IMPROVING NATIONAL AIR QUALITY FORECASTS WITH SATELLITE AEROSOL OBSERVATIONS

BY JASSIM AL-SAADI, JAMES SZYKMAN,* R. BRADLEY PIERCE, CHIEKO KITTAKA, DOREEN NEIL, D. ALLEN CHU, LORRAINE REMER, LIAM GUMLEY, ELAINE PRINS,+ LEWIS WEINSTOCK, CLINTON MACDONALD, RICHARD WAYLAND, FRED DIMMICK, AND JACK FISHMAN

Satellite aerosol observations—which are particularly helpful in tracking long-range transport aloft—can overcome some of the limitations of surface monitoring networks and enhance daily air quality forecasts associated with particle pollution.

Public awareness of local air quality is growing rapidly. Air quality is often considered like the weather—it changes, and some days are better than others. While poor air quality impairs visibility and can damage vegetation and structures, most importantly it can cause serious health problems, including respiratory difficulties and even premature death. Accurate air quality forecasts can offer significant societal and economic benefits by enabling advance planning. Individuals can adjust their outdoor activities to minimize the adverse health impacts of poor air quality. The severity of local pollution episodes may even be reduced by allowing early implementation of mitigation procedures commonly referred to as "action days." Yet air quality forecasting is quite complex. While pollution episodes are typically associated with local meteorological conditions and nearby emissions, it is increasingly recognized

AFFILIATIONS: AL-SAADI, PIERCE, NEIL, AND FISHMAN—NASA Langley Research Center, Hampton, Virginia; SZYKMAN—Office of Research and Development, U.S. EPA, Research Triangle Park, North Carolina; KITTAKA—SAIC, Hampton, Virginia; CHU—Joint Center for Earth Science Technology, University of Maryland, Baltimore County, Baltimore, Maryland; REMER—NASA Goddard Space Flight Center, Greenbelt, Maryland; GUMLEY—SSEC/CIMSS, University of Wisconsin—Madison, Madison, Wisconsin; PRINS—NOAA/NESDIS/ORA, University of Wisconsin—Madison, Madison, Wisconsin; WEINSTOCK, WAYLAND, AND DIMMICK—Office of Air Quality Planning and Standards, U.S. EPA, Research Triangle Park, North Carolina; MACDONALD—Sonoma Technology, Inc., Petaluma, California

***CURRENT ASSIGNMENT**: NASA Langley Research Center, Hampton, Virginia

+**CURRENT AFFILIATION**: SSEC/CIMSS, University of Wisconsin—Madison, Madison, Wisconsin

CORRESPONDING AUTHOR: Jassim Al-Saadi, MS 401B, NASA Langley Research Center, Hampton, VA 23681
E-mail: j.a.al-saadi@nasa.gov

DOI:10.1175/BAMS-86-9-1249

In final form 18 March 2005

that long-range transport of nonlocal pollutants is often a factor (NARSTO 2003). So in addition to all the difficulties inherent in weather forecasting, local air quality forecasting also requires knowledge of pollutant concentrations and emissions at both surrounding and distant locations and the ability to predict the movement, transformation, and in situ production of the many constituents comprising pollution.

National air quality forecasts for major U.S. metropolitan areas have been provided to the public through a partnership between the U.S. Environmental Protection Agency (EPA) and state, local, and tribal agencies since 1997. These forecasts have considered air quality associated primarily with ground-level ozone, but in October 2003 forecasts of air quality due to particulate matter were started. Forecasters rely on a variety of information sources and tools to conduct these forecasts, including empirical and statistical models and, increasingly, numerical forecast guidance (e.g., McHenry et al. 2004; Vaughan et al. 2004). But, as with weather forecasting, knowledge of recent and current conditions is fundamental to accurate forecasts. The most direct way to obtain such constituent information is from the pollutant measurements routinely made at surface monitoring stations across the country. However, large regions of the United States are devoid of surface monitors, and coastal regions are often influenced by polluted air approaching over water. Pollution layers and plumes may also be transported aloft over long distances, undetected by surface monitors, and then descend to influence air at the ground.

Observations made from satellites can help address these limitations by augmenting the surface network. Just as space-based imagery of clouds and water vapor allows weather patterns to be identified and monitored, satellite sensors capable of detecting trace constituents can show the "chemical weather" over the globe (Fig. 1). The potential benefit of such observations for air quality forecasting is comparable to the revolution experienced by weather forecasters with the advent of operational weather satellites decades ago. Remote sensing of trace gases and aerosols[1] from space has matured rapidly over the past few years and current instruments aboard National Aeronautics and Space Administration (NASA) and European Space Agency satellites can provide derived measurements of trace gases and aerosols relating directly to most of the EPA's criteria pollutants (Burrows 1999; King et al. 1999; Fishman 2000). The retrieval of these derived measurements is now transitioning from scientific research and development to the routine near-real-time status required for use in operational forecasting.

During September 2003, a team of NASA, National Oceanic and Atmospheric Administration (NOAA), and EPA researchers demonstrated a prototype for using satellite constituent observations in daily air quality forecasts known as IDEA (see sidebar below). Aerosol observations from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor aboard the NASA Earth Observing System (EOS) *Terra* satellite were combined with other near-real-time datasets, including hourly surface measurements and half-hourly wildfire locations, to improve forecaster knowledge of the continental-scale distribution and transport of particulate matter across North America. Data products were provided through a Web interface for use and evaluation by a group of forecasters working for the EPA and state and local air quality management agencies. Based on the positive response from air quality managers and forecasters, this prototype has been expanded and transitioned to the University of Wisconsin—Madison (UW)/NOAA/NASA Cooperative Institute for Meteorological Satellite Studies (CIMSS) at the UW Space Science and Engineering Center (SSEC) for operational use.

FINE PARTICULATE MATTER AIR QUALITY AND FORECASTING.

Airborne particulate matter (PM) is one of the major air pollutants that the EPA is responsible for monitoring as mandated by the Clean Air Act. Some particles are emitted directly, from both human activities and natural events, while others are formed in the atmosphere from other pollutants. Airborne particles exist in a wide range of sizes, and those less than 10 μm in diameter

ABOUT IDEA

Infusing satellite data into environmental applications (IDEA) is a partnership between NASA, EPA, and NOAA in an effort to improve air quality assessment, management, and prediction by infusing satellite measurements (from NASA) into analyses (by EPA and NOAA) for public benefit. IDEA is a part of the NASA Applied Sciences Program strategy to demonstrate practical uses of NASA-sponsored observations from space and predictions from scientific research.

---

[1] Aerosol refers to solid and liquid particles suspended in the air, or airborne particulate matter.

are so small that they can penetrate deep into the lungs, potentially causing serious health problems. Particles smaller than about 2.5 μm in diameter are collectively known as fine particles or $PM_{2.5}$. They are found in smoke and haze, and generally result from combustion, including motor vehicles, power plants, residential wood burning, forest fires, and agricultural burning. Particles between 2.5 and 10 μm in diameter are referred to as coarse. Sources of coarse particles include wind-blown dust from exposed soil and unpaved roads, evaporation of sea spray, and mechanical activities such as demolition, crushing, and grinding.

