Application of Satellite Remote-Sensing Data for Source Analysis of Fine Particulate Matter Transport Events

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ABSTRACT
Satellite sensors have provided new datasets for monitoring regional and urban air quality. Satellite sensors provide comprehensive geospatial information on air quality with both qualitative imagery and quantitative data, such as aerosol optical depth. Yet there has been limited application of these new datasets in the study of air pollutant sources relevant to public policy. One promising approach to more directly link satellite sensor data to air quality policy is to integrate satellite sensor data with air quality parameters and models. This paper presents a visualization technique to integrate satellite sensor data, ground-based data, and back trajectory analysis relevant to a new rule concerning the transport of particulate matter across state boundaries. Overlaying satellite aerosol optical depth data and back trajectories in the days leading up to a known fine particulate matter with an aerodynamic diameter of <2.5 μm (PM$_{2.5}$) event may indicate whether transport or local sources appear to be most responsible for high PM$_{2.5}$ levels in a certain location at a certain time. Events in five cities in the United States are presented as case studies. This type of analysis can be used to help understand the source locations of pollutants during specific events and to support regulatory compliance decisions in cases of long distance transport.

INTRODUCTION
Air quality monitoring at urban and regional scales has traditionally been performed using a network of ground monitoring stations combined with dispersion models that predict air quality between monitor locations. Satellite remote sensing can provide a synoptic picture of air quality in a regional airshed, including information about sources and source locations for isolated events. Satellite sensors can provide a broad view of urban haze and help determine when there is impact on urban air quality by local fires, dust storms, or transboundary transport of pollutants from more distant sources. These sensors also can potentially be used to monitor air quality in rural or remote regions with no ground-based monitoring network.

In prior work, it has been shown that satellite data and imagery can be applied to air quality policy. Researchers have also begun to conduct quantitative analyses comparing satellite sensor data to ground-based air quality measures. Specifically, researchers have documented that there is generally a strong correlation in the eastern region of the United States among the moderate resolution imaging spectroradiometer (MODIS) aerosol optical depth (AOD) data, fine particulate matter with an aerodynamic diameter of <2.5 μm (PM$_{2.5}$), and other air quality data taken at ground level. With this knowledge, one can begin to develop techniques to apply these data to air quality monitoring and policy questions.
The U.S. Environmental Protection Agency (EPA) has proposed a rule related to the transport of PM$_{2.5}$ in the eastern portion of the United States.$^8$ The research to support this rule included source apportionment modeling with speciated PM$_{2.5}$ datasets combined with back-trajectory analysis to identify potential source regions for PM$_{2.5}$ pollution.$^9$ The source apportionment analysis decomposed the speciated PM$_{2.5}$ data to identify both source category profiles of a few major sources of particulate matter, as well as the relative strengths of those source categories on each of the monitored days. Once the strength of each source category on each monitored day had been identified, back-trajectory analysis was used to find the possible locations of individual contributors to each source category. Back-trajectory analysis relies on the geospatial trajectory of air packets traced backward in time. By examining the trajectory over which air packets traveled on days when the source strength is high for a given source category, it is possible to find potential locations of sources. Whereas source apportionment can effectively identify the source type of air pollutants (e.g., coal burning, biomass burning, or crustal sources), and back trajectory analysis can point to the direction the pollutants came from, it is not clear where along the trajectory the source of pollution is encountered. Consequently, additional geospatial data are required to support these models if knowledge of source locations is desired.

This paper presents a new visualization technique that builds on an increased understanding of the satellite AOD related to PM$_{2.5}$ and may aid in identifying geographical locations of sources of particulate air pollution. This graphical technique integrates AOD, particulate matter concentrations, and back trajectories. The combination of these data sets indicates the location along the back trajectory where the pollutants were encountered.

**Review of Satellite Remote-Sensing and Air Quality Data**

Many satellite remote sensors have been launched and are managed by the United States and nations in Europe and Asia. In the United States, access to the full quantitative datasets of the National Aeronautics and Space Administration (NASA) Earth Observing System satellite sensors is generally provided through eight Earth Science Distributed Active Archive Centers (DAACs).

