Transboundary Movement Of Airborne Pollutants

A Methodology for Integrating Spaceborne Images and Ground Based Data

UNEP EPA USGS science for a changing world NASA

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EXECUTIVE SUMMARY

The availability of relevant and accurate environmental information is essential for environmental policy-makers. Recent improvements in satellite remote sensing technologies, ground-based monitors, and data access have resulted in the ability to observe and assess major atmospheric and ecological events around the world on a timely basis.

Each of these monitoring technologies reveals different and useful information, yet rarely are the resulting data sets used together in an integrated manner. The U.S. Environmental Protection Agency (EPA) and the United Nations Environment Programme (UNEP) Global Resource Information Database (GRID) office in Sioux Falls identified an environmental issue of global interest as a test case for applying an integrated approach: the transboundary movement of atmospheric pollutants.

Transboundary movement of atmospheric pollutants has ramifications for human and environmental health, as well as economic impacts. As a result, it is the focus of many bilateral, regional, and international policy efforts. A central question with atmospheric pollutant transport is how to monitor pollutant movement and how to merge different monitoring datasets into useful information. Highly visible regional plumes of dust, smoke, and urban haze can be seen with satellite sensors, while ground-based monitoring of air pollutants such as fine particulates, SO_2, and toxics occurs at the local level. Integration of these two kinds of measurements allows the user to remotely observe large environmental effects in many areas of the world, while obtaining more detailed information from ground-based monitors. Hence, the combination of satellite-based sensor data and ground-based monitoring data promotes greater understanding of the movement of pollutants than either data set alone. Combined data sets are important for use by both scientists and international policy-makers.

A standard methodology did not exist to guide and encourage integrated use of satellite images and ground-based data to monitor and understand major pollution events, such as air pollution. Thus, a small team was assembled to develop a methodology for the integration of satellite images and ground-based data. First, we conducted a literature and project review covering past and current integrated remote and ground-based data projects, a literature search of published work, and a search of data sets and technologies that could be used in a combined form. Second, based on this search and documentation, a general methodology was developed for using integrated spaceborne and ground-based data sets, intended as a guide for general scientists and policy-makers. Third, we found an existing project that was willing to be a pilot for testing the methodology: a U.S. EPA-NOAA project that was using aerial and ground-based sampling to learn more about the airborne sources of mercury deposition in the Florida Everglades.

This document presents the results of the literature and project review, the complete methodology, and the outcome of the Florida Everglades pilot project.

Review Of Prior Work

A review of the literature, existing projects, and existing satellite sensors and ground-based monitors was conducted. Several projects integrated satellite imagery and ground-based monitoring data, primarily in the area of trans-ocean dust storms, forest fires, and urban haze. All of these projects were conducted in the last 5 years and were of limited scope. The data, techniques, and projects identified through the review confirm that improved satellite and ground-based data are becoming available and can be integrated effectively; however, this data integration has not been done extensively to-date. Additionally, for global assessment and monitoring, many regions of the world do not have adequate ground sampling, and where data are available, the data are often not readily available for incorporation in integrated applications. Satellite monitoring in conjunction with limited ground-based monitoring would be very useful in these regions.

Methodology

The methodology described herein is designed to overcome both technical and institutional barriers to integrating disparate information from multiple agencies in multiple countries. To achieve this task: 1) the project must be well defined, articulated and constructed on a sound practical and theoretical foundation; 2) appropriate partners who are committed to the project must be identified to ensure that critical technologies and policy concerns are addressed; 3) critical data sources must be identified and made available through cooperating partners; 4) the knowledge of the partners and the data must be shared through common standards and electronic communication; and 5) the project must be implemented to fulfill the needs of the partners.

Pilot Project

Although the methodology is applicable to a wide range of pollutants, a single pilot project was needed to test the methodology. The chosen pilot application was an environmental issue of current international concern: transboundary air pollution and mercury deposition. This pilot project supplemented an existing study of the airborne sources of mercury found in fish living in the Florida Everglades. Possible airborne sources of mercury included local sources, non-local U.S. sources, long-distance sources from other countries, or combination of these. This pilot project supplemented the existing project by providing satellite information on general air pollution movement and sources to be combined with the ground and aircraft measurements of the mercury that were collected in the Everglades and offshore.

The methodology proved an effective mechanism for integrating satellite information into ground and aircraft mercury monitoring, for identifying the relevant data sources, and for building the necessary partnerships to help identify mercury sources.

Conclusions And Future Direction

Our findings include:

- Integrating satellite images and ground-based data can be beneficial for understanding environmental issues.
- Recent technological advances, including launch of new satellite technologies, growth of ground-based air monitoring networks, and increased on-line accessibility of satellite sensor images and surface based observations, make the integrated use of satellite images and ground-based data possible.
- The general methodology for integrating satellite images and ground-based data, including defining a project, finding partners and resources, selecting data sources, communicating electronically, and conducting a project, is valid and has been confirmed through a pilot project.
- Satellite images integrated with ground-based data provide more information about an environmental phenomenon than either dataset alone.

The combined use of satellite sensors with ground sampling systems can be an effective tool to help policy-makers with decisions concerning the protection of human health and our environment. The spatial resolution and temporal frequency coverage from satellite sensors will only improve over time. Many countries are improving their ground sampling capacity. The usefulness and success of an integrated data approach will necessarily depend on the availability of local ground-based data that can be combined with satellite imagery.

In the future, the methodology developed in this study may be applied to other regions around the globe and to a wider range of pollutants and media. Projects could include water pollution monitoring, local air pollution analysis, or analysis of specific global policy issues. The benefits include a greater understanding of important environmental issues and an increasing ability to clearly visualize the impact. Ultimately, we hope to encourage a more collaborative relationship between the satellite and ground-based monitoring scientific and policy communities.

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1. OBJECTIVES AND APPROACH

Transboundary movement of atmospheric pollutants has international policy, economic, human health, and environmental ramifications. Atmospheric pollutants, such as aerosols, persistent bioaccumulative toxics, and gaseous pollutants, have significant impact on human and environmental health. A new generation of ground monitoring systems in connection with new satellite imaging systems provides an opportunity to investigate, design and implement effective monitoring strategies for these atmospheric pollutants.

Atmospheric pollutants are of particular concern since air masses flow freely across borders, leaving the geographic and political jurisdiction of the originating country and becoming the responsibility of another. For example, sulfur dioxide emissions from one industrial region may be transported hundreds of miles and ultimately deposited as acidic compounds into a neighbor's ecosystem. Wind blown desert dust and forest fire smoke cross international borders and increase particulate matter concentrations to levels that may exceed regulatory standards and harm human health. The stable chemical properties of persistent organic pollutants (POPs) promote their long range transport and their ability to bioaccumulate, which may increase toxicity in environments where they have never been used or produced.

A fundamental question associated with transboundary pollutant transport is how to effectively monitor pollutant movement. Ground-based sensors can monitor conditions at specific geographic points and times on either or both sides of a political border but they provide a limited picture of pollutant sources, receptors, and the path they took to get from one to the other. They provide a particularly limited view, especially when large water masses separate the countries involved in the source-receptor relationship. Integrating satellite images with point monitoring can fill in the spatial and temporal gaps. An integrated monitoring effort can aid the tracking of pollutant plumes, early detection and advance warning systems, identification of pollutant sources, and the general knowledge base of pollutant physical and chemical characteristics – all of which can be translated into information useful for negotiating international policies.

The U.S. Environmental Protection Agency (EPA) and the United Nations Environment Programme (UNEP) Global Resource Information Database (GRID) office in Sioux Falls formed a small team to implement a joint project related to transboundary movement of pollutants. Our main objective was to develop and verify a methodology to assess and monitor the movement of pollutants across international boundaries using a combination of ground-based monitoring and space imaging data. The implementation of this project involved three general tasks:

1. Reviewed the science and current activities in the combined use of remote satellite images and ground-based monitoring data for transboundary pollutant movement
2. Developed a general methodology to use integrated spaceborne and ground-based datasets
3. Demonstrated the methodology through a pilot project.

Due to the expertise and interests of the agencies and staff involved, the project focused on air pollutant transport, while attempting to remain general enough to be applicable to a wider range of pollutants and regions.

This document represents the achievement of above objective and presents the results of the three tasks.

2. PROJECT AND LITERATURE SEARCH

The initial task was to document past and current projects, datasets, and technologies that integrated data from some combination of satellite, aircraft and ground sensors. The immediate goal of the review was to guide the selection of a pilot project that could be used to test the robustness of our general methodology for using integrated datasets. The task was conducted within the context of how these kinds of projects could be used to assess and monitor transboundary movement of pollutants.

2.1 BACKGROUND

The most obvious model of integrated use of spaceborne and in situ ground-based data was the National Weather Service. The National Weather Service predicts and reports weather information consisting of a blend of weather satellite images with ground-based data such as wind speed, precipitation, barometric pressure, and temperature. In a few other cases, ground-based data has been collected specifically to verify and refine satellite data models. However, besides these notable exceptions, the experts in remote sensing and the experts in ground level monitoring have not consistently communicated or worked closely with each other, especially with time-relevant environmental or human health data.

Based on preliminary discussions with the experts in these fields, we determined that these collaborations would be useful and would be facilitated by three recent developments:

- Rapid advances in the quality and availability of satellite images from government and private space organizations;
- Expansion of ground-based monitoring networks by government environmental agencies as well as development of better on-line monitoring devices for a wider variety of constituents; and
- Increased ability for rapid electronic communication of data and images and the expansion of monitoring information available on the Internet.

Recent developments in satellite remote sensing technologies and improved accessibility to satellite data have resulted in the ability to observe major ecological events around the world on a daily basis. Scientists and regulators have observed very diverse events, from dust storms in the Sahara and China, to dense industrial and urban haze in the United States, to forest fires in Mexico, to algae blooms from pollution in the Mediterranean. Additionally, ground-based monitors have detected potential contaminants from cross-boundary events, indicating the existence of long-range atmospheric transport of various pollutants. These monitoring data indicate that global events may be important contributors to the total environmental concentrations of these pollutants in many countries around the world.

The technological developments to monitor these events are so recent that, when combined with the isolation of the respective communities, they have not translated into routine use of integrated datasets. Based on this preliminary literature search, the advances in technology, and the interest expressed by colleagues, there exists a clear multi-community interest in further investigation into the use of integrated datasets that contain both spaceborne remote sensing images and ground-based data.

Since the integrated use of spaceborne and ground-based datasets was too large a subject to approach with available resources, we sought to focus our study on a single subject area that could

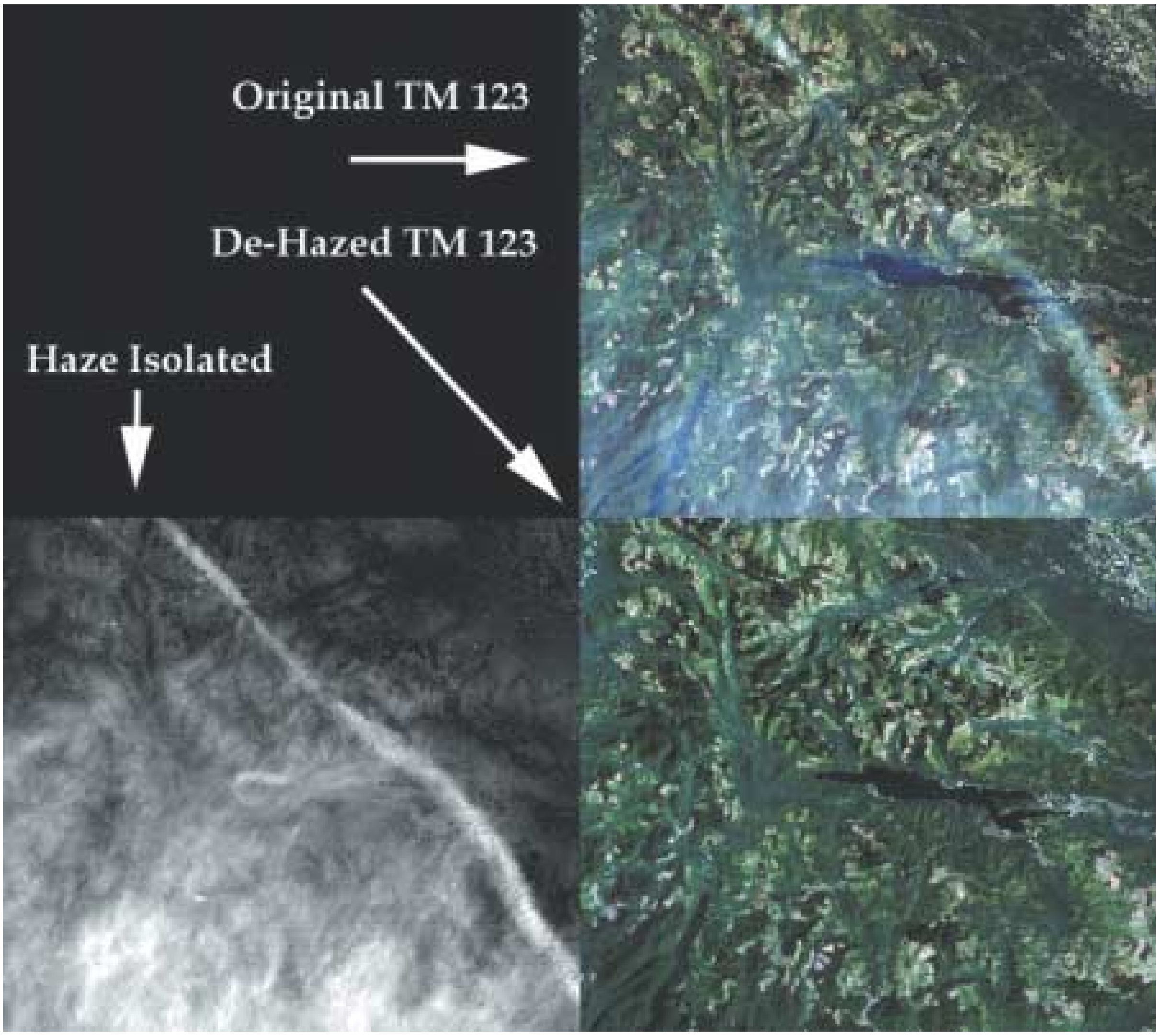

Figure 2-1. Landsat 7 Thematic Mapper Image of Vancouver Island, Canada, showing how aerosols can be enhanced or removed from the image. Image courtesy of Robert Crippen, NASA, 2000.

serve as an example. Some subjects, such as weather, natural disasters, and landuse change, were eliminated since they are already being intensely monitored and studied at a number of organizations internationally. Two other areas emerged as possibilities: water quality monitoring in a watershed (in particular algae blooms and sediment plumes) and air quality monitoring of the transport of dust and other particulates. We chose to focus our study on the transboundary motion of air pollution, in particular, aerosols/ particulates and toxics.

Air pollution monitoring was selected for several reasons. Air pollutants, generated locally and transported long distances, have a significant effect on human health, particularly those with asthma, the elderly, and children. Additionally, the transport of air pollutants is a significant contributor to acid rain, poor visibility, climate change, and bioaccumulation of toxics in remote areas. Thus, air pollutant monitoring is an important issue for both human and environmental health on a global scale. UNEP is involved in forty one "air" related treaties as documented in ECOLEX (http://www.ecolex.org), and many of these are concerned with the long distance transport of airborne pollutants. The U.S. EPA is a party to many of these treaties. On a practical level, the transboundary movement of pollutants matched the interests and the skills of the staff involved with the project.

2.2 Search Results

The search focused on available spaceborne images, available ground-based data including aircraft-based data, modeling information, and previous projects that integrated data from these sources. This information was used to develop a general methodology for using integrated datasets and to conduct a pilot project in the area of air quality (aerosols and toxics).