While particulate matter has been regulated since the 1970 passage of the Clean Air Act, in recent years it has become clear that fine particles pose the most serious health risks (e.g., Schwartz and Neas 2000), leading to the enactment of specific $PM_{2.5}$ regulations in 1997. Elevated $PM_{2.5}$ levels have been linked to decreases in lung function and to increased hospitalization due to exacerbation of respiratory or cardiovascular diseases (EPA 1996; Pekkanen et al. 1997; Linn et al. 2000; Samet et al. 2000; Peters et al. 2001). Long-term exposure to $PM_{2.5}$ has been associated with premature death from cardiopulmonary causes and cancer (Krewski et al. 2000; Pope et al. 2002).

The EPA provides real-time air quality information to the public through the AIRNow Web site (available online at www.epa.gov/airnow). Air quality is reported in terms of an air quality index (AQI; EPA 1999), a color-coded scale in which health advisories are associated with different pollutant levels. For example, an AQI value for $PM_{2.5}$ (Table 1) between 101 and 150 (orange) means that the quality of the air is unhealthy for sensitive groups. Because of the importance of accurate forecasts for minimizing the impacts of poor air quality, the role of AIRNow has been expanded from monitoring to include air quality forecasts. Current- and next-day $PM_{2.5}$ air quality forecasts for over 140 cities were added to AIRNow beginning on 1 October 2003, and currently over 200 cities provide these forecasts on a daily basis. However, particulate forecasting is a relatively new and complex science. Sources of PM are spatially and physically diverse, transformations occur (primarily in the presence of sunlight and moisture), and particles may be removed from the air by precipitation and settling. In addition to nearby particulate measurements, forecasters rely on statistical tools relating air quality conditions to important weather features in order to estimate future $PM_{2.5}$ concentrations based on forecasted weather conditions (EPA 2003). The

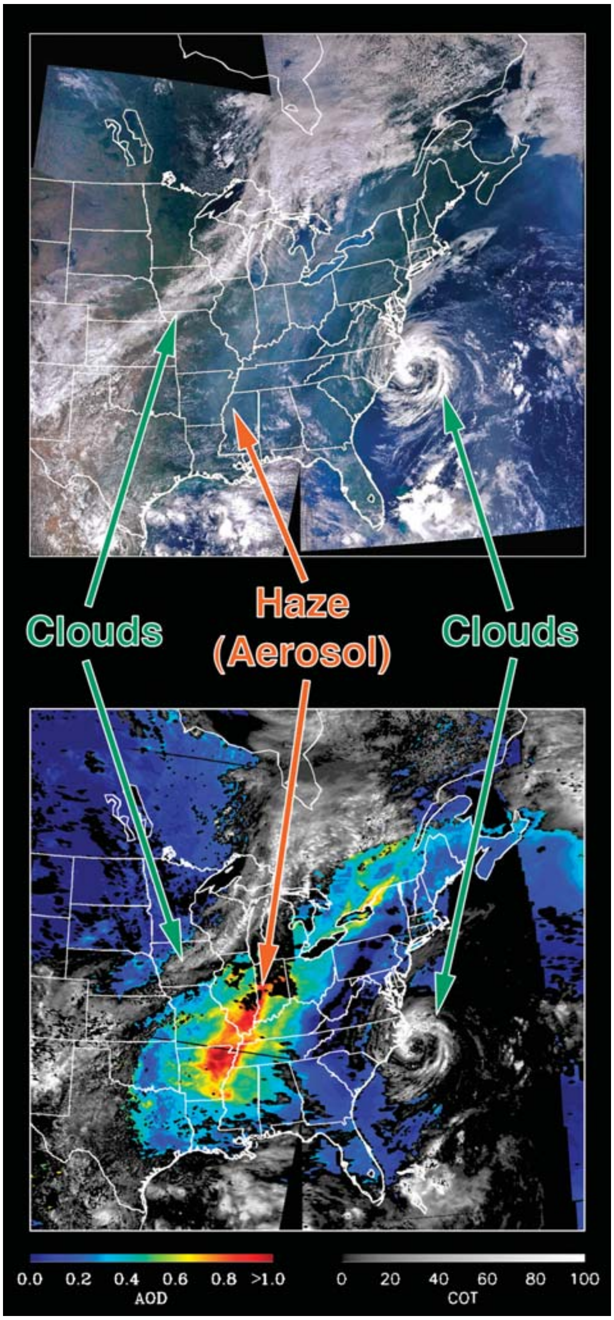

Fig. 1. Observations from the MODIS instrument provide both visible imagery showing familiar weather patterns, and derived measurements such as aerosol optical depth (AOD) and cloud optical thickness (COT). Optical depth and optical thickness (the terms are interchangeable) give integrated measures of the overall amount of light-absorbing particles throughout the depth of the atmosphere. Visualization of these derived measurements can show the distribution of pollutants, or chemical weather. (MODIS observations from NASA EOS *Terra* satellite, 10 Sept 2002.)

Table 1. The U.S. EPA Air Quality Index for Particulate Matter.

Index Values	Category	Cautionary Statements	$PM_{2.5}$ ($\mu g\ m^{-3}$)	PM_{10} ($\mu g\ m^{-3}$)
0–50	Good	None	0–15.4	0–54
51–100	Moderate	Unusually sensitive people should consider reducing prolonged or heavy exertion	15.5–40.4	55–154
101–150	Unhealthy for sensitive groups	Sensitive groups should reduce prolonged or heavy exertion	40.5–65.4	155–254
151–200	Unhealthy	Sensitive groups should avoid prolonged or heavy exertion; everyone else should reduce prolonged or heavy exertion	65.5–150.4	255–354
201–300	Very unhealthy	Sensitive groups should avoid all physical activity outdoors; everyone else should avoid prolonged or heavy exertion	150.5–250.4	355–424

Source: US EPA, 1997

prototype satellite data forecast tool described in this article was designed to greatly expand the amount of observationally based data available to forecasters to improve their understanding of developing pollution events.

AEROSOL REMOTE SENSING. Satellite remote sensing has been used to detect aerosol since the late 1970s [a historical overview is given by King et al. (1999)]. Several sensors are presently capable of making tropospheric aerosol measurements. The Total Ozone Mapping Spectrometer (TOMS) provides daily information on absorbing aerosols over land and ocean via a derived aerosol index (available online at http://toms.gsfc.nasa.gov/aerosols/aerosols_v8.html). The TOMS aerosol index has been used to track large-scale aerosol events across the globe, but low sensitivity to aerosols near the ground limits its use for air quality monitoring. The Multi-angle Imaging SpectroRadiometer (MISR) provides very detailed aerosol information by viewing the Earth in multiple wavelengths and directions (available online at www-misr.jpl.nasa.gov/). However, most locations are viewed only once every 9 days, making these measurements impractical for use in daily forecasting.

The MODIS sensors were designed to systematically retrieve aerosol properties over both land and ocean on a daily basis (Kaufman et al. 1997; Tanré et al. 1997). The MODIS data from the *Terra* satellite provide a daily late-morning view of aerosol and cloud distributions over most of the globe. *Terra* orbits cross the equator at 1030 local time and MODIS is able to observe most of the continental United States within three successive orbits, proceeding from east to west over about 3.5 h.[2] Validation efforts have demonstrated the accuracy and caveats of the aerosol retrievals (Chu et al. 2002; Remer et al. 2002). Because it is difficult to distinguish aerosol from highly reflective surfaces, MODIS AOD cannot be retrieved (or has more uncertainty) in certain situations: where it is cloudy, where there is strong sun glint from bodies of water, and over snow/ice and bright desert areas. MODIS aerosol data have been compared with measurements made at the Earth's surface and shown to be suitable for monitoring air quality events over local, regional, and global scales (Chu et al. 2003; Wang and Christopher 2003; Hutchison 2003; Engel-Cox et al. 2004).