On both the Terra and Aqua platforms, the MODIS sensor has 36 spectral channels (compared with 4–8 for most sensors), thus it was designed to provide a wide variety of information for land, ocean, and atmosphere. MODIS has good spatial (250–1000 m) and temporal (one to two overpasses daily) resolution. With the large number of visible and infrared (IR) bands, the MODIS science team has developed 44 products for a range of applications. The product most relevant to air quality is AOD (also denoted as $\tau_a$), a dimensionless measure of the scattering and absorption of light by aerosols over the total vertical column from ground to satellite. The Aqua daytime overpass time is ∼2:30 p.m. local time, behind Terra’s 10:30 a.m. overpass, enabling two observations per day by MODIS in any one region. The nighttime passes for each satellite 12 hr later have IR measurements (for clouds, water vapor, etc.) but are not relevant to fine particle measurements.

The data used in this study included MOD04 Level 2 Aerosol Product for Terra and MYD04 Level 2 Aerosol Product for Aqua.$^{10}$ These data are available at 10 × 10 km resolution. MOD02/MYD02 Level 1B datasets were used to create true color images, and these data are available at 250-, 500-, and 1000-m resolution. These datasets were downloaded from the NASA Goddard DAAC in the NASA standard hierarchical data format. Conversion to SAS data files was conducted to extract geospatial satellite derived information on AOD, specifically the variable “Optical\_Depth\_Land\_And\_Ocean” in the MODIS dataset; this variable represents a combined optical depth at 0.55 μm.$^11$ Optical depth of aerosols typically ranges from 0 to ∼5, with values over unity generally being classified as heavy haze. Statistical comparison of AOD to PM$_{2.5}$ has been conducted in prior studies.$^6$ Findings were that AOD and PM$_{2.5}$ are well correlated ($r = 0.6$–0.9) in the eastern half of the United States (east of 100° W) during the summer and fall. Poor correlation can result from pollutants being located at high altitudes in the atmosphere (e.g., lofted smoke that is not well mixed during long-distance transport events), high surface reflectance in the western United States resulting in missing AOD data, and from AOD algorithm assumptions of pollutant type and geography. Thus, for the method demonstrated in this article, we focused on events in the eastern United States during the summer and fall when the PM$_{2.5}$–AOD relationship is good.

PM$_{2.5}$ data used in this study came from the EPA’s air quality system, including 24-hr average validated federal reference method concentration data.$^{12}$ A subset of the daily PM$_{2.5}$ data also contained detailed information about the chemical species, specifically, organic carbon (OC) and sulfate.

**Integrated Analysis**

Although satellite sensor data can provide significant information about intensity and horizontal scale of a regional haze event, it cannot provide information about specific types or exact concentrations of PM$_{2.5}$. The low temporal frequency of MODIS AOD coverage (twice per
day) limits information on how a specific parcel of polluted air arrived at a region. Back trajectories are used to determine potential geospatial source regimes. However, back trajectories cannot identify where along the individual back trajectories the source(s) exists. Back trajectory analyses only assume that trajectories that correspond with high concentrations cross a source region. For example, a 72-hr back trajectory for a parcel of air on a day with a high PM$_{2.5}$ concentration may cross a potential source area hundreds of kilometers away; however, the pollutants may be

**Figure 1.** Fine mass, OC, and sulfate concentration PM$_{2.5}$ events in five cities.
local and only meet that air parcel a few kilometers before reaching the receptor. The technique presented here integrates three data sets, MODIS AOD, PM$_{2.5}$ concentrations, and HYSPLIT$^{13}$ back trajectory modeling output, to use the broad geospatial coverage of the MODIS AOD data to indicate where along the trajectory the pollutants may have been added to the air packet.

An initial investigation of this method using a PM$_{2.5}$ event in Washington, DC, was presented at the Air and Waste Management Association 2004 Annual Meeting.$^{14}$ Using a revised technique for this paper, the integrated method was applied to five air pollution events. An event was defined as a date on which the level of PM$_{2.5}$ exhibited a dramatic increase from previous levels. Several cities in the eastern half of the United States were chosen as candidates for analysis. For each of these cities, time-series plots of PM$_{2.5}$, sulfate, and OC from the monitoring site closest to the city center were examined to identify the date on which the PM$_{2.5}$ event appeared to have peaked or when the rate of increasing PM$_{2.5}$ maximized. Based on the information in the plots, the following five cities and arrival dates for the analysis were chosen (see Figure 1 for the PM$_{2.5}$ time-series): (1) Houston, TX, on September 12, 2002; (2) Charlotte, NC, on July 16, 2002; (3) Philadelphia, PA, on August 12, 2002; (4) Birmingham, AL, on August 25, 2003; and Chicago, IL, on September 10, 2003.