2.2.1 Available Spaceborne Images and Data

Hundreds of organizations use remote sensing data that are provided by a short list of satellite operators, such as the U.S. National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), the National Space Development Agency of Japan, and the Indian Space Research Organization (ISRO). The organizations and projects in the References section represent a relevant sample, although not an exhaustive list. Similarly, Appendix A (page 59) lists a few of the satellite sensors including details about their technical abilities that are potentially relevant to this work. Appendix B (page 63) lists some of the methods used to retrieve aerosol measurements from satellite observations.

Many of the satellite images are increasingly available internationally (with the exception of military information). Some agencies make data access easier and more cost effective than others. Also, obtaining data easily usually requires high-speed access to the Internet. The most relevant satellite sensors and images are discussed in more detail below.

2.2.1.1 Landsat

Landsat is one of the longest running series of earth observation satellites. The first Landsat satellite was launched in 1972 and the most recent, Landsat 7, was launched in April 1999. The strength of Landsat is its data quality and excellent spatial resolution, while its main weakness is that an image for any particular region is available only every 16 days.

Typically, Landsat data are used to monitor land use changes and to make land maps (Tømmervik et al 1998; De la Sierra et al 1995). However, Landsat data has been used for more diverse functions such as monitoring algae blooms (Rud and Gade 1999). Landsat images have been used for a variety of air monitoring projects by measuring the differences or changes in reflectively (Otterman et al 1982). This includes studies of air quality, in particular SO_2 and particulates (Retalis et al 1999; Sifakis et al 1999; Deschamps and Sifakis 1992).

An example of Landsat data and how it can be used to find and visualize haze is shown in Figure 2-1. This image from Vancouver Island uses Landsat Thematic Mapper Band 6 data to isolate areas of haze (Crippen and Blom 2000; Crippen 1999). This image shows how haze can be removed from the Landsat image for a better view of the land, or how it may be enhanced in order to better view the aerosols. This technique can be used as a qualitative view of aerosols in the region or used to validate ground-based measurements of visibility or particulate matter.

2.2.1.2 Advanced Very High Resolution Radiometer (AVHRR)

One of the most commonly used sensors for aerosol retrieval thus far is AVHRR. AVHRR technology has flown on various NOAA polar orbiting satellites since 1978, with NOAA-14 and NOAA-15 currently in orbit. Polar orbiting satellite systems offer the advantage of daily global coverage, by making polar orbits roughly 14.1 times daily, with the local solar time of each satellite's passage essentially unchanged for any latitude.

AVHRR collects data in the visible, near-infrared, and thermal infrared portions of the spectrum. Thus it is often effective to use several bands of AVHRR data to analyze the same image. AVHRR data has also been used for a variety of projects, including monitoring of algae blooms (Chavez et al 1999; Rud and Gade 1999) and sediment levels in watersheds (Walker 1996; Woodruff et al 1999). AVHRR data have been used for aerosol monitoring; the Operational Significant Event Imagery group at NOAA uses AVHRR data for monitoring significant events on a daily basis. Figure 2-2 is an example of AVHRR imagery showing a dust storm in Texas. It is also an example of using different bands of data from the same satellite to enhance an image. The second image was created by subtracting one AVHRR data band from another in order to enhance the brightness of the silicates in the air.

An interesting use of AVHRR data is the AVHRR Pathfinder Atmosphere (PATMOS) project, a joint NOAA/NASA project to develop a climatology of aerosol optical thickness (AOT) using AVHRR data from polar satellites from 1981 to the present. AOT is a measure of the effect of aerosol particles on the transmission of solar radiation to the Earth's surface; thus, the higher the AOT, the less solar radiation reaches the ground. The NOAA PATMOS team has already developed a climatology over oceans, where the background reflectance is much lower and more stable than that of land, making the retrieval of AOT more reliable. They are now beginning a similar project, working in conjunction with NASA's Global Aerosol Climatology Program, to use AVHRR data to develop a climatology over land.

2.2.1.3 Geostationary Operational Environmental Satellites (GOES)

NOAA operates GOES primarily as weather satellites. They are in a geosynchronous orbit on Earth's equatorial plane, matching exactly the

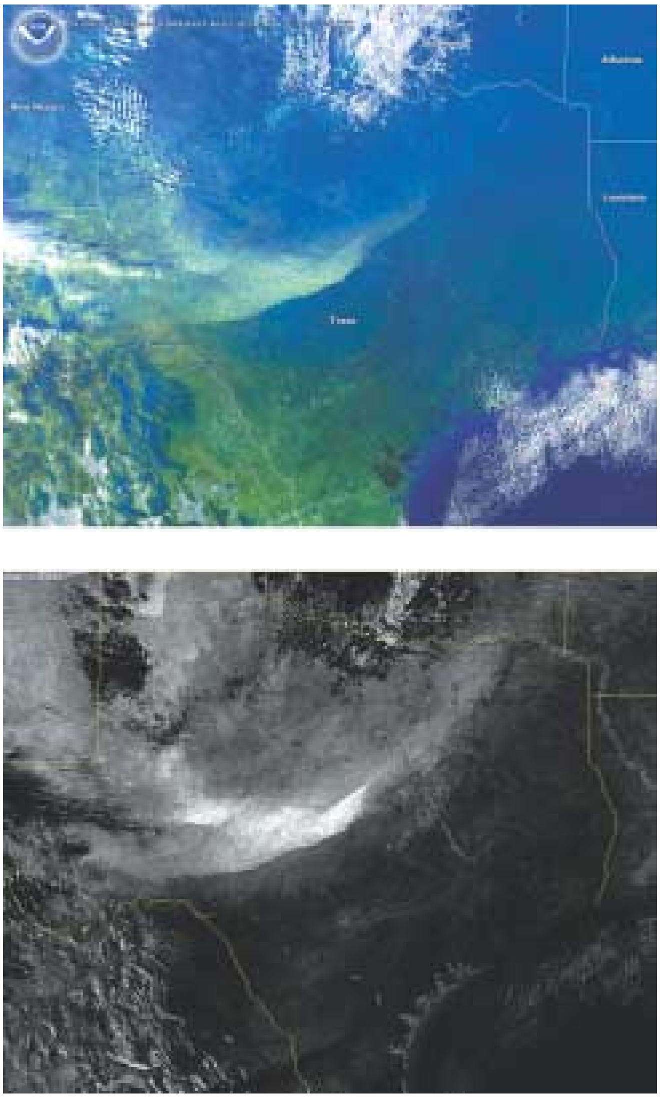

Figure 2-2. Dust Storm in Texas, 14 December 1999, with the second image enhanced by subtracting Channel 5 AVHRR data from Channel 4 to enhance silicates in the air. Image courtesy of the NOAA OSEI team.

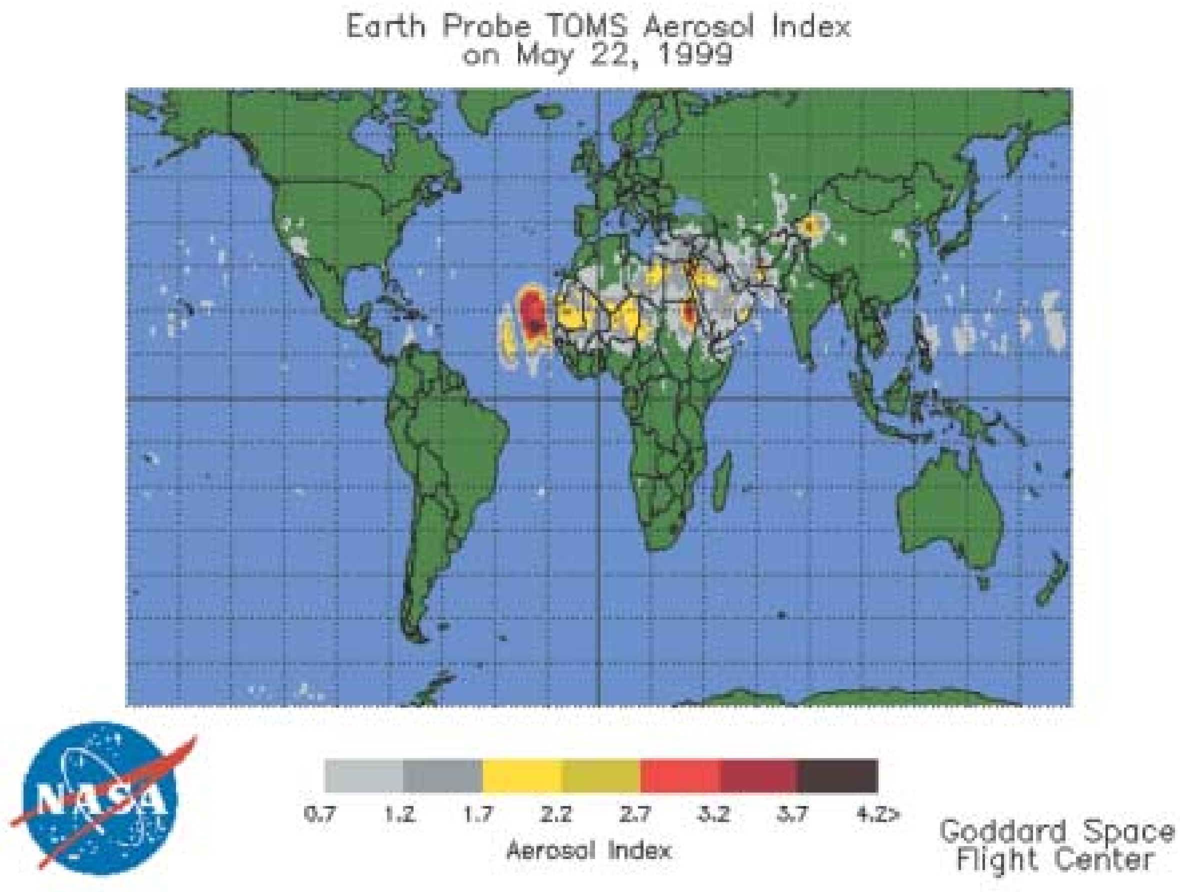

Figure 2-3. TOMS images showing dust blowing from the Sahara across the Atlantic. Image courtesy of the TOMS website and NASA Goddard Space Flight Center.

Earth's rotation about its axis. This configuration allows each satellite to view the same areas of the Earth at all times from about 35,800 km (22,300 miles) above the Earth's surface. Unlike the polar orbiting satellites, the GOES satellites can provide continuous monitoring of the Earth's atmosphere and surface over a large region of the Western Hemisphere.

Besides weather prediction, GOES data has been used for air quality monitoring, including determining aerosol optical thickness (Fraser et al 1984) and fire and smoke detection (Hotz 1998). The NOAA Operational Significant Event Imagery group and others use GOES data for both dust and fire monitoring.

A similar geostationary satellite sensor launched by the European Space Agency and operated by Eumetsat is Meteosat, which collects images in both visible and infrared wavelengths. Meteosat is designed for weather observations but has been used for aerosol optical thickness retrieval. Additional satellites and sensors are being planned for Meteosat Second Generation that will include expanded spectral coverage.

2.2.1.4 Total Ozone Mapping Spectrometer (TOMS)

TOMS has been in use since 1978 on the Nimbus-7 platform, scanning at ultraviolet wavelengths. TOMS is most well known for mapping ozone, including monitoring the Antarctic ozone hole and tropospheric ozone (Fishman and Balok 1999; Fishman and Brackett 1997). However, TOMS is sensitive to absorbing aerosols and can be used to monitor the motion of large aerosol plumes. TOMS has a very low resolution (50 km), so it is most useful for monitoring events on a global or regional scale, rather than local. Figure 2-3 is an example of global TOMS imagery showing dust from the Sahara blowing across the Atlantic Ocean.

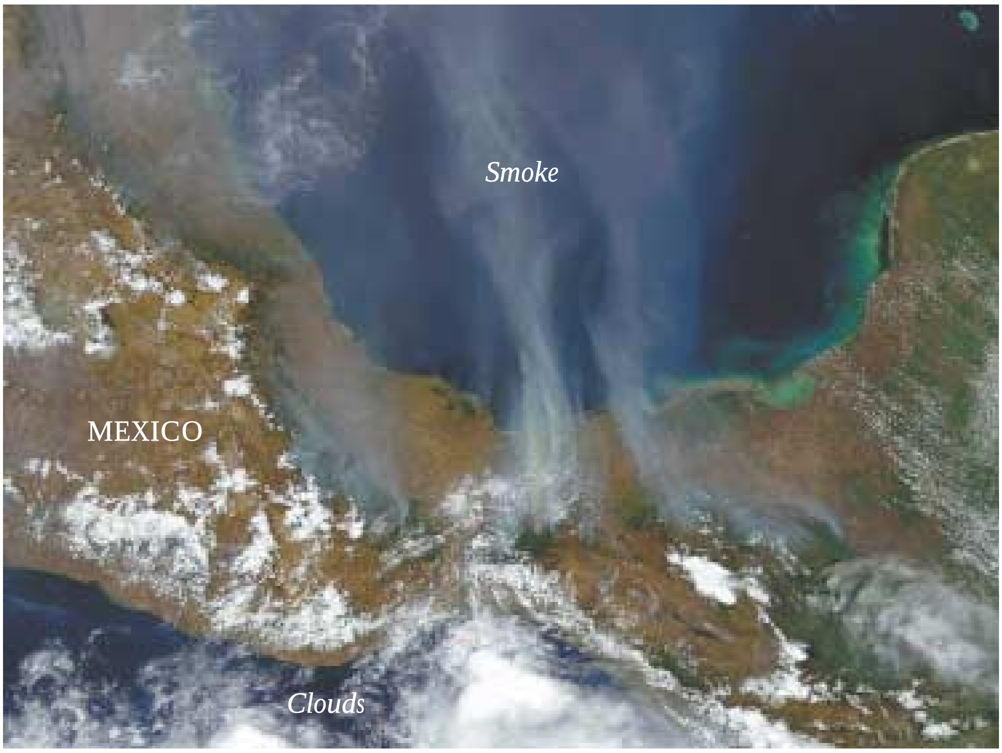

Figure 2-4. SeaWiFS image showing smoke from fires in Mexico, 5 June 1998. Image courtesy of the SeaWiFS website, NASA Goddard Space Flight Center.

2.2.1.5 Sea-viewing Wide Field-of-view Sensor (SeaWiFS)

SeaWiFS was designed as an ocean color sensor to collect sea surface color and other ocean bio-optical properties. It is used extensively for observing algae blooms, tracking oil spills, monitoring water pollution, among many other uses (Chavez et al 1999; Woodruff et al, 1999; see also the SeaWiFS website). However, its daily visible color images can provide some striking images of other non-ocean events, such as dust storms and smoke (Hotz 1999; see also the SeaWiFS website). Figure 2-4 is an example of a smoke image that was captured by SeaWiFS. In Figure 2-5, SeaWiFS reveals dense industrial pollution.