MODIS has a direct-broadcast capability to continuously transmit data to ground stations within line-of-sight of the satellite, offering near-real-time data availability. This rapid data access, combined

OPERATIONAL WEBSITE

The aerosol data and forecast products described here have been available on a daily basis since May 2004 from http://idea.ssec.wisc.edu/. In this operational configuration, SSEC/CIMSS generates the forecast products and hosts the Web site. MODIS data are also acquired through the direct broadcast capability at SSEC/CIMSS and processed at CIMSS to derive AOD and COT.

---

[2] A second MODIS instrument, launched on board the *Aqua* satellite in 2002, provides another set of measurements about 3 h later (equator crossing at 0130 local time). IDEA presently uses only the MODIS *Terra* measurements because of their earlier availability for use by forecasters.

with its relatively fine spatial resolution, daily coverage, well-characterized accuracy, and ability to detect aerosol throughout the troposphere, made MODIS an obvious choice for this application.

SEPTEMBER 2003 DEMONSTRATION.

Goals of the IDEA project were to provide MODIS aerosol information to forecasters quickly enough to be useful in the forecast cycle and to provide the needed context by combining it with other relevant data having higher temporal resolution. Such data included $PM_{2.5}$ concentration at the surface, assimilated and forecasted winds, satellite-derived wildfire locations, and air parcel trajectories. The overall data flow for this prototype is shown in Fig. 2. Five different daily aerosol forecast products were generated from a near-real-time fusion of these input data products (Szykman et al. 2004). The current configuration of IDEA is described in the sidebar titled, "Operational Website."

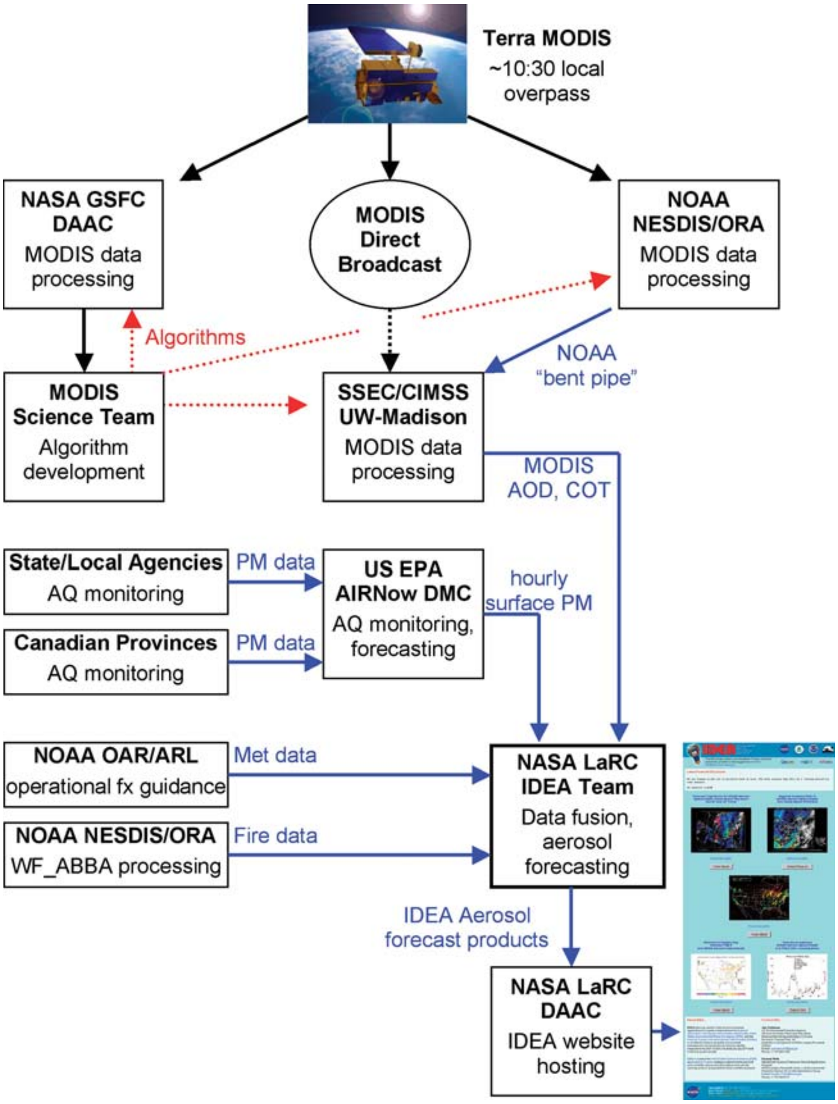

FIG. 2. Data sources and flow for development of forecast products. Effective coordination among different agencies and organizations captured both space and surface observations of aerosol and delivered compact visualizations to assist forecasters. MODIS near-real-time AOD and COT data were obtained from the NOAA/National Environmental Satellite, Data and Information Services (NESDIS) "bent pipe" link at SSEC/CIMSS. Hourly in situ $PM_{2.5}$ mass concentration data, acquired from over 300 continuous monitoring sites operated by state and local air monitoring stations, national ambient monitoring stations, and Canadian provinces, were obtained from the EPA through the AIRNow data management center (DMC). Meteorological data from the NOAA/NCEP Eta Model at 3-h intervals were obtained from NOAA/Oceanic and Atmospheric Research (OAR)/Air Resources Lab (ARL) (assimilated data) and NOAA/NCEP (forecast data). Half-hourly fire burn locations, generated by the WildFire Automated Biomass Burning Algorithm (WF_ABBA) (Prins et al. 2003) from Geostationary Operational Environmental Satellite-12 (*GOES-12*) satellite observations, were provided by NOAA/NESDIS/Office of Research and Applications (ORA) through CIMSS. Daily aerosol forecast products were generated by the IDEA team at the NASA Langley Research Center and uploaded to the IDEA Web site, hosted by the NASA Langley Distributed Active Archive Center (DAAC).

Regional view from space. The first aerosol forecast product consists of regional views of MODIS aerosol and cloud observations, along with the locations of continuous $PM_{2.5}$ monitors. These maps are uploaded to the Web site as soon as new MODIS data from an orbit crossing the United States are available. Map domains correspond to EPA regions with regions 1–3 (northeastern United States) combined into one map and regions 4–10 shown as individual maps. Figure 3 shows an example of this product for region 10, the Pacific Northwest. On this day, heavy aerosol loading is evident through much of the U.S.–Canadian border region. Clouds show synoptic weather features important to the movement of aerosols. Because AOD is not derived over cloudy regions, COT also shows areas where aerosol information is masked by clouds. White circles show the location of each continuous $PM_{2.5}$ monitor, familiar to air quality forecasters within each region.