The following section uses the September 2002 Houston event as an example to describe the integrated methodology, followed by summaries of the other four cases.

**Houston, TX, September 2002**

During mid-September 2002, the central and southern United States experienced a significant haze event. Figure 1 shows the rapid increase in PM$_{2.5}$ levels from September 10 to September 12, 2002. Figure 2 shows an image from the MODIS sensor (on the Terra satellite platform) from September 12, 2002; more detail on this event, including a series of satellite images and an analysis with a preliminary version of the integrated approach, has been presented in prior publications.$^{2}$ This image was created by layering the MODIS Level 2 AOD data over MODIS Level 1B true color images. The bright white regions indicate cloud cover. The colors represent the AOD levels.

To apply the integrated method, two types of charts were created for each event: (1) back trajectories mapped on geospatial MODIS Terra AOD data, and (2) charts of MODIS Terra AOD data versus distance/time along the back trajectory. Figures 3 and 4 are examples of these two types of charts for the September 2002 Houston, TX, event.

Construction of the back trajectories mapped over the AOD images was performed in two stages. In the first stage, images of AOD were constructed using data from both the Terra and Aqua satellites. Because some AOD measurements average over a larger area than others (those taken at more oblique angles to the ground compared with those nearer to nadir), filling in only the grid cells at the center of the AOD measurement location resulted in too many empty cells in locations away from the path of the satellite. To ensure that measurements closer to nadir covered less surface area than those taken farther from nadir, a Voronoi tessellation$^{15,16}$ defined by the locations of the satellite readings was used to create the images. Essentially, if AOD is observed in a specific location, the color assigned to the reading is applied to all of the surface area closer to that satellite data location than to any other satellite observation taken by that satellite on that day. This approach enabled the representation of the AOD measurements to encompass surface areas of varying dimension, thus avoiding discontinuities because of the elevation angle of the satellite. All of the AOD levels >1.3 were given the darkest red color on the color scale. Images were constructed for the date of the event as well as for 3 days before the event to correlate
with the back trajectories, which were traced backward for 72 hr.

After the AOD images were created for each day, the second stage of image construction was performed: HYSPLIT (version 4.6) back trajectories were added for four arrival times on the date of interest at the city being observed. The meteorological inputs for HYSPLIT were obtained from the National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory Eta Data Assimilation System archive, and the vertical velocity fields

Figure 3. Terra and Aqua images of the 3 days preceding a PM$_{2.5}$ event in Houston, TX, with back trajectories. Colors are MODIS Terra AOD, and lines represent back trajectories over the 72 hr preceding the start time, with the black segments representing the trajectory relevant to that satellite data. Trajectory data points indicate the location of the back trajectory every 3 hr. All times in Coordinated Universal Time.
of these data were used in calculating HYSPLIT’s vertical motion. All of the back trajectories arrive at a height of 500 m above the city being observed. Although more robust ensemble techniques for determining a representative HYSPLIT back trajectory may be warranted (e.g., averaging over several back trajectories with different arrival heights), only a single height was used in this study. The incorporation of ensembles or longer back trajectories would be a logical extension to this work. Plotting symbols were added to the back trajectory paths at the location of the back trajectory every third hour. Finally, for each image, the section of the back trajectory corresponding to that day and that satellite was highlighted in black. The final result can be seen in Figure 3.