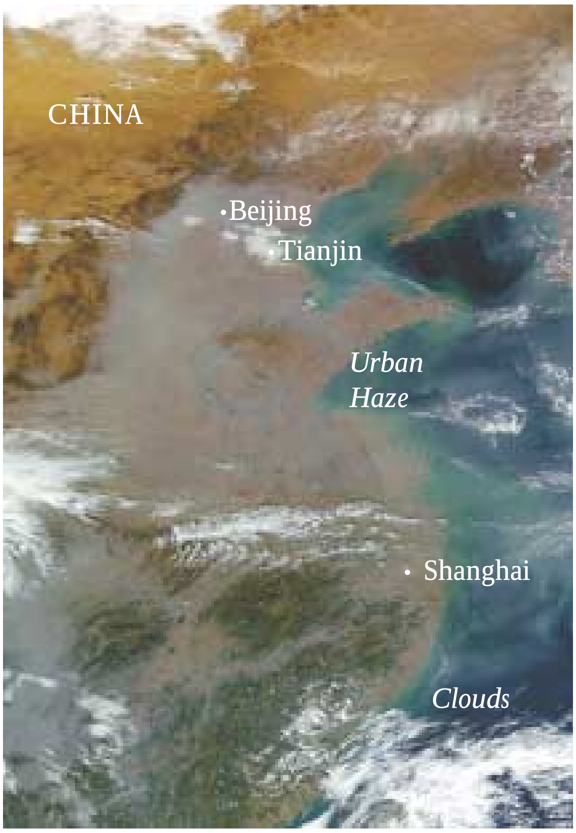

Figure 2-5. SeaWiFS image showing industrial pollution in eastern China, 2 January 2000. Image courtesy of the Visible Earth website, NASA Goddard Space Flight Center.

2.2.1.6 New Satellites

The space agencies have launched or plan to launch several new earth observing satellites that will greatly increase the types of data available for monitoring the earth's environment. Of particular note are the instruments on the Terra satellite launched in December 1999, which have data

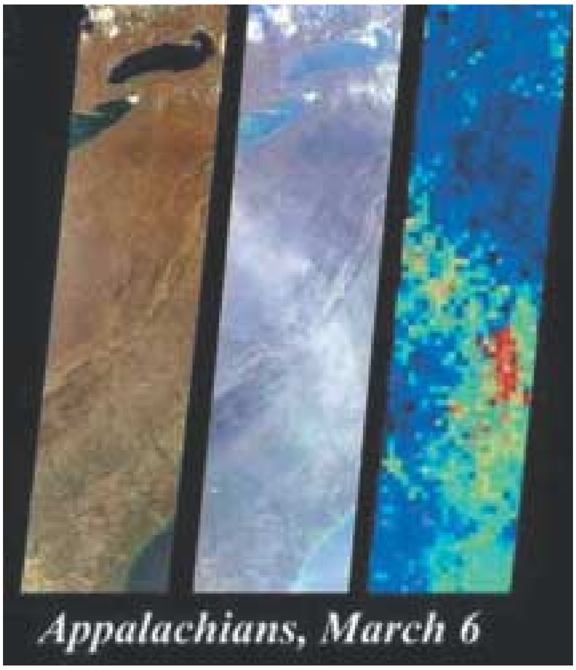

Figure 2-6. MISR Images and Data of Appalachians, March 6, 2000. The first panel is the downward-looking (nadir) view camera. The middle panel is forward-viewing at 70.5-degree camera. At this increased slant angle, the line-of-sight through the atmosphere is three times longer, and a thin haze over the Appalachians is significantly more apparent. The third panel shows the airborne aerosol amount, derived using new methods that take advantage of MISR's moderately high spatial resolution at very oblique angles; gradations from blue to red indicate increasing aerosol abundance. Image and explanatory text courtesy of NASA Jet Propulsion Laboratory, http://visibleearth.nasa.gov/cgi-bin/viewrecord?5898.

available for use in late 2000 and 2001. The NASA Goddard Space Flight Center manages the Terra program.

One instrument launched on the Terra satellite, Multi-angle Imaging Spectro-Radiometer (MISR), uses 9 cameras to image each piece of the earth from nine angles, providing the ability to see in 3-dimensions, as well as distinguish and highlight haze, dust, plumes, clouds, and other events. Figure 2-6 is a MISR image on March 6, 2000, showing images from two angles and aerosol data derived from the oblique angle data.

A second instrument on Terra, Measurements of Pollutants in the Troposphere (MOPITT), measures carbon monoxide and methane in the troposphere, thus will directly measure ground-level pollutants. Figure 2-7 shows an early image from MOPITT, of carbon monoxide over the United States, including the beginnings of a plume moving over the Atlantic. The NASA Earth Observing System (EOS) AURA satellite mission planned for launch in June 2003 will enhance the capabilities of MOPITT.

Several other instruments on Terra will provide significant imagery and data as NASA and its

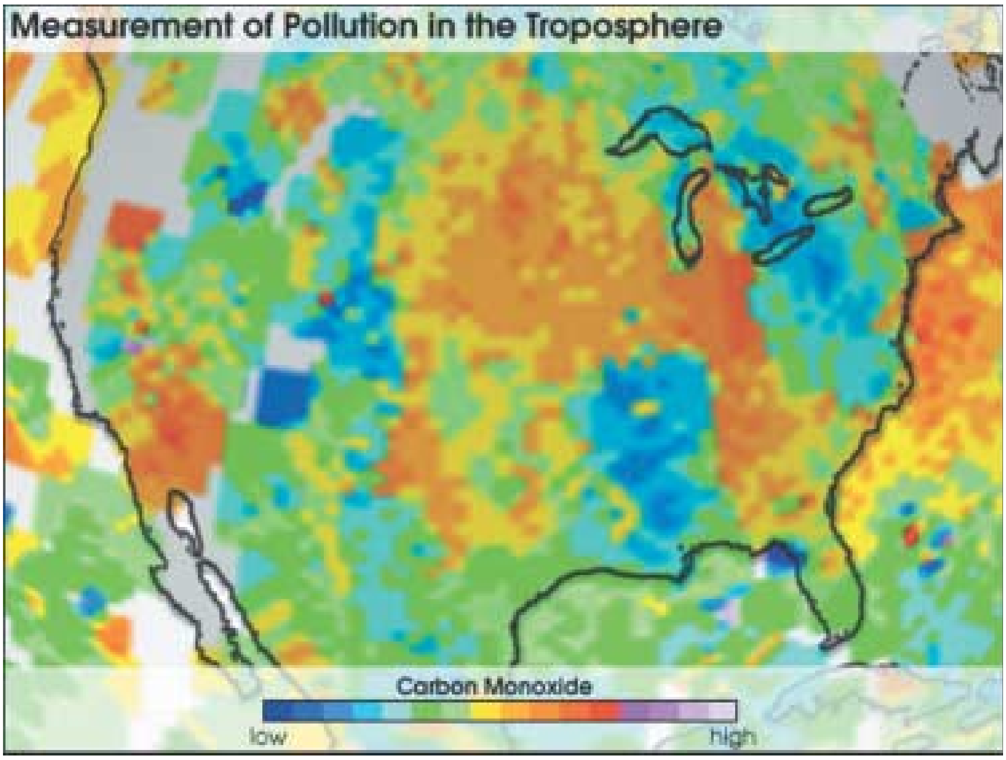

Figure 2-7. MOPITT Carbon Dioxide Data, March 5-7, 2000. Note plume moving off eastern coast. Image courtesy of the MOPITT Instrument Team, NASA Visible Earth and the Canadian Space Agency, http://visibleearth.nasa.gov/cgi-bin/viewrecord?551

partners begin to refine analysis methods and make data sites operational.

2.2.2 Available Ground-based Data

Many government environmental organizations collect and use ground-based data. In the United States, the most important organizations for air pollutant related data are EPA's Office of Air and Radiation (OAR) and the OAR Office of Air Quality Planning and Standards (OAQPS).

OAQPS maintains databases of air monitoring data collected by EPA and the state governments for compliance purposes. The best single source of ambient data, updated on a monthly basis, is Aerometric Information Retrieval System (AIRS). AIRS is an electronic database with air quality data from monitoring stations throughout the U.S. collecting data about the criteria pollutants (CO, NO_2, O_3, Pb, PM_{10}, $PM_{2.5}$, SO_2), which have a large impact on human health. Daily data is not currently available from the website, but they are stored in the main AIRS databases and are available on request. Expected upgrades to the website will allow access to the full set of data via the web. Currently, a number of individual states have air quality data available in "real-time" on their own websites.

There are some research databases that could be tapped depending on project requirements. One example is the Indian Ocean Experiment (INDOEX) database for 1995-1999. The limited availability of INDOEX data precludes their operational use, but may be helpful for validating algorithms employed in projects using the methodologies discussed in this report.

Regulatory agencies throughout the world are making their data available to researchers and to the public. Ground-based data are increasingly available from major government sources, although in some countries, access to data may be impeded by administrative and national limits on the distribution of information. While the following discussion of pollutants is focused on U.S. EPA sources, similar programs exist at some level in most countries that regulate air pollutants.

2.2.2.1 Particulate Matter

Particulate matter has impacts on human health by reducing lung function and is of particular concern to those with asthma, children, and the elderly. Generally, ground-based monitors measure particulate matter under 10 microns, which is considered inhalable, or fine particulate matter under 2.5 microns, which has the most impact on human health.

EPA and other regulatory agencies internationally have extensive existing network of PM_{10} monitors, which collect information for urban compliance purposes. For fine particulate matter data, OAQPS is in the process of establishing a network of about 1,000 fine particulate monitors. These data will be available via the AIRS system as the sites are established. Additionally, a set of approximately 54 "supersites" will also be established (Mobley and Shaver 1999). The supersites will collect very detailed data beyond regulatory requirements (such as metals speciation of the particulate data) in order to gain a more complete view of the sources of air pollution and to advance monitoring technologies and systems. The supersites will be launched in several phases, with the first set located in Atlanta and Fresno, and Phase 2 in New York City, Baltimore, Pittsburgh, St. Louis, Houston, and Los Angeles.

2.2.2.2 Air Toxics

EPA typically considers toxic air emissions as the 188 Hazardous Air Pollutants (HAPs) as defined by the Clean Air Act. A few examples of HAPs include mercury compounds, lead compounds, benzene, chlorine, DDE, and many pesticides such as chlordane. Human health effects are diverse, including possible links to cancer, chronic eye, lung, or skin irritation, and neurological and reproductive disorders. Environmental effects are also considerable, for example, toxics can poison waterways or bio-accumulate to cause disease, neurological and reproductive disorders in fauna.

HAPs are well documented as point source emissions but unlike the criteria pollutants, *ambient* levels of the HAPs are not measured on

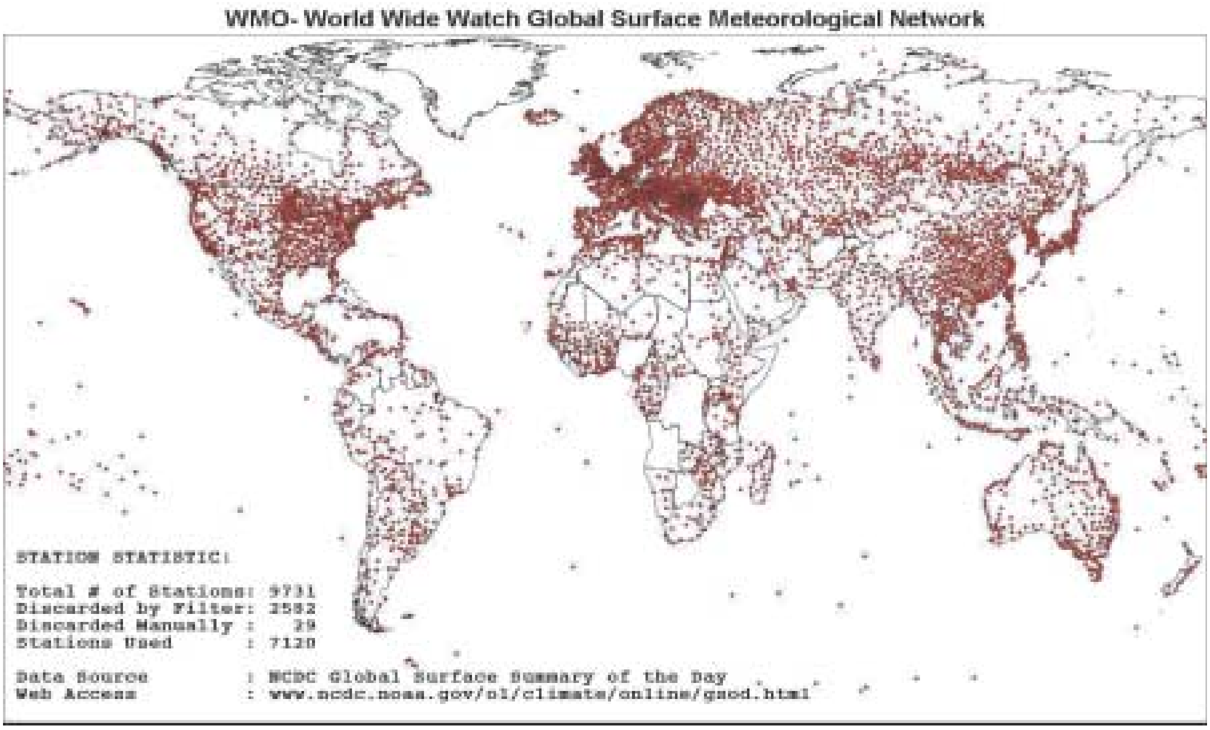

Figure 2-8. NCDC Visibility measurement station location density (Husar et al 2000).

widespread basis, either in the U.S. since there are no federal requirements for ambient attainment, or worldwide. However, the U.S. EPA is in process of developing a national air toxics program, including increased ambient air toxics monitoring at sites across the U.S. (Mobley and Shaver 1999). As part of this program, 33 urban air toxic HAPS are identified as the initial priority pollutants, including volible organic compounds (VOCs), mercury compounds, and other toxics that have the greatest impact on urban air quality (Mobley and Shaver 1999). This program builds on current monitoring that already occurs, including 8 VOCS in 20 cities that are already stored in AIRS and the near future speciation data for 10 HAPS metals from over 50 cities participating in the $PM_{2.5}$ network (Mobley and Shaver 1999).

2.2.2.3 Visibility

The global Summary of Day (SOD) database distributed by the National Climatic Data Center (NCDC) contains data that are derived from the World Meteorological Organization (WMO) World Weather Watch Program. Data from over 8000 stations are typically included each month and are accessible through the NCDC web server. Figure 2-8 shows the locations and density of the stations.

The SOD data include visibility observations. The visual range, or visibility, is the maximum distance at which an observer can discern the outline of an object against a horizon sky. It can be used as a surrogate for fine particulate matter concentrations because of the strong relationship between increased fine particulate concentrations and decreased visibility.