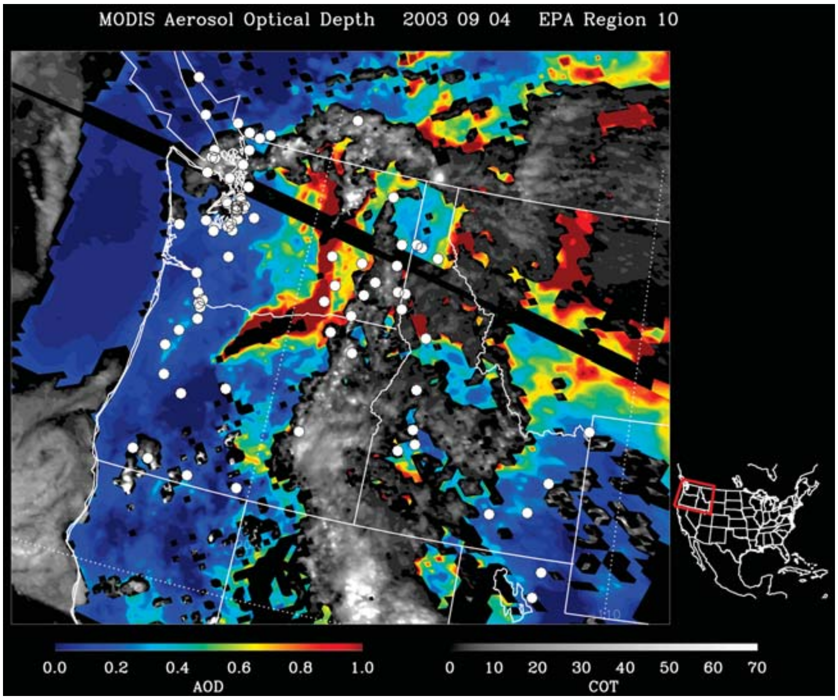

Fig. 3. Regional summary plots provide aerosol and cloud information soon after the satellite overpass. The AOD, MODIS MOD04_L2 product at a horizontal resolution of 10 km × 10 km, is shown on a color scale of 0.0 to 1.0 with blues indicating clean air and reds indicating large amounts of aerosol. The COT, MODIS MOD06_L2 product at a horizontal resolution of 1 km × 1 km (degraded to 5 km × 5 km for display), is shown on a grayscale with brighter whites indicating more cloud coverage. Surface monitor locations (white circles) are shown to orient local forecasters.

Data fusion animation. The second product is a 3-day composite animation of all input data products. The animation shows the simultaneous variation of AOD, COT, surface $PM_{2.5}$, fire locations, and 850-mb winds (Fig. 4). These composite visualizations offered unprecedented insight to air quality forecasters and air management agencies. The

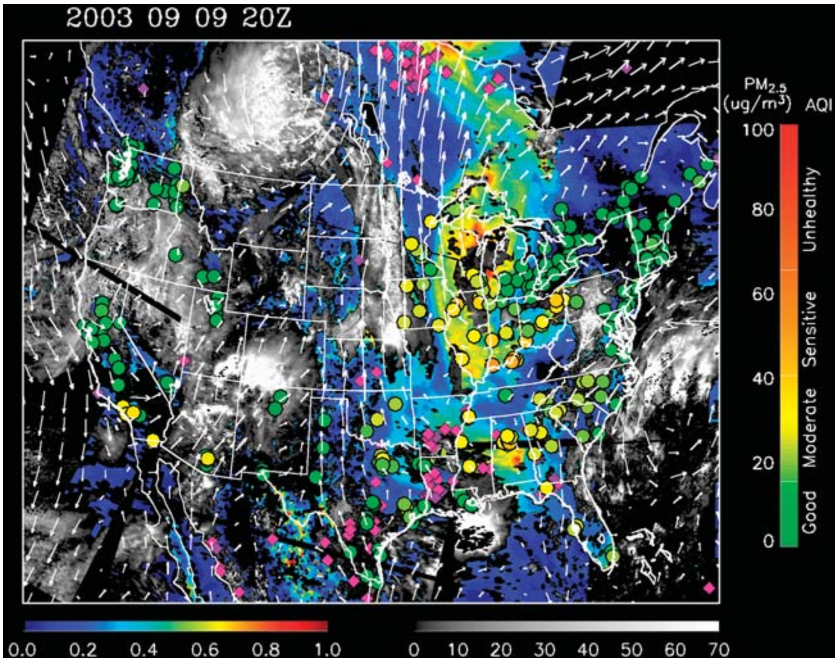

Fig. 4. A single frame extracted from a 3-day composite animation of all input data products. The animation shows aerosol movement in the context of weather systems, surface air quality, and emissions from active fires. MODIS data are displayed as in Fig. 3. The location of each continuous $PM_{2.5}$ monitor is shown as a circle color-coded by the hourly concentration [scale on the right, with associated AQI levels (Table 1) shown for reference]. Fire locations as identified by the half-hourly WF_ABBA product are shown as diamonds color-coded according to the fire probability: bright pink for higher probability fires and violet for lower probability. The 850-mb wind direction and speed from the NCEP Eta Model are shown as white vectors; 850-mb winds can be used to infer horizontal transport of aerosol near the surface and are often used to qualitatively identify areas of convergence and divergence indicative of vertical air motion.

animations provide a nearly synoptic view of aerosol events across North America over the previous 72 h. It is clearly seen that aerosol pollution events occur on a range of scales form urban to national, that there is often a close qualitative agreement between the integrated measure of aerosol observed from space and local $PM_{2.5}$ at the surface, and that real-time indicators of relevant emissions can give early warning of pollution events. Large-scale aerosol events evolve in concert with weather systems, as shown by changes in the winds and clouds. Regional-scale events are also apparent, such as the high AOD values observed over the southeastern United States during this time that are associated with persistent fire activity in the region.

Some of the limitations of AOD for inferring air quality are also evident in Fig. 4. There are expected AOD gaps in cloudy regions and where there is strong sun glint off the ocean (seen near south Florida). Gaps also exist in locations where it is difficult to distinguish between very large AOD values and thin clouds (central Wisconsin) and where the AOD values appear to be very small (New York). Sometimes there is no apparent correspondence between AOD and surface $PM_{2.5}$. An example is seen here between Lakes Superior and Michigan (Sault Ste. Marie, Michigan), where the AOD is moderately large (about 0.5–0.6), but the surface $PM_{2.5}$ concentration is very low. This condition usually indicates that MODIS is observing aerosol that is aloft, above the boundary layer, and therefore is not influencing surface air quality.

