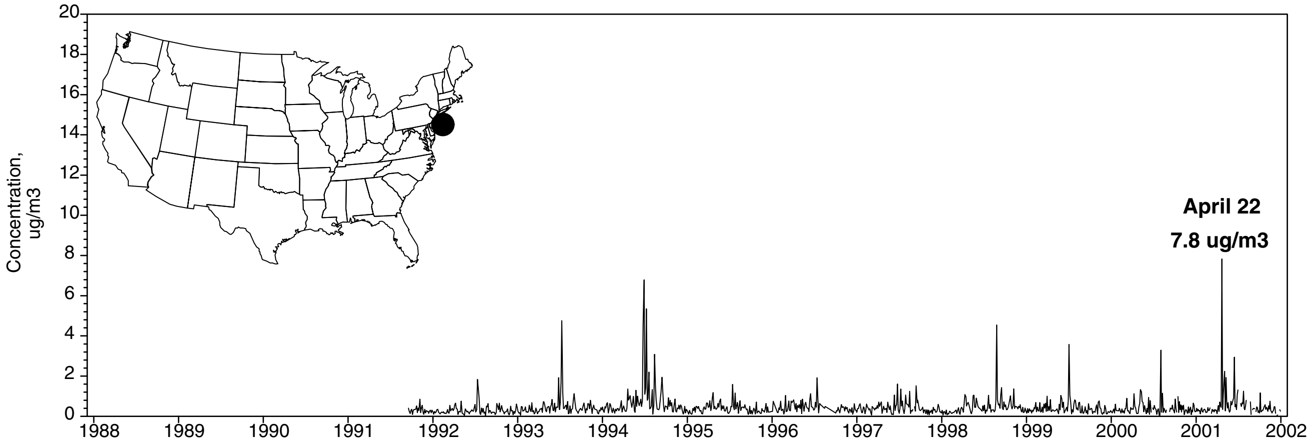


Figure 12. Historical $PM_{2.5}$ soil concentrations at Brigantine National Wildlife Refuge.



April 22. Other sites along the East Coast, from Florida to Maine, had modest increases in soil concentrations from mid to late April.

Estimating Asian Dust Contribution to PM2.5 Mass

A logical next step in assessing the impact of this dust event on $PM_{2.5}$ mass concentrations was to estimate the soil increment associated with Asian dust on days with peak soil concentrations. The IMPROVE network provided enough historical data to develop a baseline of "typical" April soil concentrations. The typical April soil concentration was represented by the median of all April observations from years other than 2001. An estimate of Asian dust contribution was obtained by subtracting the typical April soil contribution from the peak soil concentration on a site-by-site basis. In this way, an estimate of Asian dust contribution was obtained for every IMPROVE site having adequate data. A graphical illustration of this procedure is provided in Figure 13.

Table 1 groups the sites by date of peak soil concentration. Because it is less resistant to extreme values, the median among sites is used to represent typical values for each date. As might be expected from the dust cloud location shown earlier in this paper, most sites in the West had peak concentrations on April 16. The median Asian dust contribution was 7.4 µg/m^3, ten times as much as the median of the typical April soil concentrations (0.7 µg/m^3). The highest Asian dust contribution on this date (21.2 µg/m^3) occurred at a site in Death Valley, CA. The $PM_{2.5}$ and PM_{10} mass values at this site were 30.7 µg/m^3 and 59.9 µg/m^3, respectively.

On April 19, sites in the Midwest and Southeast experienced peak soil concentrations. The Asian dust contribution on this date was 3.6 µg/m^3, compared to 0.5 µg/m^3 for typical April days. The site with the highest contribution (12.9 µg/m^3) was the Okefenokee National Wildlife Refuge in southeastern Georgia. The $PM_{2.5}$ and PM_{10} mass values at this site were 22.2 µg/m^3 and 50.7 µg/m^3, respectively.

On April 22, sites in the mid-Atlantic and Northeast experienced peak soil concentrations. The Asian dust contribution was 3.1 µg/m^3, compared to typical April soil concentrations (0.4 µg/m^3). The site at Brigantine National Wildlife Refuge had the highest Asian dust contribution (7.4 µg/m^3). The $PM_{2.5}$ and PM_{10} mass values at this site were 24.4 µg/m^3 and 50.6 µg/m^3, respectively.