2.2.2.4 AErosol RObotic NETwork (AERONET)

AERONET is an optical ground-based aerosol monitoring network and data archive supported by NASA's Earth Observing System and used by many non-NASA institutions. The network consists of automatic sun-sky scanning spectral radiometers, or sun photometers, that measure the direct sunlight in specific spectral bands, and from which the aerosol optical thickness can be determined. The sun photometers are operated by

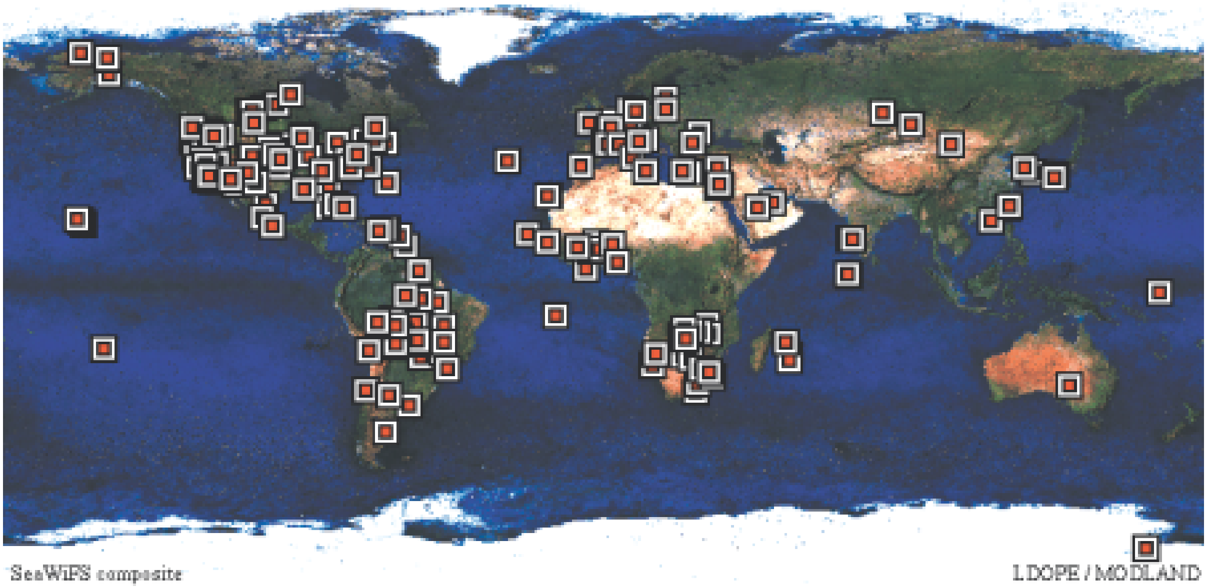

Figure 2-9. AERONET sun photometer site locations (map courtesy of Aeronet NASA GSFC).

a variety of universities and organizations. Data from this collaboration provide globally distributed near real time observations of aerosols. The real time data undergo only preliminary processing, while the final quality-controlled data are further reviewed and made available about 6 months after data collection. The data provide characterization of aerosol properties that are unavailable from satellite sensors and help to validate the satellite data. Figure 2-9 shows the locations and density of the AERONET stations.

2.2.2.5 Special Research Studies

Special studies of air monitoring and transport occur within the research organizations of government environmental agencies, universities, and non-profit institutes. These projects typically collect detailed information in a specific area for a limited amount of time. Often these studies can be tapped as sources of additional information or supported with satellite images. For example, the Indian Ocean Experiment (INDOEX) was designed to study regional consequences of global warming due to the cooling effect of aerosols. These tiny particles, about a micron or smaller in diameter, scatter sunlight back to space and cause a regional cooling effect. These aerosols consisting of sulfates, soot, organic carbon and mineral dust are produced both naturally and by human activities. Still, the complex influence of

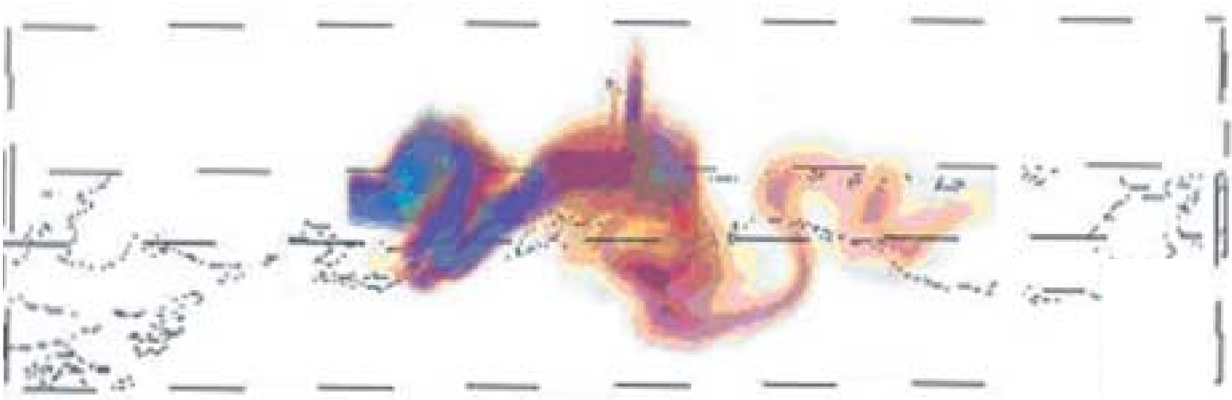

Figure 2-10. Modeling study showing the concentration of a hypothetical tracer released in China as it moves across the Pacific. (Hanna et al 1999; Keating 1999) Image courtesy of Joe Pinto, EPA ORD/NCEA.

aerosol cooling on global warming is not clearly understood.

INDOEX field studies occurred over the tropical Indian Ocean where pristine air masses from the southern Indian Ocean including Antarctica and urban pollution from the Indian subcontinent meet. The data collections involved multiple aircraft, ships and island stations over the Arabian Sea and the Indian Ocean. The INDOEX dataset spans from 1995-1998, and includes data from an intense field campaign undertaken during January to April 1999. Further details about INDOEX may be found at http;//www-indoex.ucsd.edu/index.html

2.2.3 Aircraft-Based Information

Aircraft and balloons provide the opportunity for obtaining aerosol characteristics as a function of altitude. These data are typically available on a limited basis as part of special research projects. Aircraft data can often be a link between ground-based and satellite remote sensing information. For the purpose of this paper, aircraft data are considered a type of ground-based data.

2.2.4 Models

Models use ground, aircraft, and satellite data as their inputs, forming a new dataset that is applicable to data integration for understanding aerosol transport. Two examples are:

- Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) 4 Model. HYSPLIT is the newest version of a complete system for computing simple air parcel trajectories to complex dispersion and deposition simulations. It is a result of a joint effort between NOAA and Australia's Bureau of Meteorology. HYSPLIT models the dispersion of a pollutant both horizontally and vertically (NOAA 1999).
- Navy Aerosol Analysis and Prediction System (NAAPS). NAAPS is a global, multi-component aerosol analysis model that combines the current and expected satellite data streams with other available data. NAAPS predicts and simulates the motion of global aerosols in near real-time (NRL 2000).

Some models are modified and applied to specific subjects. A relevant example is a modeling study conducted by the U.S. EPA and the North Carolina Supercomputing Center to analyze the motion of air toxic pollutants from China to North America. Figure 2-10 shows the modeled concentrations of a hypothetical tracer released in China and stretching across the Pacific in varying colors according to a logarithmic scale (Hanna et al, 1999).

2.2.5 Previous Integrated Work

Projects in the published and Internet literature have used integrated datasets composed of both satellite remote images and ground-based data. One term applied to the integration of monitoring data (both spaceborne and ground-based) is data fusion (Pohl et al 1998; Wald 1999). In fact, one website calls itself the Data Fusion Server, although most of its examples are fusing information from different satellites as opposed to fusion with ground-based data. Several organizations are dedicated to different types of data integration although they also usually specialize in satellite data integration, including Committee on Earth Observation Satellites (CEOS), an international coordinating body for satellite providers with NASA and NOAA as the U.S. representatives, and the Centre for Earth Observation (CEO) Project, a similar European program.

Data integration has been applied in chlorophyll monitoring (Kester et al 1996; Rud and Gade 1999; Walker 1996; Woodruff et al 1999), land use change (De la Sierra et al 1995; Tømmervik et al 1998) and ocean monitoring (Chavez et al, 1999), among other areas. However, the focus of this study is to review the integrated use of data to monitor air pollution transport.

In the earliest work, EPA scientists used satellite imagery and airport visibility (real time particle monitoring) to track haze moving around the U.S. and out to sea as early as the 1970s (William Wilson, 1999). While there has been significant EPA interest since these early studies, very little published work exists. Non-EPA published work indicated that scientists have used Landsat data and ground-based data for a broad range of purposes, for example, to characterize tropospheric desert aerosols over both land and ocean (Otterman et al 1982). Work was also done to estimate the transport of SO_2 by combining aerosol optical thickness over land from GOES satellite measurements with wind vectors (Fraser et al 1984). They noted the need for validation through a independent well designed ground-based sampling experiment that is coordinated with satellite observations.

A substantial amount of work related to data integration has been done in the 1990s, which is to be expected since the advances in satellite and ground-based monitoring have all been fairly recent. This work typically falls into three subject categories: the monitoring of an Asian and African dust events; fire and smoke detection especially in Central America; and the monitoring and verification of urban air quality.

2.2.5.1 Asian and African Dust Storms

Massive dust storms originating in the Gobi desert region of western China have been monitored using SeaWiFS satellite images. The Center for Air Pollution Impact and Trend Analysis (CAPITA) at Washington University in St. Louis monitors and publicly reports when these dust storms reach the west coast of the U.S. The data are enhanced through ground-based data and other satellite images provided by experts who accessed the CAPITA web site. The CAPITA project was conducted using "just in time" scientific input. It made use of NASA and NOAA images placed regularly onto the Internet. They also used SeaWiFS, GOES, AVHRR, and TOMS data with ground-truthing and limited particulate ground monitoring (Husar et al 2001). State and regional EPA staff used these images to monitor for the dust as it approached and arrived on the U.S. West Coast.

Aerosol Characterization Experiment-Asia (ACE-Asia) is another project that plans to monitor trans-Pacific motion of pollutants, although they take a more historical and long-term research based approach. ACE-Asia is a NOAA and National Science Foundation funded program that plans to combine ground-based monitors, aircraft flights, and satellite remote sensing to monitor aerosols and their transport in and around Asia. This is a multi-year program that is just beginning to fund research projects aimed at a long-term understanding of trans-Pacific pollutant movement.

Scientists have also been interested in the dust moving from the Sahara and northern Africa across the Atlantic towards the Caribbean and the Americas. Only a few studies of this phenomenon have used satellite and ground-based data in an integrated fashion. One study used satellite imagery in conjunction with soundings from ships positioned in the Atlantic, combining those datasets with wind and weather data through an algorithm (Ott et al 1991). Another study conducted by the University of Miami used ground-based sampling data of airborne aerosols collected on a small island 4 km east of mainland Florida (Prospero 1999). Their sampling data indicated a peak of aerosols from non-mainland sources during June, July, and August, consistent with an African source. These data were compared with qualitative studies from the literature that used AVHRR and TOMS data. The University of Miami study discussed how the relationship between the images and the sampled data could impact EPA's administration of the new $PM_{2.5}$ regulation.

2.2.5.2 Fire and Smoke Detection

Fire and smoke detection are both possible with satellite imagery. Satellite images from TOMS, GOES, and SeaWiFS have been combined with ground data from forest fighters in order to understand the scope and the motion of fires and smoke (Hotz 1998).

Major fires in Central America and Mexico were monitored in 1998 by CAPITA as the smoke moved into the U.S. Using a website format similar to the Asian dust event, ground-based information was submitted by experts. This included data from the $PM_{2.5}$ network from four cities in Texas (see CAPITA's website on Central America http://capita.wustl.edu/Central-America). These images and PM data were later used by EPA to evaluate the compliance status of cities who were most affected by the smoke.

The NOAA National Weather Service International Activities Office, in conjunction with NOAA NESDIS and other offices, has a project called Program to Address ASEAN Regional Transboundary Smoke (PARTS), which installed an integrated forest fire monitoring network in southeast Asia. This network will include access to polar orbiting satellite imagery, ground-based atmospheric monitoring (meteorology, air sampling, optical depth), and a computer-based model to provide the capability to 10 countries in southeast Asia to model and monitor fires and other aerosol events in real-time. This project is being piloted in early 2000.

2.2.5.3 Urban Air Quality

Several studies have been conducted in Athens, Greece to determine urban air quality (Retalis et al 1999; Sifakis et al 1999; Deschamps and Sifakis 1992). Typically, the studies used Landsat images from one clear and one polluted day to quantitatively determine the aerosol distribution in the city. They also compared the satellite derived aerosol values to a network of ground-based air monitors that measure CO, NO_2, O_3, SO_2, and particulates. They found a correlation between the satellite-measured optical density and both the SO_2 and particulate ground-based measurements. The Ecole des Mines de Paris, Center for Energy Studies, Remote Sensing and Modeling Group have proposed similar work for Nantes, France.

A large international research project called Indian Ocean Experiment (INDOEX) monitored aerosols and urban haze over the Indian Ocean tropical region, primarily in relation to climate change. They used integrated data from 4 aircraft, 2 ships, 8 satellite platforms, and numerous ground stations (Nguyen et al 1998). One of their discoveries was a large cloud of dense haze, consisting of soot, sulfates, nitrates, organic particles, fly ash, and mineral dust, which forms over the Indian Ocean. They were able to identify the haze with satellites and determine its constituents with ground-based sampling stations on ships and islands.

Significant interest has been expressed in the transport of urban pollutants from the east coast of the U.S. to Canada and to Europe. These pollutants and their transport are just beginning to be understood, especially the long-range transport to Europe, although there is evidence that they may contribute 30-50% of the urban air pollutants in the North Atlantic (Keating 1999).

The AVHRR Pathfinder Atmosphere (PATMOS) project is developing a climatology of aerosols over land over the next 2 years. This information will likely be correlated as much as possible with any existing ground-based data.

2.3 SEARCH CONCLUSIONS

The results of this literature and project search confirm that the integrated use of satellite images and ground-based data is possible and useful for environmental monitoring and assessment. The recent advances in satellite technology, the growth of ground-based air monitoring networks, and the increased on-line accessibility of satellite sensor images and ground-based observations support the effective implementation of integrated projects. Their newness combined with the institutional separation of scientists in their fields and their countries has prevented the extensive integration of datasets in both research and real-time monitoring. The dialog started by this literature and project search confirms the interest of many researchers and policy staff in the integration of these fields.

Based on these positive results, the following general methodology for using integrated spaceborne and ground-based datasets was developed.

3. METHODOLOGY

The methodology was developed in a manner that would provide any interested individual or organization with a basic framework for developing and implementing a project that integrates the use of ground-based data and spaceborne images. The methodology is not intended to be comprehensive; rather, it is designed to be flexible enough to be used by general scientists and policy makers to measure many types of environmental phenomena with integrated datasets. It was tested and refined through application to a pilot project and we used the assessment of transboundary motion of air pollutants as a basis for its development. Table 3-1 outlines the methodology that is then described in detail.

Table 3-1. Outline of Methodology

Step A.	Define project
A.1	Define project goal and objectives
A.2	Define the information of interest
A.3	Conduct a literature search
A.4	Determine if the information of interest is observable with satellite imagery
A.5	Determine if the information of interest can be monitored at ground level
A.6	Determine temporal resolution requirements
A.7	Select a specific geographic region of interest
A.8	Determine if qualitative or quantitative data is needed or both
A.9	State your expected outcomes
Step B.	Find appropriate partners and resources
B.1	Find appropriate remote sensing partners
B.2	Find appropriate ground-based data partners
B.3	Address resource availability issues
Step C.	Select data sources
C.1	Select satellite(s) and the appropriate channels
C.2	Select ground-based monitoring measurement systems
C.3	Ensure compatibility of datasets
C.4	Develop methods for quantitative data analysis
Step D.	Apply techniques for electronic communication
D.1	Collect data and images from existing on-line databases
D.2	Use servers and websites to share large images
D.3	Use e-mail to notify others of new developments or data availability
Step E.	Conduct project
E.1	Secure resources
E.2	Finalize roles and responsibilities
E.3	Develop project plan
E.4	Launch project
E.5	Produce deliverables and monitor the project
E.6	Complete the project and celebrate with your team

3.1 STEP A. DEFINE PROJECT

Integrated use of satellite images and ground-based data can be a valid and productive method to study many environmental phenomena. While not utilized extensively to-date, researchers have successfully used joint datasets to study chlorophyll and algae blooms, land use change, volcanoes, weather conditions, and general ocean monitoring, among many other environmental phenomena. Joint datasets have also been used to study urban air pollution (SO_2 and particulates) for specific cities, movement of forest fires plumes, and trans-Pacific and trans-Atlantic dust storms. Current research efforts are underway to incorporate satellite sensors and ground monitoring stations to study other air constituents directly, such as toxics, ground level ozone, and ozone precursors.