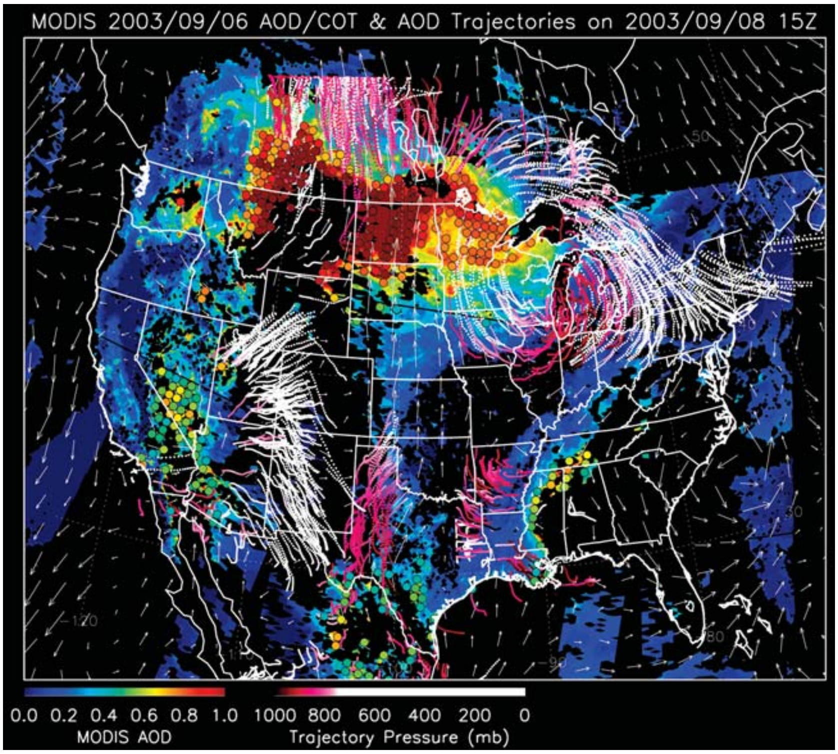

Fig. 5. A single frame extracted from a 48-h trajectory forecast animation of high aerosol loading. Trajectory calculations provide a basis for forecasting aerosol transport. The background of the animation shows the MODIS AOD and COT observations for the first day as well as the trajectory initial locations, shown as circles colored according to the AOD scale. Trajectories are initialized where mean AOD values (averaged over 50 km × 50 km areas) exceed a predetermined threshold value. Trajectory positions are calculated using forecast winds from the NCEP Eta Model. The trajectory motions and forecast wind vectors are shown evolving over this background during the 48-h forecast period. Each frame of the animation displays trajectory positions during the most recent 12 h, color-coded in red shades and white according to the altitude (pressure). Red colors are limited to pressure values greater than 800 mb, to help distinguish trajectories moving within the boundary layer, and white indicates higher altitudes.

Aerosol trajectory forecast. The third product was designed to offer guidance for identifying potential episodes of poor air quality by showing the expected horizontal and vertical movement of boundary layer aerosol over the next 48 h. The product consists of an animation showing the motions of forecast air parcel trajectories that have been initialized near the surface in locations where MODIS observes high AOD. A single frame from one of these animations is shown in Fig. 5. A subtlety of this approach is that the AOD, being an integrated quantity, cannot identify the vertical location of aerosol. Because we are most concerned with air quality at the ground, at each starting location we initialize a trajectory at each of 4 50-mbar increments above the surface (e.g., 950, 900, 850, and 800 mbar). Therefore, this product specifically shows the forecasted motion of air that is initially near the ground and that may be associated with significant aerosol. As the forecast trajectories progress in time, trajectories darkening in color (evolving from white and pink toward darker reds) indicate descent of air toward the surface and a potential worsening of air quality at the ground. Conversely, lightening trajectories (evolving from darker reds toward white) indicate that upward motion may be lofting aerosol away from the ground, suggesting that the aerosol observed by MODIS will not influence air quality.

View from space compared with local measurements. The final two forecast products are used to help assess where the satellite observations provide useful information about particulate matter characteristics at the ground. AOD has no relation to surface $PM_{2.5}$ when aerosol is entirely aloft, but has some relation when there is aerosol near the surface, even if other aerosol layers also exist at higher altitudes. The simplest measure of such a correspondence is given by the linear correlation between AOD and $PM_{2.5}$ concentration.[3] If the two measures are well correlated it suggests that the satellite observations can be used to predict changes in surface $PM_{2.5}$. The minimum requirement for a good correlation is that much of the aerosol observed by the satellite is uniformly mixed near the surface (i.e., within the boundary layer). Even so, the actual relation between AOD and $PM_{2.5}$ can vary because of changes in humidity and aerosol composition, meaning that different relationships may hold for different regions and seasons.

The fourth product consists of individual time series plots, one for each site reporting to AIRNow, of surface $PM_{2.5}$ concentration and those MODIS AOD observations made over the site. These plots give forecasters detailed information about particulate matter trends in their vicinity. An example is shown in Fig. 6 for August and September 2003 at a monitoring site to the west of Chicago, Illinois. According to the surface observations, the air quality at this site fluctuates between good and moderate during most of this period, but there is an episode of poor air quality between the 10th and 14th of September. The MODIS observations show similar behavior throughout the period, and generally track the fluctuations of the surface measurements quite well. High AOD, about 0.8, is observed on 10 September during the episode of poor air quality. Even higher AOD is observed 2 days earlier, but the surface values do not show a similar increase, suggesting that MODIS observed an aerosol layer that was not located near the surface. AOD measurements are not available over this site during the rest of the episode, mainly because of cloudiness. The correlation between AOD

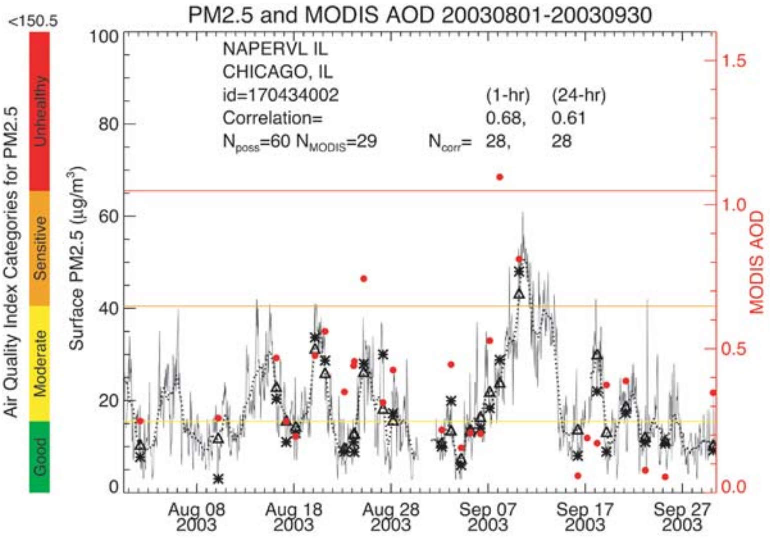

FIG. 6. Time series of surface $PM_{2.5}$ concentration (black lines, left axis) and MODIS AOD measurements (red circles, right axis) for an individual site. This information is provided for over 350 locations. Both 1-h (solid line) and running 24-h mean (dashed line) $PM_{2.5}$ values are shown. The 24-h values are included because the AQI is based on them, and AQI categories are shown for reference; $PM_{2.5}$ measurements made at the same time as the MODIS observations are indicated by black symbols: asterisks for 1-h values and triangles for 24-h values. Linear correlation coefficients between AOD and the coincident $PM_{2.5}$ measurements are shown (see discussion in text). Other printed information gives details about the measurement characteristics during this period: N_{poss} is the number of satellite overpasses (typically 1 day^{-1}), N_{MODIS} is the number of valid AOD retrievals, and N_{corr} is the number of time-coincident AIRNow and MODIS measurements; N_{MODIS} is usually smaller than N_{poss} because of clouds; N_{corr} is smaller than N_{MODIS} if $PM_{2.5}$ measurements are not obtained at the time of a satellite overpass. The proportionality between the vertical axes for $PM_{2.5}$ and AOD was derived (as the slope of a linear regression between AOD and $PM_{2.5}$) using data over the eastern U.S. during summer and is used at all sites for consistency. Wang and Christopher (2003) show a similar relation using one year of data over the southeastern United States.