The dates of the peaks in soil concentrations correspond directly to the meteorological and satellite information presented in earlier sections. The median Asian dust contribution ranges from 3.1 to 7.4 µg/m^3 during the April 16–22 period, with double-digit contributions in some locations.

Examining Soil Composition on Peak Days

There is some uncertainty associated with the composition of transported dust, mainly because of the lack of speciation data, especially for the coarse fraction. However, some insights can be gained by examining the $PM_{2.5}$ speciation data measured during the April 2001 Asian dust event.

We examined various elemental concentrations and ratios in search of potential indicators of Asian dust. Specifically, we compared the primary elemental soil components on the April 2001 peak days with typical April days (represented by the median of April data from other years). We then identified a subset of 20 sites with peak soil concentrations

Figure 13. $PM_{2.5}$ soil concentrations, April 2001 vs. typical April days, at Brigantine National Wildlife Refuge.

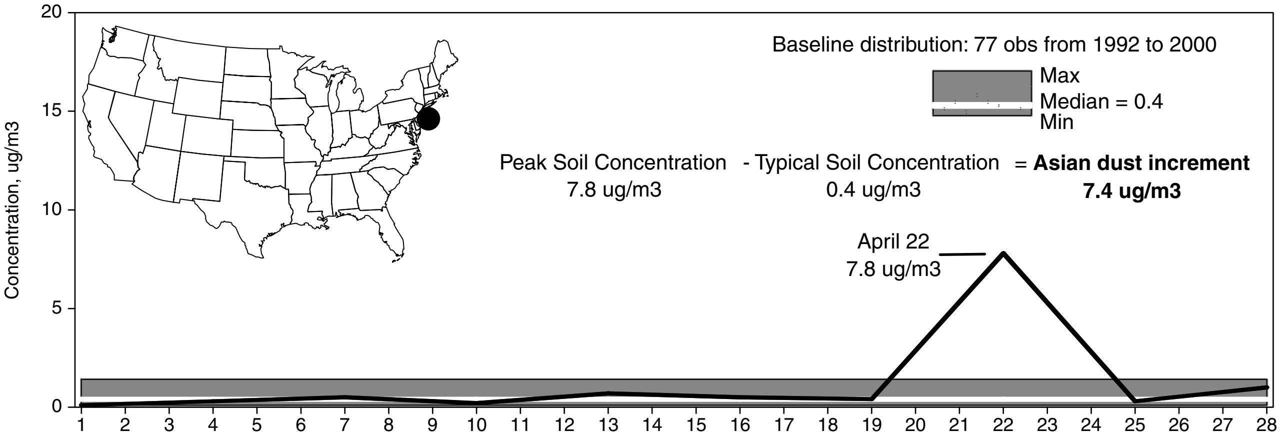


Table 1. Summary of Asian Dust Contribution by Date

Date	Number of Sites	Site Locations	Median Typical April Soil Concentration (µg/m^3)	Median Asian Dust Contribution (µg/m^3)	Maximum Asian Dust Contribution (µg/m^3)
4/16/01	43	West (AZ, CA, CO, ID, MT, NM, NV, OR, UT, WA, WY)	0.7	7.4	21.2
4/19/01	19	Midwest and Southeast (FL, GA, MI, MN, NC, ND, SC, SD)	0.5	3.6	12.9
4/22/01	16	Mid-Atlantic and Northeast (DC, KY, ME, NJ, VA, VT, WV)	0.4	3.1	7.4