Therefore, when developing a new monitoring project, it is important to review how satellite imagery and ground-based data can be used together and to define the project boundaries to be able to successfully use both. The following steps will help define the scope of the project.

A.1 Define project goal and objectives.

Define the purpose of conducting the project, what the project will accomplish, and what is outside of the project scope.

A.2 Define the information of interest.

Examples include water turbidity, algae blooms, dust storms, forest fire plumes, criteria air pollutants, aerosols, toxic air pollutants, and many others. To the extent possible, define specific measurement and precision requirements.

A.3 Conduct a literature search.

Review the literature, the Internet, and other sources of information about projects that may be similar to yours. This will provide information to help you: define your project, determine feasibility, find partners, find data sources, understand existing methods of integrating those data sources, and avoid reinventing a project or activity.

A.4 Determine if the information of interest is observable with satellite imagery.

Generally, a phenomenon can be monitored with satellite instruments if it creates a plume or obscures visibility (in air or water), changes the thermal reflectance at specified spectral wavelengths, alters the reflectively of the atmosphere (by changing its constituents), or is a visible land-based event. Often, images and data need to undergo significant analysis in order to observe the event clearly and correctly.

At this early point in the project, conduct an initial review of the literature and available satellite sensors, especially how investigators have used them in other projects. Many phenomena that at first glance seem to be "invisible" to satellite imagery can be monitored now or in the near future using new sensors, combinations of satellite channels, or other spectral analysis techniques. Also, some events can be monitored by satellite sensors that, when combined with ground-based data, can provide qualitative indicators for the information of interest. For example, monitoring the transport of particulates, combined with ground-based analysis of the particulate constituents, can provide information on the source of air toxics that cannot be seen directly with satellites alone.

A.5 Determine if the information of interest can be monitored at ground level.

Ground level data can be collected by your own instruments or can come from an existing network. Weather related information is monitored worldwide by organizations like World Meteorological Organization. Related meteorological data, such as visibility, are also available at a relatively high spatial resolution. Environmental agencies in most countries and cities monitor ground level ambient data, typically including particulates, SO_2, NO_X, lead, ozone, and volatile organics, and sometimes soot and a variety of toxics. These same agencies also usually monitor for water quality in certain water systems, including temperature, turbidity, dissolved oxygen, algae blooms, and sometimes toxics. All of these data are typically available from national organizations, as well as state and local organizations. Finally, government, academic, and private organizations conduct a wide variety of research projects that collect specific data for certain areas or events.

A.6 Determine temporal resolution requirements.

How rapidly the information you are collecting changes over time will directly influence the sources and quality of data. Depending if conditions change hourly, daily, monthly, seasonally, or annually, different satellites and ground sensors would be used to characterize the environmental parameter you are interested in. Geostationary (geosynchronous) satellites often measure a large region several times an hour while some polar orbiters measure a region twice daily. High-spatial resolution land monitoring satellites may pass over an area on the order of only every two weeks. Ground-based data are also collected over a wide variety of time periods, from hourly to daily to every few weeks.

Also important at this stage is to determine if you are interested in near real-time data in order to make immediate decisions, or if long-term series (historical) data are desired to analyze longer trends or past events, or both. How often your data are collected will also influence the ways you share and archive this data. Determine the rate of change and timing you are interested in order to select the appropriate data sources later.

A.7 Select a specific geographic region of interest.

The geographic region of interest should be defined using process-based criteria as opposed to only political or economic criteria. In order to remain manageable, most projects focus on a specific area, such as a certain city, a watershed, a border region between two countries, an ecosystem, or a trans-ocean region. Exceptions to this are when pollutants have an essentially global impact, for example chlorofluorocarbons or greenhouse gases. Others, such as persistent bioaccumulative toxics, may be emitted from specific locations, but transported long distances and concentrated in areas far from their source. If you are interested in the influx of pollutants to a certain region, then the surrounding areas at a considerable distance may also be of interest. Choose a region of a size that is most informative to the event or pollutant you are interested in, yet manageable with available monitoring. Keep in mind that once a project is completed in a specific location, the methods used there can often be expanded to similar regions elsewhere.

A.8 Determine whether qualitative or quantitative data are needed or both.

For some projects, general satellite images are all that are needed; in other cases, specific processed data such as the aerosol optical thickness are required. Qualitative data are easier to obtain, although it still requires enhancement and skilled interpretation of the satellite images. Most ground-based data are more quantitative, although simple visual observations on the ground can be useful, such as observations of fog or haze. Initial consideration should be given the comparability of data, covered in more detail in section 3.3.

A.9 State your expected outcomes.

Based on all this input, clearly define the deliverables and the outcomes you hope to achieve by the end of the project. Relate those outcomes to a human or environmental impact.

3.2 STEP B. FIND APPROPRIATE PARTNERS AND RESOURCES

By its very nature, using integrated spaceborne and ground-based datasets is a multi-disciplinary activity. Therefore, it is important to find the appropriate people and partners to conduct various elements of the work. One difficulty in achieving this is overcoming the barriers within and between technical fields and organizations. These barriers include lack of knowledge about the abilities of other fields, how to find the right people in the right organizations, issues related to funding and resource availability, and other physical and institutional barriers.

Finding and recruiting partners will be linked to the next step of selecting data sources, since you want partners who possess the experience with and the access to the required data. However, finding available people with the right expertise is of primary importance, since they can lead you to the data themselves, no matter their source.

B.1 Find appropriate remote sensing partners.

A few private companies and several national space organizations, such as U.S. National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), and the National Space Development Agency of Japan, conduct the actual launch of the majority of earth monitoring satellites. However, the operation and collection of data from these satellites is done by many organizations. In the U.S. government, major satellite information sources include:

- NASA – Coordinates the overall earth observation programs and almost all types of satellite data of various kinds.
- NOAA – Collects and analyzes weather, ocean, and air related data.
- USGS – Collects and analyzes land processes including land cover, geology, landforms, hydrology, biodiversiy and natural hazards.
- Other Government Organizations – Process data, produce data products, and disseminate required products to internal and external clients.

Internationally, many satellites and organizations exist and a significant amount of data from these satellites is available. Three of the many organizations include:

- European Space Agency (ESA) – The ESA launches and maintains satellites, collects and stores data, and also uses other organizations to operate and collect the data from its satellites, including Eumetsat, which operates Meteosat and other satellites.
- German Remote Sensing Data Center (DFD) – DFD is a part of the German Aerospace Center, Deutsches Zentrum für Luft- und Raumfahrt (DLR), which manages the German satellites and data collection.
- Canadian Space Agency (CSA) and the Canada Centre for Remote Sensing (CCRS) in Natural Resources Canada – CSA has several satellites of interest and remote sensing data are collected and used by the CCRS.

Other organizations that should be considered as potential partners are international monitoring groups. Examples include the UNEP/GRID Centers, the Center for Earth Observations, and many academic institutions and universities. The best way to find these organizations is to review the literature and search the Internet to find others that have published work similar to your area of interest.

Many of the government and international organizations that provide satellite data are described in more detail in the Research Results section. Private companies are another resource for satellite remotely sensed data. Although engaging private companies can be a costly option, if high spatial resolution images (1 km or less) are necessary for your project, they should be considered.

When looking for partners from government organizations and monitoring groups, start with the organizations in your country since they will likely be the easiest partners at first. Next, choose those that have placed their information for easy use by researchers on the Internet. Finally, given the ability to share data and information via email and the Internet, there is no need to limit your project to domestic partners, so international organizations, scientists, and partners can be sought.

B.2 Find appropriate ground-based data partners.

Unlike satellite data, ground-based information can be available from all levels of government (federal, state, local), from organizations with diverse missions, and from many university and academic-type research institutions. For example, these data could be from national regulatory air monitoring networks, airport visibility databases, local water quality monitors, or research projects on specific subjects. The source of data that you choose depends on the size of the region and the time period of interest. Often several ground-based datasets can be used, such as single data sets collected for a specific project (such as, an air or water sampling campaign during a pollution event), combined with data from an on-going existing network (such as, a network of air monitoring stations or ocean buoys).

Other examples of sources of ground-based data are described in the section 2.2. The importance of searching the literature and the Internet cannot be overstated when seeking partnerships and data sources. Data are scattered widely among diverse groups and organizations, thus they must be actively sought out.

B.3 Address resource availability issues.

Once data sources have been found and potential partnerships identified, the availability of resources must be addressed. A significant amount of data is available on the Internet or from government service-type organizations at little or no cost. However, having the resources to analyze and process that information is what makes partnerships essential. Some organizations are willing and able to partner if your work is similar or additive to work they are conducting. Most organizations are always interested in well-defined, interesting projects that could use their unique skills.

Another resource option is volunteers, who are people or organizations that have specific skills or interests, but may lack the resources to dedicate interested personnel to your project. Signed agreements (e.g., memorandum of understanding) or more informal written agreements are two approaches to overcome these resource barriers, especially if the agreements are specific about the roles and responsibilities of all parties, the deliverables, and other details. Seeking joint funding or sharing available funding is another approach. Regardless, it is important that the issue of resources, including funding, be addressed when partnerships are being developed and monitored carefully as the project progresses.

3.3 STEP C. SELECT DATA SOURCES

The next step for the team (the project manager and partners) is to more thoroughly explore the sources of available information and data, from both spaceborne satellites and ground-based monitors. It is also important to characterize relevant datasets. A well-defined project scope will make data selection easier.

There are two general kinds of data that you might consider adopting, at least initially. They are:

- real-time data
- time-series (historical) data

Real-time data are needed if decisions made with that data would influence rapidly changing situations or would assist in the timing of sampling, such as increasing ground-based particulate sampling during a forest fire or sending a ship to sample an algae bloom identified with a satellite. Time-series (historical) data are used for change or trend analyses through a review of past conditions or a past event. They can also be used to plan for future real-time monitoring.

C.1 Select satellite(s) and the appropriate channels.

Using the data sources that you investigated when finding partners and resources, select the specific satellites and channels (wavelengths) that will work for your project. Often, multiple satellites can be used to monitor and analyze the same event, each providing different information and insight, such as using AVHRR to visualize the transport of a dust plume and TOMS to quantify the aerosol optical thickness. Also, different channels of the same satellite can be used to enhance images; for example, the subtraction of one channel from another can sometimes allow dust to be more easily distinguished from clouds. More information on these techniques is available in section 2.2.

Investigate all the satellites that you think may have relevant data, since their names do not always accurately describe their complete abilities (such as TOMS, the Total Ozone Mapping Spectrometer, which has also successfully been used to map aerosols). Rely on your literature search of similar projects and work with your expert partners.

C.2 Select ground based monitoring measurement systems.

Using the data sources that you investigated when finding partners and resources, select the specific ground-based networks that will work for your project. If collecting your own primary ground-based data, consider ways that existing networks could enhance your dataset.

C.3 Ensure compatibility of datasets.

Once you have determined the datasets you will be using, you need to compare their characteristics and valid applications. Integration of ground and image data requires comparison of detailed point data with larger, more general image information. Some of the more important characteristics that should be considered are:

- Spatial coverage: Make sure that data are available in the region or area of interest using both datasets, i.e., ground-based data are collected in that region and a satellite images of a comparable area.
- Scale/Resolution: Data from satellites have a specific resolution ranging from several hundred meters to 50 or more kilometers. Ground-based point source data may be impacted on a very small local scale, such as an air sampler next to a highway or refinery. Consider how the resolutions of the data sources compare when reviewing specific data.
- Atmospheric vertical layer: When retrieving atmospheric constituents (i.e., pollutants) from satellite data and comparing them to ground-based data, it is important to know where the retrieved satellite data quantities exist within the atmosphere, i.e., are they gas concentrations within the stratosphere, the troposphere, on the ground, or are they cumulative of multiple layers.
- Temporal frequency: Ensure that your images and ground data are taken at comparable times. It is important to understand the relationship between the time and date of ground samples and features in the images. For example, if you are using Landsat data that takes a single image of your city once every 16 days, and your particulate monitor collects data every 6 days, it is important that those monitoring days correspond and their relationship is understood.
- Temporal duration: Duration is important when the data collected from ground monitors may be an 8-hour or multi-day average, but a satellite image is a single snapshot. Understand and carefully consider how conditions change over time and how they compare to a single or a series of discreet images.
- Application: Compare the qualities of what is being measured. For example, some satellites measure aerosols under 1 micron, but ground-based monitors may measure particulates under 10 or 2.5 microns.

These data characteristics define why you cannot readily assume that all of your datasets will match in space and time. This does not mean that datasets have to be a perfect match to use them. In fact, it would be difficult to find perfectly matched data given that the monitoring systems were usually developed for very different purposes (for example, global warming versus human health). However, as long as the differences are recognized, then appropriate comparisons can be made. This is particularly true when the parameter you are interested in is not being directly measured, and properties of related measured data are combined to derive information; for example, gaining an understanding of the movement of toxics by monitoring particulate movement combined with ground-based chemical analysis.

C.4 Develop methods for quantitative data analysis.

The transformation of data into information typically follows several steps 1) data processing, quality assurance, data reduction and cataloging; 2) data modeling and analysis; 3) feature or information extraction from images; and 4) visualization and decision support. One type of data model is data integration. In order to compare data in a quantitative manner, it is necessary to combine, reconcile and transform these into a form relevant to the specific effects of concern. Each sensor provides a unique view into the multidimensional features of the effect. The multiple features can support each other and when fused can identify the event being studied with more certainty. For example, multiple satellite images can be fused by simply georeferencing and superimposing them or, more complexly, conducting mathematical operations to combine them. These types of integration can also incorporate point data such as surface observations from AERONET. The resulting integrated images are analyzed for trends, such as the spatial extent of an aerosol plume, its size distribution, or chemical composition. These features from the multiple data sources are then assembled to formulate a more complete picture of environmental conditions. Your project should investigate existing data integration techniques and their applicability to your data.

3.4 STEP D. APPLY TECHNIQUES FOR ELECTRONIC COMMUNICATION

Often when working on multi-disciplinary projects, and especially if the data is real-time or collected in the field, communication and data transfer between those involved is critical. The Internet and affordable high memory computers have made this process much easier, and they can be configured to obtain essentially all satellite data and some of the ground-based data automatically. However, as with any automated system, well-documented and especially working backup plans are imperative. Internet and e-mail can be used to coordinate a small project involving 2 or 3 people or a large program of early warning and image processing. Occasional face-to-face meetings can be important for making rapid progress and building teams.

D.1 Collect data and images from existing on-line databases.

A significant amount of data and images are already available on-line, including many satellite images and ground-based datasets from federal agencies, such as air quality data and aerosol optical thickness from nationwide networks. Some of these data may be obtained through web-based servers, although some data must be ordered via Internet request forms. Using on-line databases is an efficient way to collect data, both real-time and historical. They are also useful for identifying and browsing available data and determining the datasets that are relevant to your project.

Many researchers are beginning to put images and data from their models on-line in an operational mode. Typically, these model runs are available for use for research purposes if developers are given proper credit. These models often include a summary of the data and images used to develop them on a daily basis. The ability to access data, images, and models on-line can greatly reduce the amount of resources needed by a small qualitative project.

D.2 Use servers and websites to share large images.

Large images that have been downloaded and processed can be placed on a server and accessed through the worldwide web. This avoids some of the problems of sending large amounts of data through e-mail, which is especially important if any of your team is accessing the data remotely. The web can also serve as a platform for dialog or feedback.

D.3 Use e-mail to notify others of new developments or data availability.

E-mail can be used to communicate changes and developments in the project and to notify the team when data or images are available on the website. If you have a project and many people interested in its activities a listserver can enable you to send mass mailings to interested people.