---

[3] The numerical correlation is determined by comparing AOD and $PM_{2.5}$ measurements made at the same time. The linear correlation coefficient can have values between 1.0 (perfectly correlated: the measurements rise and fall in unison) and –1.0 (perfectly anticorrelated: one measurement rises as the other falls). A value of 0.0 indicates that the measurements are independent of each other.

and 1-h $PM_{2.5}$ is 0.68 at this site during this period, meaning that the MODIS observations can explain about 46% (the square of the correlation) of the variation in surface $PM_{2.5}$. The correlation is diminished by deviations such as the high AOD on 8 September that is not associated with a similarly strong increase in $PM_{2.5}$.

National correlation summary. The final forecast product consists of a national summary map displaying the correlation between AOD and hourly surface $PM_{2.5}$ at all AIRNow sites (Fig. 7). This map provides a quick overview of where the satellite observations can provide significant information for air quality forecasting.

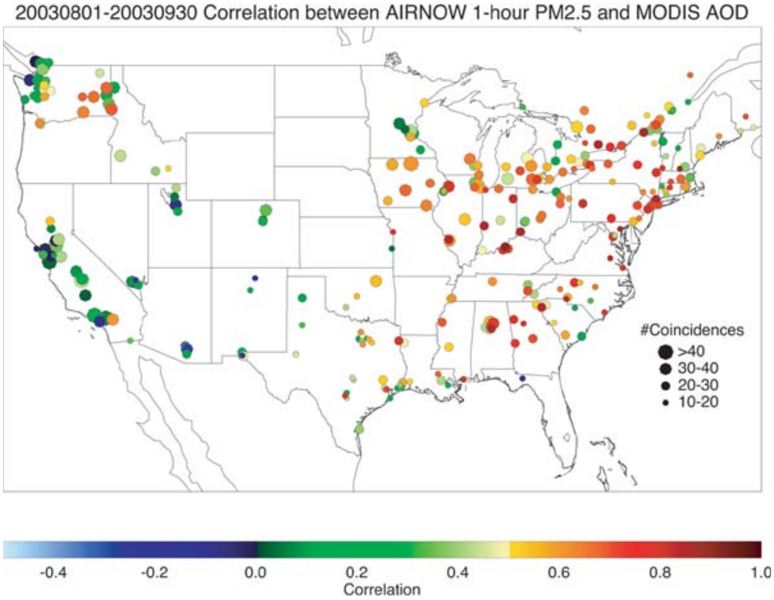

Fig. 7. National summary of the correlation between MODIS AOD and surface $PM_{2.5}$ concentration for late summer. A circle color-coded by the correlation value is shown for each AIRNow site and the size of the circle indicates the number of coincident observations available for determining the correlation. Because the significance of the correlation generally increases with increasing number of coincidences, observations from the preceding 60 days are used to determine correlations. Higher correlations exist in the eastern United States and in locations experiencing episodic pollution events such as result from large wildfires.

Figure 7 shows that correlations are generally quite good (greater than 0.6) in the eastern half of the United States during this late-summer period. The correlation is poor over most of the western United States although good correlations are found in specific areas, such as eastern Washington. Interpretation of these broad patterns is aided by analysis of the individual time series plots.

September was selected for this demonstration because it is typically near the end of the summer wildfire season in North America and fires are one major source of fine particles. We have found that the highest correlations are often associated with sites where the air quality is generally good, yet one or more significant episodes of poor air quality are experienced during the period. This is true of the site shown in Fig. 6, where a large episode occurs in early September and several smaller episodes occur during August. The eastern Washington sites exhibiting good correlations also show this characteristic and episodes of poor air quality and high AOD at these sites can be associated with smoke from wildfires in the region. Nearby sites where the correlation is not as good also experience very high AOD values (even greater than 1.6) but no corresponding change in $PM_{2.5}$. At these locations MODIS is probably detecting smoke plumes that do not influence the ground because they have been lofted to high altitudes.

Low correlations tend to exist in relatively clean areas experiencing little variability in PM levels, such as the Olympic Peninsula and Puget Sound area of Washington and much of the desert Southwest. Low correlations can also occur in areas with generally poor air quality, such as the Los Angeles, California, area. Here, changes in $PM_{2.5}$ are dominated by large hourly and daily variability of very local emission sources rather than by larger-scale episodic events. Where correlations are low, the IDEA products have limited use under typical conditions, but are still quite valuable for providing early notice of exceptional events related to long-range transport.

CASE STUDY. The usefulness of these tools can be illustrated with an example from September 2003. Early in the month, several very large wildfires were burning in western North America from British Columbia to Oregon. The AOD observations in Fig. 3 show a large region of enhanced aerosol near the U.S.–Canadian border on 4 September, and an individual smoke plume is seen emanating from a fire in northern Oregon. The aerosol trajectory forecast initialized from MODIS observations on 6 September (Fig. 5) indicates that by 8 September, aerosol associated with these fires should be approaching the Great Lakes region. Rapid aerosol movement to the northeast, into central Canada, is also shown. On 9 September (Fig. 4), several surface stations to the south of the Great Lakes reported poor air quality. The AOD observations on this day are consistent with the earlier trajectory forecast, showing aerosol enhancements in the central United States and north-central Canada. This poor air quality episode is apparent in $PM_{2.5}$ measurements to the west of Chicago between the 10th and 14th of September (Fig. 6). Further analysis has shown that this particular episode in the Midwest probably resulted from a complex combination of locally produced pollution and long-range transport of smoke particles (Kittaka et al. 2004; Strohm et al. 2004). The contribution from the fires would not have been detectable without the satellite aerosol observations and the context provided by the IDEA forecast products.

CONCLUSIONS. The IDEA air quality demonstration achieved its primary objective of prototyping a new forecast guidance tool, based on observations from space, to improve daily particle pollution forecasts during the month of September 2003. The group of forecasters who participated indicated that they used the IDEA products and found them valuable in their daily forecasts, although at present it is difficult to quantify any improvement in forecast skill (see sidebar on forecaster's perspective). Perhaps equally important, the forecasters and partners identified multiple uses for the forecast products and underlying data that were not envisioned in the planning stage. Additional uses identified by the forecasters included tracking of natural aerosol events (fires and dust storms) and associated impacts as related to EPA's regional haze regulations, retrospective analysis assessing regional and long-range transport impacts on $PM_{2.5}$ as related to EPA's National Ambient Air Quality Standard, and performance evaluation of atmospheric chemical transport models. In addition to the use for daily air quality forecasting, the operational hosting of these products at CIMSS is resulting in a growing archive of these combined datasets appropriate for these and other applications.