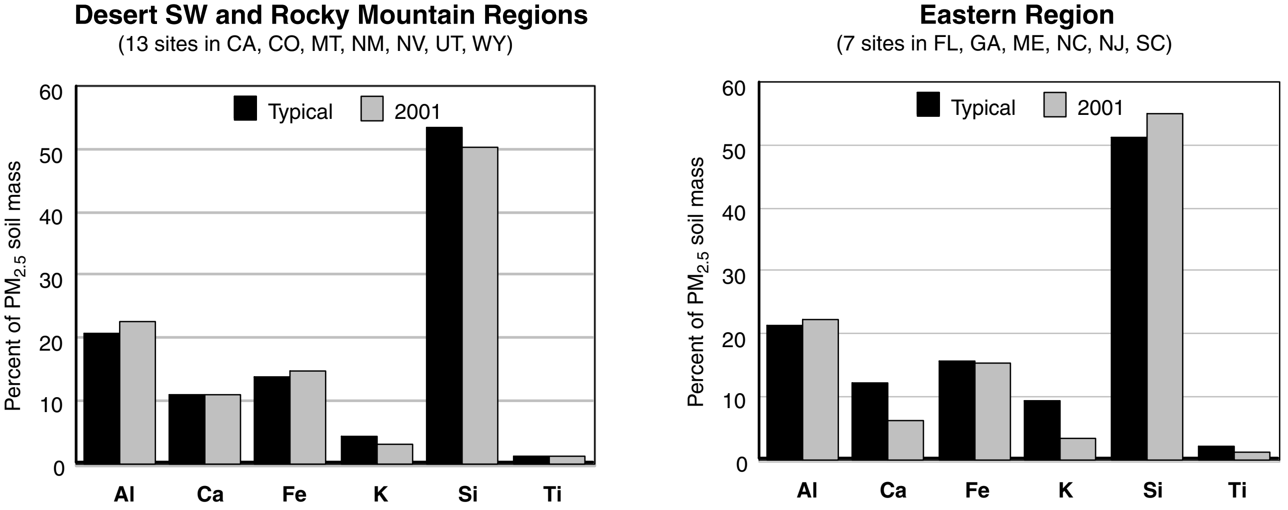
corresponding to the position of the dust cloud. The most distinctive contrast among the indicators was potassium (K) as a percent of total $PM_{2.5}$ soil mass. The percent of potassium (%K) was 3 to 4 on the peak days. In eastern areas where %K is typically much larger, this appears to be a good indicator that the soil composition is atypical. However, in the desert Southwest and Rocky Mountain regions, where the %K is typically 4, the ratio is of little help. Figure 14 is an aggregation of the data at sites in these regions.

In addition to %K, the percent of calcium (%Ca) and the percent of silicon (%Si) between 2001 peak days and typical days are significantly different in the eastern sites. Because the peak day %Ca and %Si are different in the western locations vs. the eastern locations, it is too early to speculate whether they could be potential indicators of Asian dust. It is certainly possible that the dust size and composition differ after several days and several thousand miles of transport. More speciation data, especially in the coarse range, could help explain differences in composition of transported dust.

Assessing Potential Health Impact

As the satellite and meteorological information suggests, only certain regions (coinciding with the position of the dust cloud and the vertical movement of air) experienced elevated soil concentrations and, consequently, higher PM_{10} and $PM_{2.5}$ concentrations. Sometimes the increase was reflected evenly in the coarse and fine fractions, but in most cases the coarse fraction showed a larger increase than the fine. Two examples of the effect of this Asian dust event on PM_{10} and $PM_{2.5}$ mass are shown in Figures 15 and 16. The peak at the Salt Lake City site occurred on April 16. In this example, most of the increase is reflected in the coarse fraction. On April 22, several days later, concentrations peaked at the Acadia National Park site in Maine. Unlike the Salt Lake City example, more of the increase here is reflected in the fine fraction.

Figure 14. Summary of $PM_{2.5}$ soil composition on April 2001 peak days vs. typical April days, by region.



Desert SW and Rocky Mountain Regions
(13 sites in CA, CO, MT, NM, NV, UT, WY)

Eastern Region
(7 sites in FL, GA, ME, NC, NJ, SC)

In the preceding examples, the resulting PM mass concentrations show an increase, but the peaks are not above a significant level of health concern for the general population. EPA has designed an index, the Air Quality Index, to communicate information about daily air quality and associated health concerns. According to the AQI, cautions for sensitive populations (people with heart or lung disease, older adults, and children) are associated with daily $PM_{2.5}$ and PM_{10} concentrations greater than 40.4 µg/m^3 and 154 µg/m^3, respectively. These concentrations correspond to an AQI value of 100. The cautionary statement associated with PM concentrations at this level of concern says that "people with heart or lung disease, older adults, and children should limit prolonged or heavy exertion." There are additional health concerns associated with higher concentration ranges.[22]