3.5 STEP E. CONDUCT PROJECT

The previous four steps pave the way to implementation of the project. The following steps are final preparation and implementation guidelines. Many of these are basic well-known concepts of project management and thus are presented in outline form only.

E.1 Secure resources.

Ensure that you have sufficient resources, both financial and labor, to implement the project. This should be done using standard project management and planning concepts. The more specific you are about your project, the more accurate your resource estimates. If needed, reduce scope or plan for a phased implementation in order not to overestimate the amount of work that can be accomplished.

E.2 Finalize roles and responsibilities.

Similar to ensuring resources, finalize the role that each partner will play. Make sure they understand what is expected and their level of effort.

E.3 Develop project plan.

Using the basic materials developed thus far as well as the resource information and defined roles and responsibilities, develop a project plan. The project plan will be specific to your information need, and should guide the project throughout its life. It should include the following elements: scope, partners and their roles and responsibilities, proposed project description, schedule, milestones, quality requirements, deliverables, budget, project constraints, project resources, and reporting requirements.

E.4 Launch project.

Initiate the project, follow the project plan, and communicate regularly with partners.

E.5 Produce deliverables and monitor the project.

Document your successes and review the areas that were less successful. Always keep in mind the development of future work, partners, and resources while the project is on-going, especially if you had to reduce scope to fit available resources. Place your data and reports on the Internet, present at conferences, and publish, in order to allow others use your data.

E.6 Complete the project and celebrate with your team.

Broadcast your successes to others and congratulate your team.

4. PILOT PROJECT

We used several criteria to select an existing study as a pilot project to refine and demonstrate our methodology for monitoring transboundary aerosol transport. First, the study had to be relevant to a U.S. environmental issue, as required for work funded by the U.S. EPA. Second, it had to be relevant for other countries, as required by UNEP/GRID Sioux Falls Center. Third, it had to use the capabilities of the partners involved, particularly U.S. EPA, UNEP/GRID Sioux Falls, Battelle Memorial Institute, U.S. Geological Survey's EROS Data Center, and Washington University in St. Louis.

The selected pilot study tested the methodology on an existing EPA-NOAA Florida Everglades aerial and ground-based mercury monitoring project. Table 4-1 outlines the application of the methodology followed by a

Table 4-1. Methodology Used for Transboundary Aerosol Transport Pilot Study

A. Define Project. The selected study is an existing EPA-NOAA ground-based and aerial mercury monitoring project conducted in southern Florida. It is investigating the airborne sources of mercury found in fauna living in the Everglades. This study used an airplane equipped with innovative equipment to measure various forms of mercury, as well as particulates, NO_X, CO_2, and other factors that help identify the airborne sources of ambient mercury concentrations. Our role is to provide satellite imagery that will qualitatively support their analytical data.

B. Gather partners and resources. Our *partners* are U.S. Environmental Protection Agency (Office of International Activities and other offices), UNEP/GRID Sioux Falls related staff (including Raytheon staff from the USGS EROS Center), National Oceanic and Atmospheric Agency (NOAA), Battelle Memorial Institute, and Washington University in St. Louis. Our *resources* include National Aeronautic and Space Administration (NASA), NOAA Operational Significant Event Imagery Server (OSEI) project, Naval Research Laboratory (NRL), and information from the main partner organizations.

C. Select data sources. Data sources for this project include:

- Images from TOMS, SeaWiFS, AVHRR, Landsat 7, and Meteosat 7
- NOAA daily operational significant event imagery report data
- Aerial and ground-based data from the Florida sampling team (not yet available)
- EPA AIRS data for Monroe and Dade counties, Florida
- NRL NAAPS model and associated images
- Model results from HYSPLIT

D. Apply techniques for electronic communication. The team communicates through e-mail as well as through a website provided by Washington University (http://capita.wustl.edu/Databases/UserDomains/EDISSM/).

E. Conduct project. Selected results from the pilot project are presented in this document.

more detailed description of the project and the results.

4.1 PROJECT DESCRIPTION

The selected pilot study provided assistance to an existing EPA-NOAA Florida-based aerial and ground mercury monitoring project being conducted because of high levels of mercury found in fish living in the Everglades. The source of the mercury is unknown and may be coming from several sources (Guentzel 1997). The EPA-NOAA project is examining the deposition of mercury to the Everglades and trying to further determine its source. Current theories suggest that airborne mercury may be coming from local sources, non-local U.S. sources, the Atlantic Ocean, Africa, Central America, or some combination of these. This study used an airplane equipped with innovative equipment to measure various forms of mercury, as well as particulates, NO_X, CO_2, and other factors that will help identify the sources of ambient mercury concentrations. Ground level air sampling was also used as a baseline and included measurements similar to those made on the aircraft. Intensive monitoring periods occurred during January and June 2000. Table 4-2 shows the airborne sampling information; ground-based sampling continued

Table 4-2. Airborne Sampling Dates and Locations

January Sampling Runs			June Sampling Runs		
Date	Altitude (feet)	Water Body	Date	Altitude (feet)	Water Body
01/18/00	5000	Atlantic	06/03/00	10000	Atlantic
01/18/00	10000	Atlantic	06/03/00	1500	Atlantic
01/20/00	1500	Gulf of Mexico	06/03/00	500	Atlantic
01/20/00	8500	Gulf of Mexico	06/04/00	10000	Atlantic
01/20/00	1500	Atlantic	06/04/00	1500	Atlantic
01/20/00	8500	Atlantic	06/04/00	200	Atlantic
01/23/00	8000	Atlantic	06/06/00	1000	Everglades
01/23/00	11500	Atlantic	06/06/00	5000	Everglades
01/25/00	1500	Atlantic	06/09/00	11500	Atlantic
01/25/00	7500	Atlantic	06/09/00	11500	Atlantic
01/26/00	1500	Atlantic	06/12/00	10000	Atlantic
01/26/00	7500	Atlantic	06/12/00	4500	Atlantic
01/27/00	1500	Everglades	06/14/00	10000	Atlantic
01/27/00	7500	Everglades	06/14/00	5000	Atlantic
01/31/00	8000	Atlantic	06/15/00	1000	Everglades
01/31/00	750	Atlantic	06/15/00	1000	Everglades
02/01/00	500	Everglades	06/18/00	1000	Atlantic
02/01/00	500	Everglades	06/18/00	200	Atlantic
			06/21/00	10000	Atlantic
			06/21/00	5000	Atlantic
			06/22/00	5500	Atlantic
			06/22/00	5500	Atlantic
			06/22/00	10000	Atlantic
			06/25/00	10000	Atlantic
			06/25/00	1500	Atlantic
			06/26/00	10000	Atlantic
			06/26/00	5000	Atlantic

for several days before and after the airborne sampling.

This pilot project supplemented the existing Florida mercury research project by providing spaceborne images and data to monitor the transport of aerosols/particulates. Satellite remote sensing and models based on satellite information enhanced this project by providing visual evidence of pollutant transport that may be bringing mercury and other toxics to the area. The satellite images were used to track aerosols as they advect away from their respective source regions, in a time series (historical) manner over the January and June sampling campaigns. These images will be combined with aerial and ground-based sampling to determine the constituents (including mercury) of the particulates and aerosols that can be seen by the satellites. The goal was to help the researchers gain a greater understanding of the transport of airborne toxics than could be obtained from ground-based sampling only.

A literature search confirmed the types of events visible to satellites that may be of interest to the Florida mercury project and also revealed the following example source regions for these events:

- Dust storms (Africa, southern U.S.)
- Fires (Southern Florida, South America, Central America, and Caribbean)
- Urban Pollution and Haze (Southern and Eastern United States)
- Volcanoes (Caribbean as well as stratospheric transport)

4.2 PARTNERS AND RESOURCES

The emphasis of this project is on the methodology. As such the pilot project selected was one that best fit the criteria of the methodology and which was ongoing so that the methodology could be evaluated in a timely fashion. The partners and resources contributing to the pilot project are as follows.

4.2.1 U.S. Environmental Protection Agency

This project originated from the EPA Office of International Activities (OIA) due to their connection with UNEP/GRID Sioux Falls, their interest in transboundary pollution, their participation in the persistent organic pollutant treaty, and their support of the Florida mercury project. They supported the contract with Battelle Memorial Institute to coordinate this work.

The EPA's Office of Research and Development (ORD) is one of the partners in the Florida mercury study. The ORD researchers helped the pilot project by identifying the most useful imagery for their project.

4.2.2 UNEP/GRID Sioux Falls and USGS EROS Data Center

UNEP/GRID Sioux Falls is part of UNEP's Division of Early Warning & Assessment. Among the missions of this division is the evaluation of methodologies that contribute to UNEP's mission of support for international treaties and conventions. The investigation of assessment and monitoring strategies is crucial to this mission.

The UNEP/GRID Sioux Falls partnership with USGS EROS Center and NASA promoted access to expertise and data available through these partners. Atmospheric and radiometric scientists at the USGS EROS Data Center have extensive experience in the analysis of the atmosphere component in the image signature. This expertise translates into a detailed knowledge of the constituents of the atmosphere. This expertise is backed up by years of direct observations, which are correlated to the image overpasses.

4.2.3 National Oceanic and Atmospheric Agency (NOAA)

NOAA is one of the major partners in the Florida project, providing the airplane for sampling as well as research services and project management.

4.2.4 Battelle Memorial Institute

Battelle provided project coordination and management, as well as knowledge of environmental pollution, visualization, and data integration.

4.2.5 Washington University at St. Louis

Staff at the Center of Air Pollution and Impact and Trend Analysis (CAPITA) provided knowledge of aerosol transport and internet services as well as access and communication of images and analytical techniques.

4.2.6 Other Resources

While not direct partners in this project, several organizations provided critical data or analysis that supported this project. These included: NOAA Operational Significant Event Imagery Server (OSEI) project, which analyzes and posts daily satellite images on major visible events such as dust storms and fires; and the Naval Research Laboratory (NRL), which develops and posts atmospheric modeling data based on input from satellites and ground weather monitors.

4.3 DATA SOURCES

The data used for this project included ground-based/aerial data, modeling data, and spaceborne data. The majority of the data were from accessible sources on the Internet or from various organizations.

Ground-based data sources included:

- Aerometric Information Retrieval System (AIRS) for Monroe and Dade counties, from the EPA Office of Air Quality Planning and Standards
- Airplane and ground monitoring data from the NOAA-EPA Florida team (not yet available)

Modeling data included:

- Navy Aerosol Analysis and Prediction System (NAAPS), both world scale models and tropical Atlantic models, as available, from the Naval Research Laboratory NAAPS website
- Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) 4 Model, which uses meteorological inputs to compute air parcel trajectories

Satellite data included:

- Advanced Very High Resolution Radiometer (AVHRR), for aerosol optical thickness, from the NOAA OSEI Team website and the NAAPS website
- Total Ozone Mapping Spectrometer (TOMS), for absorbing aerosols and the motion of global or regional aerosol clouds, from the NASA Goddard Space Flights Center TOMS website and the NAAPS website
- Sea-viewing Wide Field-of-view Sensor (SeaWiFS), for visible color images, from the NASA Goddard Space Flights Center SeaWiFS website
- Meteosat 7, for images of the beginning of African dust storms, from the NOAA OSEI Team website
- Landsat 7 Thematic Mapper, for qualitative view of aerosols, from the USGS EROS Data Center

Data compatibility issues were minimal since the images were used in a predominately qualitative manner. Information was reviewed on a daily timescale.

4.4 COMMUNICATION

The pilot project team members were located in multiple states (District of Columbia, North Carolina, South Dakota, Missouri) and the sampling was conducted in Florida, so electronic communications were essential. This was primarily accomplished through e-mail. Large images were also placed on the Internet, through a server and site provided and maintained by Washington University in St. Louis (http://capita.wustl.edu/

databases/userdomains/EDISSM/). This allowed the team members to share information easily. Other electronic resources were also contributed by Washington University.

4.5 PROJECT IMPLEMENTATION

Once resources and partners were secured, a short project plan was developed. The following steps were taken to implement this project:

(1) Obtained sampling dates and locations from the Florida team once sampling was completed.

(2) Reviewed images and information from the appropriate satellites, ground-based monitors, and models during the dates and times the team was sampling.

(3) Based on the images and data, determined the general trends of possible influences (e.g., none, local, non-local U.S., African dust) in the Florida Everglades area.

(4) Chose a few specific events on which to prepare more detailed data.

(5) Prepared final report.

(6) Evaluated success of methodology.

An approximate implementation schedule was as follows:

July 2000: Confirmed partners, roles, and resources. Conducted final scope review.

August 2000: Reviewed project and determined appropriate data sources.

September 2000: Collected images and data.

October 2000: Conducted general trends and detailed case analysis.

November 2000: Prepared final report and complete preliminary analyses.

4.6 PILOT PROJECT RESULTS

The NOAA-EPA Florida team conducted two airplane sampling campaigns during late January-early February 2000 and during June 2000. Using a range of satellite imagery, models, and ground-based data, a general review of the date range was conducted. Table 4-3 (page 30 & 31) presents a summary of the data used for that analysis. The data in this table were developed based on a qualitative visual inspection of the images and not on quantitative image analysis.

Based on this summarized information, three types of events were noted as possibly influencing air quality over Florida, specifically:

- Local fires, likely from agricultural field burning: January 21, 2000 and June 1-2, 2000
- Entrainment of U.S. air pollution from offshore to southern Florida: February 2-4, 2000 and May 30-June 2, 2000
- Dust storms from Africa reaching the Florida coast: June 20-30, 2000 (most intense on June 28-30, 2000)

4.6.1 Local Fires

Farmers in southern Florida often burn their crop stubble after harvest throughout the year. Three significant incidences of this were noted by the NOAA OSEI team and reported on their website during the January and June sampling campaign timeframes (see Figure 4-1). Additionally, a Landsat 7 image on February 5, 2000 revealed several fires throughout the agricultural area in south-central Florida producing smoky hazy skies on an otherwise clear day (see Figure 4-2). The NOAA-EPA Florida team could see plumes from fires during the January sampling campaign and they attempted to sample them with the airplane.

The images in Figures 4-1 and 4-2 indicate that local fires may impact south Florida on a regular basis in late January and early February and perhaps other times of the year. None of the observed fires appeared to be occurring in the Everglades, so this influence may be weak unless ground observations indicate otherwise.

High-resolution satellite images are required to observe these agricultural fires from space unless the fires are unusually large or produce

Clear	7-Jun-00				less than 0.04					
Clear	8-Jun-00				less than 0.04					
Clear	*9-Jun-00*	*			*less than 0.04*					
Clear	10-Jun-00				less than 0.04					
Clear	11-Jun-00		19	14	less than 0.04					
Africa	*12-Jun-00*	*			*0.04*	*Africa Dust*	*less than 0.7*	*0.3*	*Not clear*	*
Clear	13-Jun-00				less than 0.04					
Clear	*14-Jun-00*	*			*less than 0.04*					
Clear	*15-Jun-00*	*			*less than 0.04*					
Clear	16-Jun-00				less than 0.04					
Clear	17-Jun-00		25	15	less than 0.04					
Clear	*18-Jun-00*	*			*less than 0.04*					
Clear	19-Jun-00				less than 0.04					
Africa	20-Jun-00				0.04	Africa Dust	less than 0.7	0.3	Not clear	
Africa	*21-Jun-00*	*			*0.04*	*Africa Dust*	*less than 0.7*	*0.3*	*South of FL*	
Africa	*22-Jun-00*	*			*less than 0.04*					
Africa	23-Jun-00		30	18	less than 0.04					
Africa	24-Jun-00				less than 0.04				Yes	
Africa	*25-Jun-00*	*			*0.04*	*Africa Dust*	*less than 0.7*	*0.2*	*Yes*	
Africa	*26-Jun-00*	*			*less than 0.04*				*Yes*	
Africa	27-Jun-00				less than 0.04					
Africa	28-Jun-00				0.04	Africa Dust	0.70	0.2	Near FL	*
Africa	29-Jun-00		45	36	0.04	Africa Dust	less than 0.7	0.2	Not clear	
Africa	30-Jun-00				0.08	Africa Dust	0.70	0.2	Yes	

Note: Africa influence continues to July 3, after that a mix of Africa and US influences

Key: *Entries in italic*s represent days where aerial data were sampled.