Figure 3 shows a set of images for a PM$_{2.5}$ event that peaked in Houston, TX, on September 12, 2002. The back trajectories for the days leading up to that event all start in the Midwest 72 hr before the date on which the event begins, and although they begin in Missouri and Tennessee, the high AOD values indicate a large pollution mass over southern Indiana and Illinois. It is known that the error in the position of the back trajectory increases with the extent of the trajectory. It is apparent that the MODIS data actually provide a more firm indication of the source of the pollutants than does the trajectory. Over the next 3 days, the back trajectories move south toward Houston, and the mass of high AOD values moves along with it. In fact, on September 10, a band of high AOD values can be seen stretching toward Texas from the Midwestern states in both the Terra and Aqua images. On September 11, 2002, the mass of high AOD values is observed spreading out east to west rather than north to south. The change in flow and stagnation in the event is also indicated by the relatively short length of the trajectory segment for that day. Aqua provides a higher resolution image on this day, because it appears to have passed more directly over Houston, TX, than Terra. On the date in which the PM$_{2.5}$ event began (in Houston), September 12, 2002, no data were reported in the NASA DAAC for Aqua, so only the Terra image is available. In this final image, the mass of high AOD is observed directly over Houston, TX, with very high AOD readings on either side of the city.

The second type of chart (Figure 4) plots MODIS Terra AOD data versus distance/time along the back trajectory. The sections corresponding with the first eight hour of the morning were highlighted in the Terra images, and the sections corresponding with the last 16 hr of the day were highlighted in the Aqua images. Dotted lines mark the break in the MODIS day. State boundaries are also marked. The combination of these two types of charts indicates the location on the back trajectory where the pollutants were detected by the satellite. Figure 4 shows the values of AOD along the four back trajectories leading up to the event in Houston, TX. As would be expected from the spatial plots of AOD, there is no clear buildup of pollutants in any of the four panels of the figure. The air packets along the back trajectory seem to have stayed in the mass of high AOD values for the entire duration, indicating transport from the Midwest at least three days before arriving in Houston.

**Figure 4.** AOD values by hour for the four back trajectories leading up to a PM$_{2.5}$ event in Houston, TX. Solid lines are state boundaries; dashed lines indicate satellite dataset boundaries.
Other Case Studies
The other events reviewed are summarized in Figure 5. The images for the event in Charlotte, NC, show the source location as northern Ohio and Indiana. In the spatial AOD images, a buildup of larger AOD values can be seen over northern Ohio and Indiana on July 13, and the following days show the buildup (with possible addition of pollutants in Virginia) being swept southward toward Charlotte. The figures showing the level of AOD along the back trajectories add credibility to the assessment. They show that the AOD values increased most dramatically over Ohio. The events in Philadelphia and Birmingham indicate that pollutants increased over 48 hr before their arrival, likely indicating a combination of transport and local pollutants. The plot for the Chicago event combined with an analysis of the AOD plots indicated a large stationary regional haze event. The region during that time was strongly influenced by massive smoke plumes from the north and west (see Figure 6). A low pressure system retained the smoke over the Midwest resulting in sporadic levels of AOD over the 72 hr study period, with peaks likely arising from high-altitude smoke mixing down to the boundary layer.

CONCLUSIONS
This integrated satellite data analysis is a promising technique for determining the source regions for particulate matter sources, enhancing back trajectory models. Understanding of the sources and transport of air pollution can be improved using satellite data combined with other data sources and models, both in general and to analyze specific events. For example, smoke from a major wildfire in Canada or Mexico could result in concentrations well above PM2.5 standards. Determining whether this occurred and what regions may have been impacted could be clearly and rapidly documented using these visualization techniques. Because MODIS AOD data cover broad geospatial areas, the addition of that data can help indicate where along the trajectory the pollutants may have been added to the atmosphere. This technique could also be a real-time forecasting tool through the use of real-time hourly PM2.5 data and a combination of back and forward trajectories.

The technique could be improved generally through the addition or use of other datasets. For example, because MODIS data is only available at most twice per day, data discontinuities can occur in the plots caused by the temporal gap between datasets. When continuous monitors, such as Geostationary Operational Environmental Satellite and its successors, begin to produce more validated AOD data, they could be used to provide a more continuous data set. Another improvement could be the addition of point and nonpoint sources (such as major urban areas) to the geospatial plots to understand the location of potential particulate sources. The addition of these emissions data could increase our understanding of the conversion of SO2 emissions to sulfate-dominated particulate matter, refining the determination of source location. All of these improvements would improve the ability of this method to provide more quantitative information on the sources.

Figure 5. AOD values by hour for representative back trajectories leading up to a PM2.5 events in Charlotte, NC; Philadelphia, PA; Birmingham, AL; and Chicago, IL. Solid lines are state boundaries; dashed lines indicate satellite dataset boundaries.
transport, and source location of fine particulates during pollution events.

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