Several ongoing developments and new sensors will improve the utility of space-based aerosol measurements for air quality forecasting. Knowledge of aerosol altitude would significantly improve the value of AOD measurements, and current research is exploring whether additional information from the MODIS sensors can be used to provide an aerosol height estimate. Instrumentation on the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite (available online at www-calipso.larc.nasa.gov/), scheduled for launch in 2005, will provide detailed information on aerosol vertical distribution that can be used to improve such estimates. The Ozone Monitoring Instrument (OMI) launched on the Aura Spacecraft in July 2004 will be able to distinguish between smoke, mineral dust, and other aerosols with a horizontal resolution about four times better than TOMS (Torres et al. 2002). The Visible Infrared Imaging Radiometer Suite (VIIRS) is a next generation sensor under the National Polar-orbiting Operational Environmental Satellite System (NPOESS) program that will provide aerosol measurements similar to MODIS (Vermote et al. 2002). In addition to the daily global measurements offered by these polar-orbiting satellites, significant promise for improved forecasting is offered by the continuous observations available from geostationary satellites. Sensors aboard the current Geostationary Operational Environmental Satellite (GOES) platforms are being used to provide a developmental aerosol product known as the GOES Aerosol/Smoke Product (GASP; Knapp 2002). The GASP product offers national coverage every 30 minutes (available online at www.orbit.nesdis.noaa.gov/smcd/emb/GASP/RealTime.html), but is not as well characterized as MODIS AOD because these sensors were not designed for measuring aerosol. The Advanced Baseline Imager (ABI), currently being designed for future GOES platforms, will be able to provide an aerosol measurement similar to MODIS but at much higher temporal frequency (Gurka and Dittberner 2001). With such observations, chemical weather forecasts will soon be as common as traditional weather forecasts.

ACKNOWLEDGEMENTS. This work was funded by the NASA Applied Sciences Program with additional support provided through EPA Interagency Agreement DW-80-939419-01-3. The GOES WF_ABBA fire monitoring effort is supported by NOAA Contract 40AANE1A4073 and by NASA's ESE Interdisciplinary Science Program through Navy Subcontract N66001-00-C-0039. The views, opinions, and findings contained in this article are those of the authors and should not be construed as official National Aeronautics and Space Administration, National Oceanic and Atmospheric Administration, U.S. Environmental Protection Agency, or U.S. Government position, policy, or decision.

REFERENCES

Burrows, J. P., 1999: Current and future passive remote sensing techniques used to determine atmospheric

AN AIR QUALITY FORECASTER'S PERSPECTIVE ON IDEA AND FORECAST SKILL.[4]

When I think back to my first experience with the IDEA project, my immediate impression was the ability of the AOD data to fill in the large gaps that existed in the continuous $PM_{2.5}$ surface network. About 300 such monitors were actively reporting data to AIRNow during the fall of 2003—a relatively small number compared with the operational ozone network. One of the greatest challenges for the $PM_{2.5}$ forecaster was determining the characteristics of the inbound air mass that could influence the forecast in the days ahead. While forecasts for ozone could be based, in part, on upwind data from the dense network of ozone monitors, such guidance for $PM_{2.5}$ was often unavailable. Major gaps in spatial coverage existed over the Plains, across the Appalachian Mountains (central Pennsylvania, West Virginia, Virginia, and Kentucky), and in the northwest (Oregon and Idaho). As a result, forecasters often did not have access to any "ground truth" to help them assess the transport component of $PM_{2.5}$ concentrations. Since many programs issue forecasts for several days in advance (particularly over weekends and holidays), this lack of upwind information was particularly troubling.

IDEA addressed this issue in two primary ways: providing AOD information to allow assessment of $PM_{2.5}$ transport potential, and overlaying the forecast Eta Model trajectories to better define where upwind truly was. The combination of Eta Model winds and forecast trajectories was, in itself, a major benefit due to the time savings in packaging both products in one animated graphic. The December 2003 AIRNow strategic planning process identified the need for integrated products to help forecasters save valuable time in meeting tight forecast dissemination deadlines. The IDEA product satisfied that requirement by overlaying many useful displays in one product that was easy to access.

The science of $PM_{2.5}$ forecasting was very new at the time of this demonstration project. Although many cities began operational $PM_{2.5}$ forecasting in 2003, the actual experience level in these programs varied and was often quite limited. Some forecasters were just becoming familiar with available satellite products (visual imagery and derived aerosol measures) while also learning about the availability and interpretation of continuous $PM_{2.5}$ data being derived from the complex array of methodologies operated by state/local/tribal agencies. Because these operational $PM_{2.5}$ forecast procedures were just being developed, no baseline measure of forecast accuracy yet existed. So it is difficult to objectively assess the influence of the IDEA products on forecast skill during this demonstration.

In terms of evaluating forecast accuracy, EPA has coordinated the development of guidance for achieving some consistency in how forecasters assess performance (EPA 2003). Forecasters (weather and air quality) use a variety of products and it is difficult to allocate the contribution of individual tools to forecast success or failure. Given the evolving maturity level of $PM_{2.5}$ forecasting, such assessment probably requires a subjective or expert analysis element (e.g., Ryan et al. 2000). These techniques acknowledge that forecasters must select which inputs are the most valuable in some situations.

The value of an IDEA type of product to a forecaster is effectively nonlinear; it becomes most important in the subset of cases where transport is important, particularly over areas where $PM_{2.5}$ monitor spatial gaps exist. In some $PM_{2.5}$ forecast scenarios, the most likely decision is a relatively easy "good" (green) category because of the high distribution of ambient values toward lower numbers. IDEA has low relative value here because of the excellent ventilation characteristics of these meteorological conditions. At the other extreme, its value in helping predict episodes associated with exceptional events (such as fires, dust storms, and volcanic eruptions) is obvious, but difficult to quantify due to the relative rarity of these events. More commonly, $PM_{2.5}$ episodes involve significant transport following a buildup of locally generated pollutants. In these cases, the IDEA product becomes most valuable when forecasters need it the most—those challenging situations when the $PM_{2.5}$ AQI approaches "unhealthy for sensitive groups" and "unhealthy" categories (orange to red), and a transport component may be important. A product that allows forecasters to provide additional warning of the possibility of these high $PM_{2.5}$ values is of significant public health importance and of major value to the emerging field of air quality forecast meteorology.

---

[4] During this demonstration project Lewis Weinstock was an air quality forecaster with the Forsyth County Environmental Affairs Department, Winston-Salem, North Carolina.

constituents. *Approaches to Scaling of Trace Gas Fluxes in Ecosystems,* A. F. Bouwman, Ed., Elsevier, 317–347.

Chu, D. A., Y. J. Kaufman, C. Ichoku, L. A. Remer, D. Tanre, and B. N. Holben, 2002: Validation of MODIS aerosol optical depth retrieval over land. *Geophys. Res. Lett.,* **29,** 8007, doi:10.1029/2001GL013205.

——, C, G. Zibordi, J. D. Chern, J. Mao, C. Li, and B. N. Holben, 2003: Global monitoring of air pollution over land from the Earth Observing System-Terra Moderate Resolution Imaging Spectroradiometer (MODIS). *J. Geophys. Res.,* **108,** 4661, doi:10.1029/2002JD003179.

Engel-Cox, J. A., C. H. Holloman, B. W. Coutant, and R. M. Hoff, 2004: Qualitative and quantitative evaluation of MODIS satellite sensor data for regional and urban scale air quality. *Atmos. Environ.*, **38,** 2495–2509.

EPA, 1996: Air quality criteria for particulate matter. EPA/600/P-95/001aF-cF, 2404 pp. [Available online at http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=2832.]

——, 1999: Guideline for reporting of daily air quality—air quality index (AQI). EPA-454/R-99-010, 25 pp. [Available online at http://www.epa.gov/ttn/oarpg/t1/memoranda/rg701.pdf.]

——, 2003: Guidelines for developing an air quality (ozone and PM2.5) forecasting program. EPA-456/R-03-002, 125 pp. [Available online at http://www.epa.gov/airnow/aq_forecasting_guidance-1016.pdf.]