Orange for days with possible local fire influence.

Blue for days with possible urban haze influence.

Yellow for days with possible African dust influence.

Note: Satellite and model values based on qualitative visual inspection of the images.

Table 4-3. Summary of Data Results

Overall Assessment Of Influence	Date	FL Plane Sampling Date	EPA AIRS Data Monroe County, PM-10 Total, ug/m3, Lat 24:34:51N, Long 81:44:48W	EPA AIRS Data Dade County, PM-10 Total, ug/m3, Lat 25:50:01N, Long 80:14:32W	NRL NAAPS Model, Optical Depth, June 1-30 Trop Atlantic Runs (min 0.04), All Others World Runs (min 0.1)	NRL NAAPS Model Probable Source	TOMS Aerosol Index (min 0.7)	NESDIS AVHRR Optical Thickness (min 0.2)	SeaWiFS Image Observations	AVHRR OSEI Local Fires	Landsat 7 Image Available
Clear	17-Jan-00				less than 0.1						
Clear	*18-Jan-00*	*			*less than 0.1*						
Clear	19-Jan-00		10	18	less than 0.1						
Clear	*20-Jan-00*	*			*less than 0.1*						*
Fire-Maybe	21-Jan-00				less than 0.1					Burns N of EvG	
Clear	22-Jan-00				less than 0.1						
Clear	*23-Jan-00*	*			*less than 0.1*						
Clear	24-Jan-00				less than 0.1						
Clear	*25-Jan-00*	*	*16*	*33*	*less than 0.1*						
Clear	*26-Jan-00*	*			*less than 0.1*						
Clear	*27-Jan-00*	*			*less than 0.1*						
Clear	28-Jan-00				less than 0.1						
Clear	29-Jan-00				less than 0.1						
Clear	30-Jan-00				less than 0.1						
Clear	*31-Jan-00*	*	*9*	*26*	*less than 0.1*						
Clear	*1-Feb-00*	*			*less than 0.1*						
US	2-Feb-00				0.10	US (sulfates)	less than 0.7	less than 0.2	Not available		
US	3-Feb-00				0.10	US (sulfates)	less than 0.7	less than 0.2	Not available		
US	4-Feb-00				0.10	US (sulfates)	less than 0.7	less than 0.2	Not available		
Clear	5-Feb-00				less than 0.1						*
Clear	6-Feb-00		13	15	less than 0.1						
Clear	27-May-00				less than 0.1						*
Clear	28-May-00				less than 0.1						
Clear	29-May-00				less than 0.1						
US	30-May-00		14	21	0.20	US	less than 0.7	0.2			
US	31-May-00				0.10	US	less than 0.7	less than 0.2			
US	1-Jun-00				0.04	US	less than 0.7	0.2	Haze N of FL	Burns N of EvG	
US	2-Jun-00				less than 0.04				Haze N of FL	Burns N of EvG	
Clear	*3-Jun-00*	*			*less than 0.04*						
Clear	*4-Jun-00*	*			*less than 0.04*						
Clear	5-Jun-00		28	29	less than 0.04						
Clear	*6-Jun-00*	*			*less than 0.04*						

Figure 4-1. Burning (red spots) and smoke plumes (*faint* blue haze) in southern Florida on January 21, 2000 (top) and June 1-2, 2000 (bottom). AVHRR Images courtesy of NOAA OSEI Team.

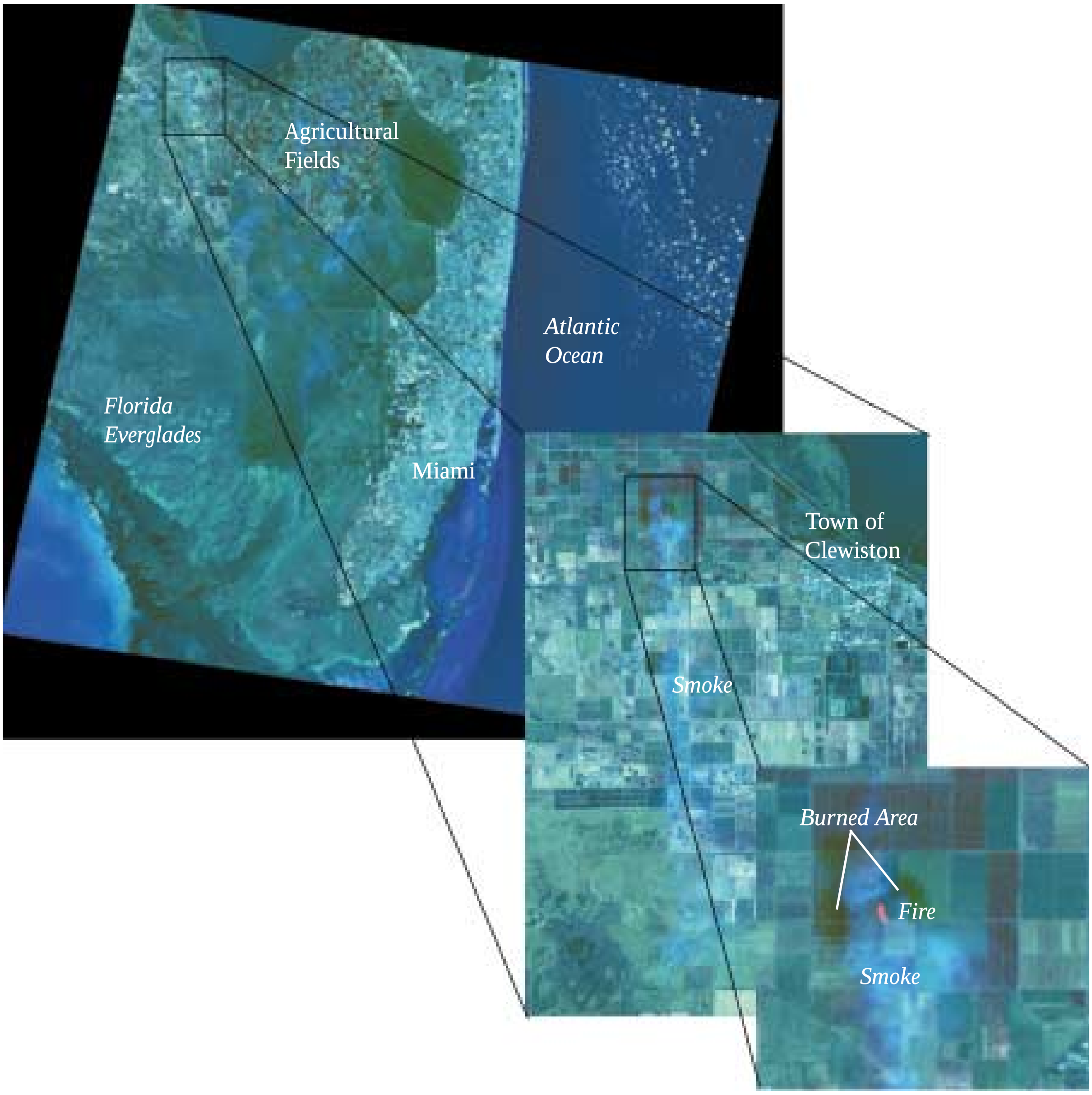

Figure 4-2. Agricultural fires in southern Florida on February 5, 2000. This Landsat-7 image, bands 731 (RGB), has been enhanced to reveal thermal signatures from agricultural fires in red and smoke plumes as faint blue. Images from top to bottom are zooming in on one fire just northeast of the town of Clewiston on the shores of Lake Okeechobee. Image and analysis courtesy of the USGS EROS Data Center and UNEP/GRID Sioux Falls.

very dense smoke plumes. This means that images from satellites such as Landsat-7 (30 meter resolution) are required to observe smaller localized fires. Since Landsat-7 images are available only every 16 days and are not easily available on the Internet, routine monitoring is not possible at this time even when combined with images from the other Landsat satellites. Large fires may be observed with lower resolution imagers such as AVHRR. Some of the new technologies such as MODIS and MISR may increase the ability to observe fires and smoke plumes on a daily basis in the near future.

4.6.2 Coastal Pollution Entrainment

Using the Naval Research Laboratory NAAPS model, we could view daily model results of pollutant movement, including sulfates that are more difficult to see with satellites in the visible range. Following the daily sequence, it was possible to follow sulfates as they were blown off the U.S. east coast, then entrained back towards southern Florida. Based on this model, this apparently happened two times during the Florida project sampling dates, with U.S-based pollutants reaching southern Florida on February 2-4 and May 30-June 2, 2000. Figure 4-3 shows a world-wide NAAPS model image on February 2, one of the peak days where U.S. influence was apparent. Figure 4-4 shows a series of images from January 29-February 5, focusing on the U.S. portion of the NAAPS model images. This series illustrates how the pollutants moved on a daily basis. To reconfirm the direction of airflow, Figure 4-5 is a back trajectory model from HYSPLIT that shows that the air in the Everglades on February 2 came

NAAPS Optical Depth for 02 Feb 2000
Smoke: Blue Sulfate: Orange/Rd Dust: Green/Yellow

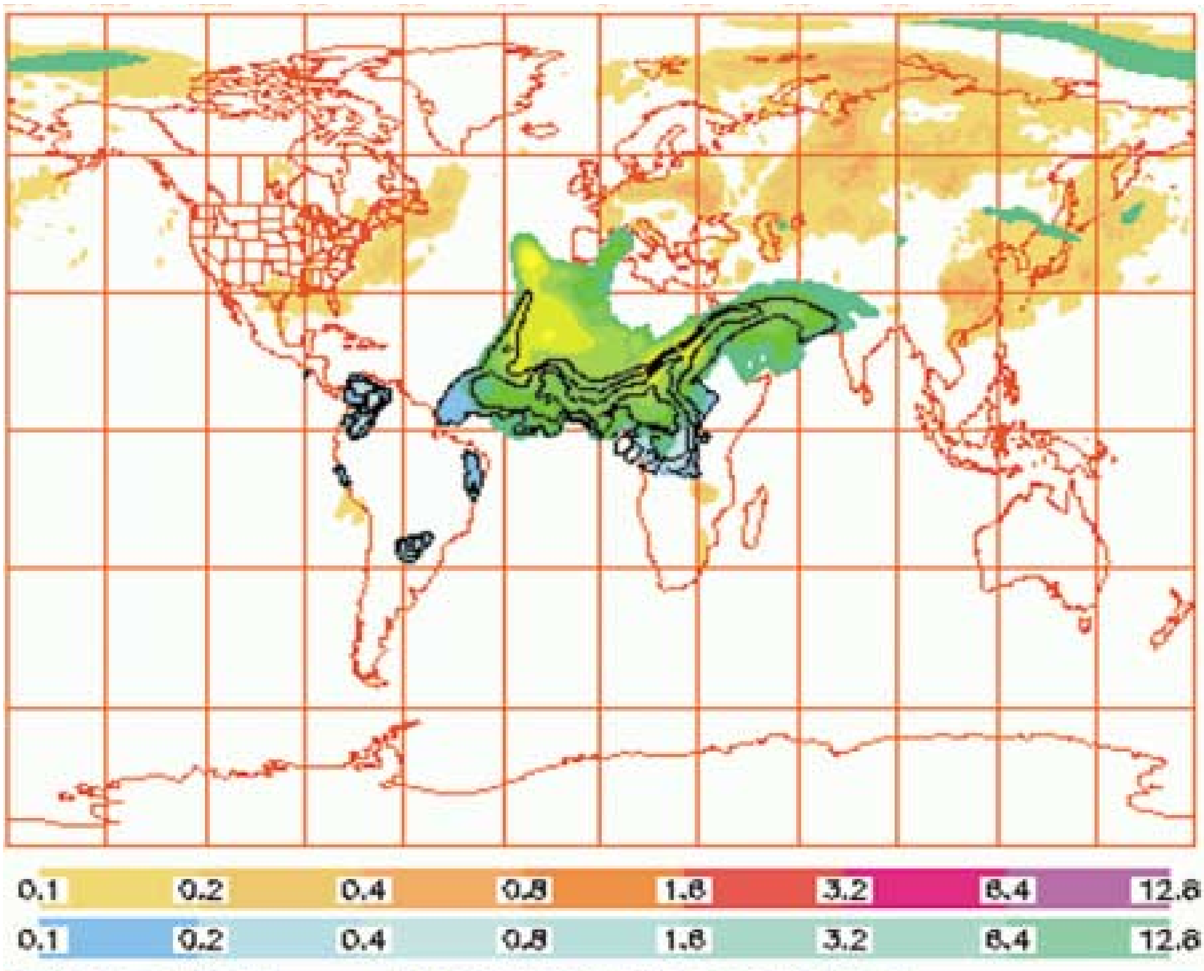

Figure 4-3. During early February, the NAAPS model suggests an influence of pollutants from the U.S. mainland to southern Florida (note orange sulfate plume over Florida). This figure is the world run of the NAAPS model on February 2, 2000. Image courtesy of the Naval Research Laboratory.

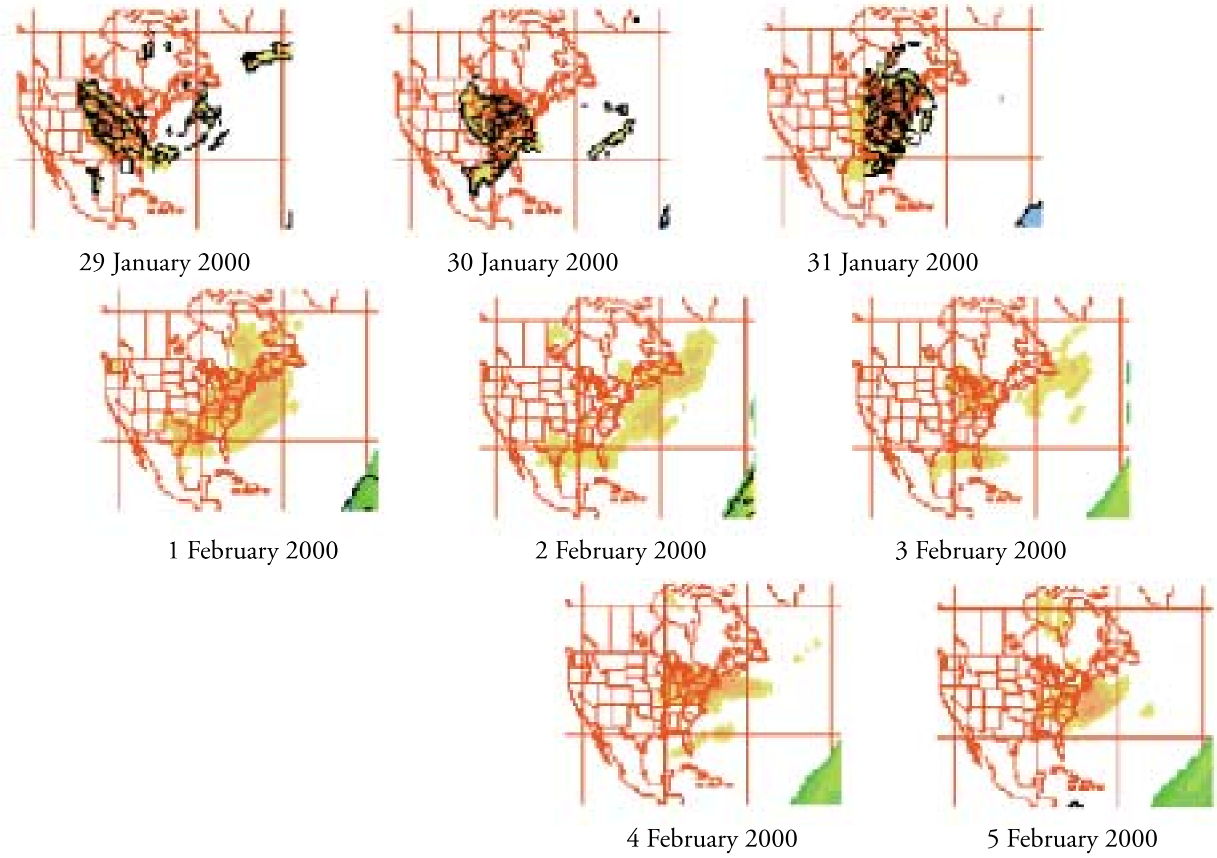

Figure 4-4. Entrainment of U.S. mainland pollutants (visible here as sulfates) to Southern Florida. From February 2-4, 2000, the NAAPS model suggests that pollutants from the U.S. that had blown offshore returned to the U.S. mainland, including southern Florida. These images show a time series of the pollutions represented in the image shown enlarged in Figure 4-3. Images courtesy of the Naval Research Laboratory.