There were nine areas (cities or counties) corresponding to the general location and movement of the dust cloud that had at least 1 day with an AQI value above 100 for $PM_{2.5}$ or PM_{10}. Four of these areas had no days above 100 during the entire spring season in the surrounding years (1999, 2000, and 2002). Unfortunately, there are no speciation data in these areas for estimating Asian dust contribution. However, based on estimates computed previously for nearby IMPROVE sites, three of the nine areas might have actually been below 100 were it not for Asian dust contribution. Still, further review and, in some cases, additional data might be needed to determine exact contributions from Asian dust versus dust from other sources.

Because this transport event occurred in April, a temperate part of the year, meteorological conditions were not conducive to the formation of sulfates, nitrates, or organic carbon (major components of $PM_{2.5}$ mass). If higher levels of any of these components were combined with the increased dust concentrations, there might have been more AQI values above 100.

With respect to EPA's long-term health standard for $PM_{2.5}$, the 1- or 2-day increases from this dust event had relatively little effect. For example, when the "Median Asian Dust Contribution" (3.1 to 7.4 µg/m^3, depending on region) from Table 1 is excluded from the 3-year averages for 1999 through 2001, the averages are 0.1 µg/m^3 lower. This small shift could be important for any sites bordering the level of the standard of 15.0 µg/m^3. For this particular 3-year period, there were three counties with averages of 15.1 µg/m^3, just above the standard. Further review would be required to determine whether or not the sites in these counties were affected by the Asian dust and to what extent.

Conclusions

On April 6, 2001, the combination of strong surface winds and an intense area of low pressure over the Gobi Desert produced a large dust cloud that was lofted into the free troposphere and transported eastward. The dust cloud, captured and tracked by satellite imagery, made its way across the Pacific Ocean and ultimately reached the United States on April 12 and 13. Once the cloud was over the United States, sinking air associated with large areas of subsidence and strong downward vertical motion appeared to coincide

Figure 15. Daily PM_{10}, $PM_{2.5}$, and soil ($PM_{2.5}$) concentrations at Salt Lake City, UT.