Fishman, J., 2000: Observing tropospheric ozone from space. *Prog. Environ. Sci.*, **2,** 275–290.

Gurka, J. J., and G. J. Dittberner, 2001: The next generation GOES instruments: Status and potential impact. Preprints, *Fifth Symp. on Integrated Observing Systems,* Albuquerque, NM, Amer. Meteor. Soc., 237–241.

Hutchison, K. D., 2003: Applications of MODIS satellite data and products for monitoring air quality in the state of Texas. *Atmos. Environ.*, **37,** 2403–2412.

Kaufman, Y. J., D. Tanré, L. A. Remer, E. F. Vermote, D. A. Chu, and B. N. Holben, 1997: Operational remote sensing of tropospheric aerosol over the land from EOS-MODIS. *J. Geophys. Res.*, **102,** 17 051–17 061.

King, M. D., Y. J. Kaufman, D. Tanré, and T. Nakajima, 1999: Remote sensing of tropospheric aerosols from space: Past, present, and future. *Bull. Amer. Meteor. Soc.*, **80,** 2229–2259.

Kittaka, C., and Coauthors, 2004: Utilizing MODIS satellite observations to monitor and analyze fine particulate matter, PM2.5, transport event. *Extended Abstracts, Sixth Conf. on Atmospheric Chemistry,* Seattle, WA, Amer. Meteor. Soc., CD-ROM, P1.3.

Knapp, K. R., 2002: Quantification of aerosol signal in GOES 8 visible imagery over the U.S. *J. Geophys. Res.*, **107,** 4426, doi:10.1029/2001JD002001.

Krewski, D., R. T. Burnett, M. S. Goldberg, K. Hoover, J. Siemiatycki, M. Jerret, M. Abrahamowicz, and W. H. White, 2000: Reanalysis of the Harvard Six Cities Study and the American Cancer Society Study of Particulate Pollution and Mortality. Health Effects Institute Special Rep. of the Particle Epidemiology Reanalysis Project, Cambridge, MA, 97 pp. [Available online at http://www.healtheffects.org/Pubs/Rean-ExecSumm.pdf.]

Linn, W. S., Y. Szlachcic, H. Gong Jr., P. L. Kinney, and K. T. Berhane, 2000: Air pollution and daily hospital admissions in metropolitan Los Angeles. *Environ. Health Perspect.*, **108,** 427–434.

McHenry, J. N., W. F. Ryan, N. L. Seaman, C. J. Coats Jr., J. Padykiewicz, S. Arunachalam, and J. M. Vukovich, 2004: A real-time Eulerian photochemical model forecast system. *Bull. Amer. Meteor. Soc.*, **85,** 525–548.

NARSTO, cited 2003: Particulate matter science for policy makers: A NARSTO assessment. [Available online at www.cgenv.com/Narsto/.]

Pekkanen, J., S. T. Remes, T. Husman, M. Linberg, M. Kajosaari, A. Koivikko, and L. Soininen, 1997: Prevalence of asthma symptoms in video and written questionnaires among children in four regions in Finland. *Eur. Respir. J.*, **10,** 1887–1894.

Peters, A., D. W. Dockery, J. E. Muller, and M. A. Mittleman, 2001: Increased particulate air pollution and the triggering of myocardial infarction. *Circulation,* **102,** 2810–2815.

Pope, C. A., III, R. T. Burnett, M. J. Thun, E. E. Calle, D. Krewski, K. Ito, and G. D. Thurston, 2002: Lung cancer, cardiopulmonary mortality and long-term exposure to fine particulate air pollution. *J. Amer. Med. Assoc.*, **287,** 1132–1141.

Prins, E. M., C. C. Schmidt, J. M. Feltz, J. S. Reid, D. L. Wesphal, and K. Richardson, 2003: A two-year analysis of fire activity in the Western Hemisphere as observed with the GOES Wildfire Automated Biomass Burning Algorithm. Preprints, *12th Conf. on Satellite Meteorology and Oceanography,* Long Beach, CA, Amer. Meteor. Soc., CD-ROM, P2.28.

Remer, L. A., and Coauthors, 2002: Validation of MODIS aerosol retrieval over ocean. *Geophys. Res. Lett.*, **29,** 8008, doi:10.1029/2001GL013204.

Ryan, W. F., C. Piety, and E. Luebehusen, 2000: Air quality forecasts in the mid-Atlantic region: Current practice and benchmark skill. *Wea. Forecasting,* **15,** 46–60.

Samet, J. M., S. L. Zeger, F. Dominici, F. Curriero, I. Coursac, D. W. Dockery, J. Schwartz, and A. Zanobetti, 2000: National morbidity, mortality, and air pollution study. Part II: Morbidity and mortality from air pollution in the United States. Research Rep. 94, Health Effects Institute, Cambridge, MA, 83 pp. [Available online at www.healtheffects.org/Pubs/Samet2.pdf.]

Schwartz, J., and L. M. Neas, 2000: Fine particles are more strongly associated than coarse particles with acute respiratory health effects in school children. *Epidemiology,* **11,** 6–10.

Strohm, D. E., T. S. Dye, and C. P. MacDonald, 2004: The influence of meteorological phenomena on midwest PM2.5 concentrations: A case study analysis. *Extended Abstracts, Sixth Conf. on Atmospheric Chemistry,* Seattle, WA, Amer. Meteor. Soc., CD-ROM, P1.11.

Szykman, J., and Coauthors, 2004: Utilizing MODIS satellite observations in near-real-time to improve

AIRNOW next day forecast of fine particulate matter, PM2.5. *Extended Abstracts, Sixth Conf. on Atmospheric Chemistry,* Seattle, WA, Amer. Meteor. Soc., CD-ROM, P1.2.

Tanré, D., Y. J. Kaufman, M. Herman, and S. Mattoo, 1997: Remote sensing of aerosol properties over oceans using the MODIS/EOS spectral radiances. *J. Geophys. Res.,* **102,** 16 971–16 988.

Torres, O., R. Decae, P. Veefkind, and G. de Leeuw, 2002: OMI aerosol retrieval algorithm. OMI Algorithm Theoretical Basis Document, Vol. III, Clouds, Aerosols and Surface UV Irradiance, P. Stammes, Ed., NASA-KNMI ATBD-OMI-03, 47-71. [Available online at http://eospso.gsfc.nasa/gov/eos_homepage/for_scientists/atbd/docs/OMI/ATBD-OMI-03.pdf.]

Vaughan, J., and Coauthors, 2004: A numerical daily air quality forecast system for the Pacific Northwest. *Bull. Amer. Meteor. Soc.,* **85,** 549–561.

Vermote, E., R. Slonaker, S. Vibert, H. Kilcoyne, D. Hoyt, T. Zhao, and W. Yang, 2002: Aerosol optical thickness and particle size parameters, visible infrared imager/radiometer suite algorithm theoretical basis document. Ver. 5, SBRS Doc. Y2388, Raytheon Systems Co., 88 pp. [Available online at http://140.90.86.6/IPOarchive/SCI/atbd/msoF1F95.pdf]

Wang, J., and S. A. Christopher, 2003: Intercomparison between satellite-derived aerosol optical thickness and PM2.5 mass: Implications for air quality studies. *Geophys. Res. Lett.,* **30,** 2095, doi:10.1029/2003GL018174.