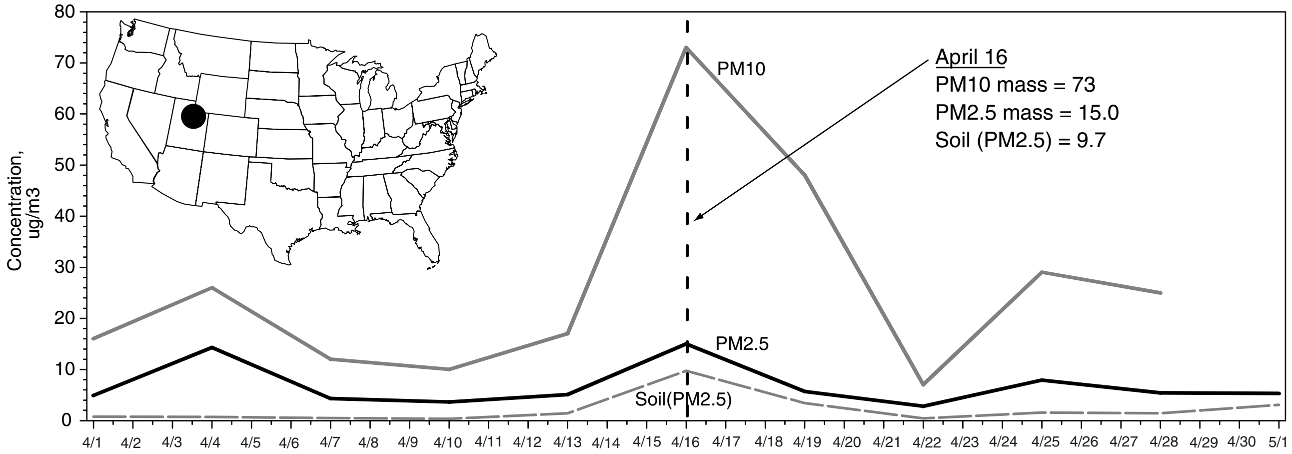
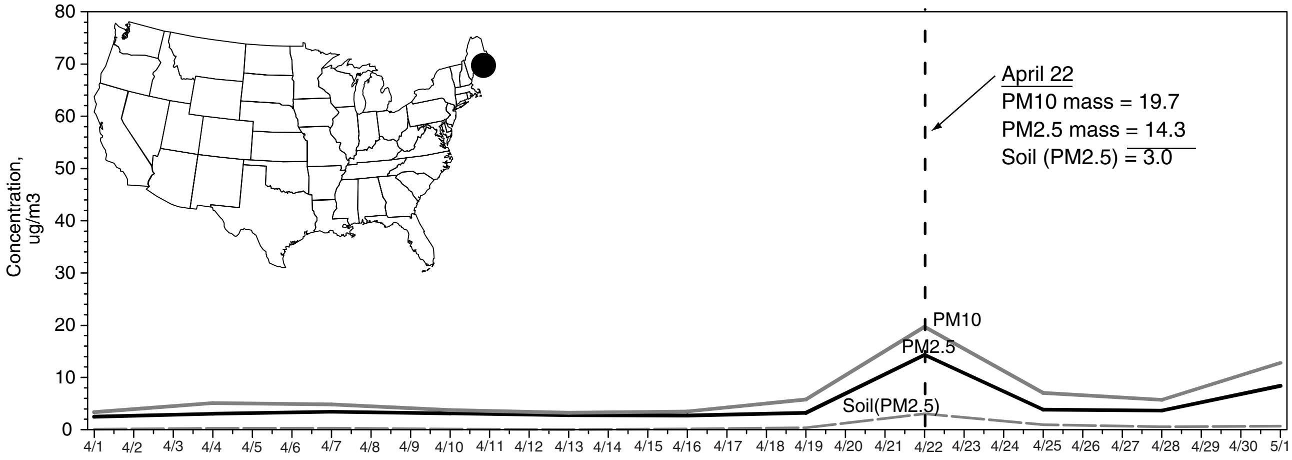


Figure 16. Daily PM_{10}, $PM_{2.5}$, and soil ($PM_{2.5}$) concentrations at Acadia National Park, ME.



with increased soil concentrations in certain areas of the country. In some instances, there appeared to be a lagged relationship (days with increased concentrations lagging days of strong downward vertical motion). This lag could be exaggerated by the once-every-3-day monitoring schedule as well as 24-hour averaging technique employed at the monitoring sites.

Although the TOMS imagery showed days with a dust cloud over much of the United States, an analysis of meteorological conditions in conjunction with IMPROVE and STN monitors indicated that large-scale transport to the boundary layer (which would result in increased particulate matter concentrations) did not occur everywhere. Ridges and troughs, rising or sinking air, and trajectories showing the origins and paths of air masses were all examined to gain an increased understanding of how and when the Asian dust cloud affected the monitors below.

In the areas identified by the satellite and meteorological information, chemical speciation data showed that Asian dust contributed "on average" 3.1 to 7.4 µg/m^3 to the total $PM_{2.5}$ mass concentrations during the April 16–22 period. There were nine areas (cities or counties) corresponding to the general location and movement of the dust cloud that had at least 1 day with an AQI value above 100 for $PM_{2.5}$ or PM_{10}. Values for three of the nine areas might have actually been below 100 were it not for Asian dust contribution. Still, further review and, in some cases, additional data might be needed to determine exact contributions from Asian dust versus dust from other sources.

Because the event occurred in the

springtime when daily concentrations of other PM components are generally low, there were relatively few areas with AQI days above 100. If higher levels of any of these components were combined with the increased dust concentrations, there might have been more AQI values above 100.

With respect to EPA's long-term health standard for $PM_{2.5}$, this dust event raised the 3-year average by an estimated 0.1 $\mu g/m^3$ in the affected regions. For most sites, this is insignificant, but there are implications for sites with 3-year averages just above the level of the standard.

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