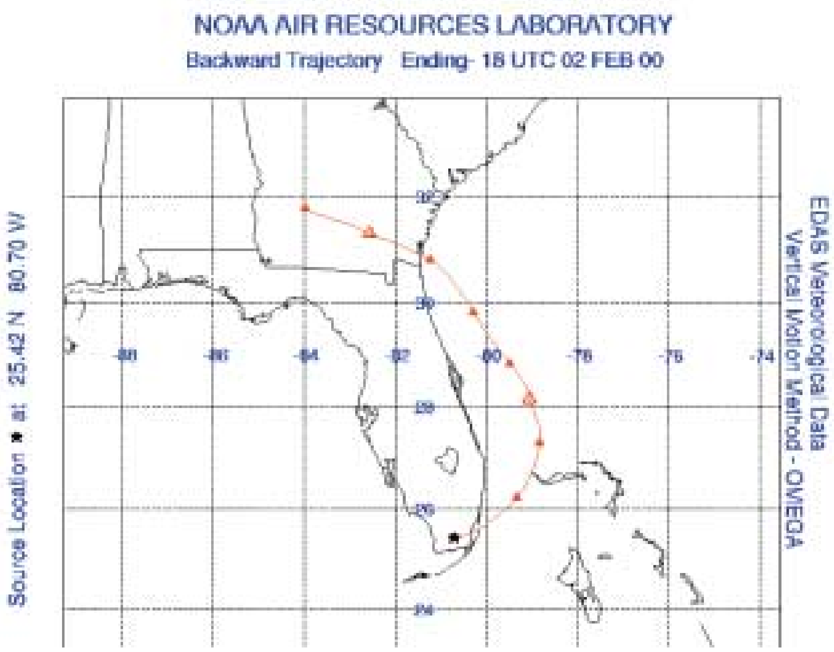

Figure 4-5. HYSPLIT model data confirming entrainment of U.S. mainland pollutants to Southern Florida. The HYSPLIT model suggests that pollutants in the Everglades on February 2, 2000 had come from the U.S. after traveling offshore from their mainland source. The triangles represent 6-hour intervals. HYSPLIT courtesy of the NOAA Air Resources Laboratory.

Figure 4-6. SeaWiFS image of urban pollutants traveling offshore on June 2, 2000, although it is not visible that they arrive in Florida in this image. Image courtesy of NASA Goddard Space Flight Center.

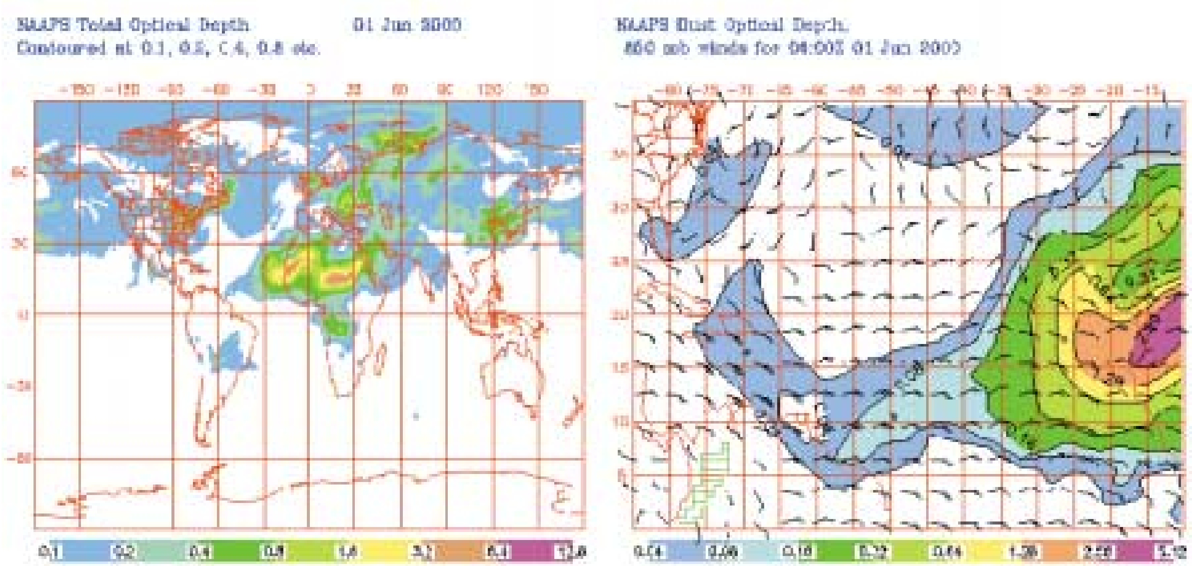

Figure 4-7. During late May and early June, the NAAPS model suggests an influence of pollutants from the U.S. mainland to southern Florida. This figure is two runs of the NAAPS model (global and tropical Atlantic) on June 1, 2000. Images courtesy of the Naval Research Laboratory.

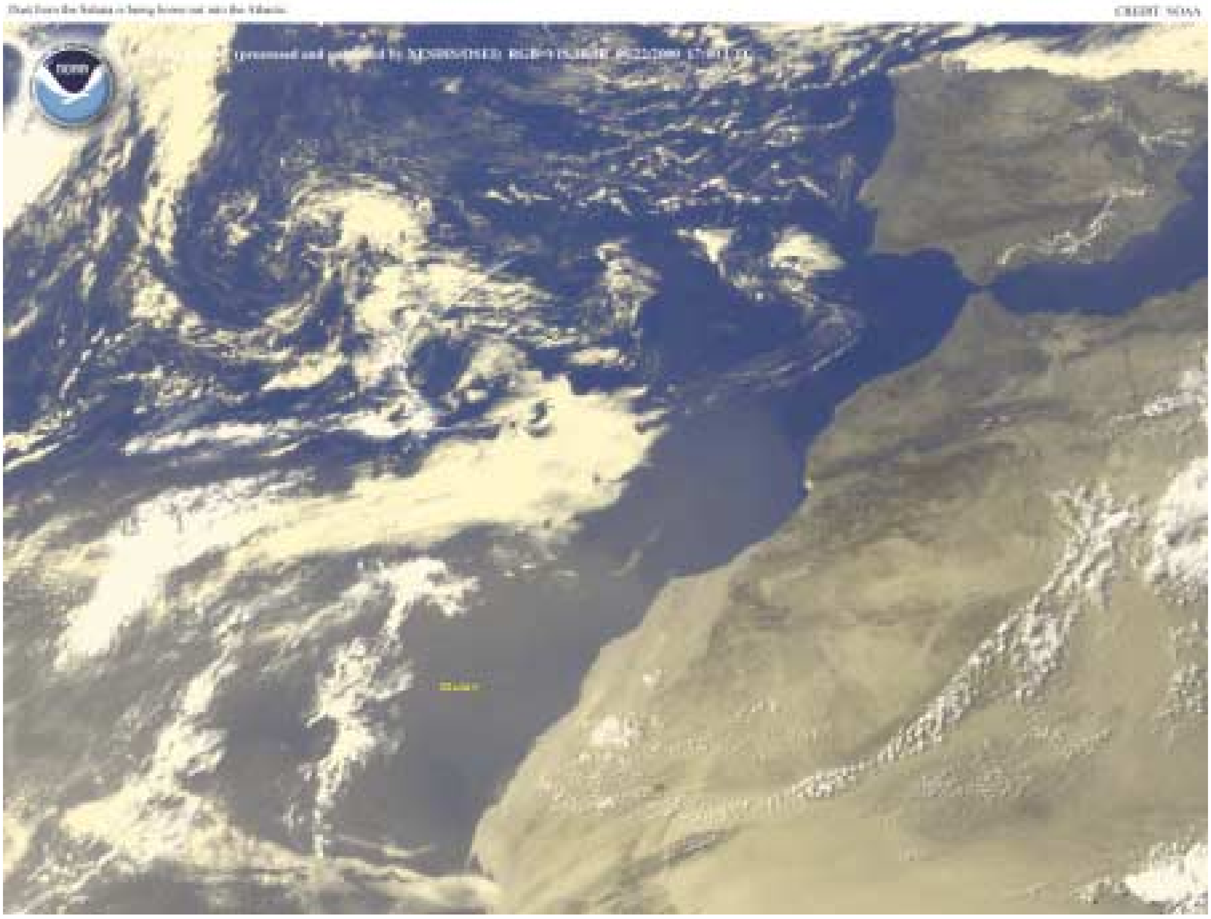

Figure 4-8. Meteosat 7 image of a dust storm from Africa on June 22, 2000. Image courtesy of NOAA OSEI Team.

from offshore and ultimately from the U.S. mainland, adding evidence to the apparent entrainment. Figure 4-6 is a SeaWiFS image from June 2, 2000 that clearly shows urban pollutants moving off the coast of the U.S., but it is not clear they are entraining back to Florida. Figure 4-7 shows a single image from June 1, 2000 where U.S. pollutant influence is also suspected, although some African dust confuses the image. The combination of the SeaWiFS image with several NAAPS models implies a U.S. pollutant influence in southern Florida during late May and early June.

4.6.3 African Dust Storms

Dust storms are visible to satellites and can indicate the long-distance transboundary travel of pollutants, in this case, from Saharan Africa to southern Florida. During the middle to late June 2000, several dust plumes could be observed to travel from Africa, appearing to arrive in Florida on June 20-21, June 25, and, most strongly, June 28-30, 2000; therefore, the last 10 days of June were likely influenced by trans-Atlantic pollutants. Figure 4-8 shows this storm at its starting point just off the coast of Africa on June 22.

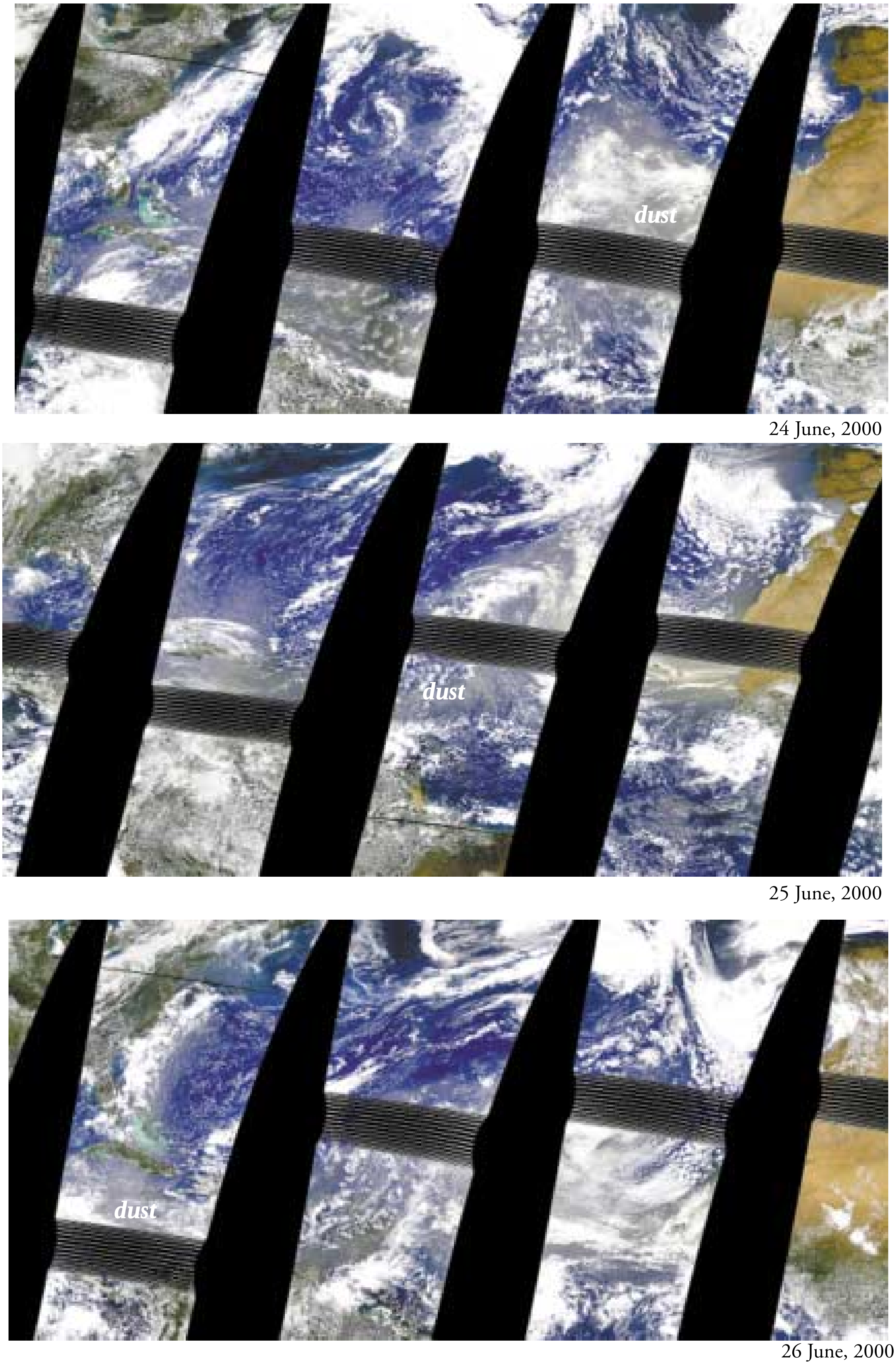

Figure 4-9. SeaWiFS images of a trans-Atlantic dust storm in Africa from June 24-26, 2000, with dust apparently reaching southern Florida. Image courtesy of NASA Goddard Space Flight Center.

Figure 4-9 is SeaWiFS images from June 24-26, showing the full trans-Atlantic images of the dust storm, including its arrival in Florida. Figure 4-10 shows images from several satellites and models of this Saharan dust event.

Ground-based and aerial data were also collected with the airplane and ground monitors in Florida, but these data are not yet available. However, the Saharan dust might be observed in the ground-level EPA AIRS data. Figure 4-11 is a graphical representation of the PM_{10} values for southern Florida locations during June 2000. Figure 4-12 shows this data in a standard chart form. The June 29 data points are significantly higher than earlier in the month and the higher concentrations are at the southern, more rural, sites, which matches the models and images of Saharan dust arriving from the south and implies

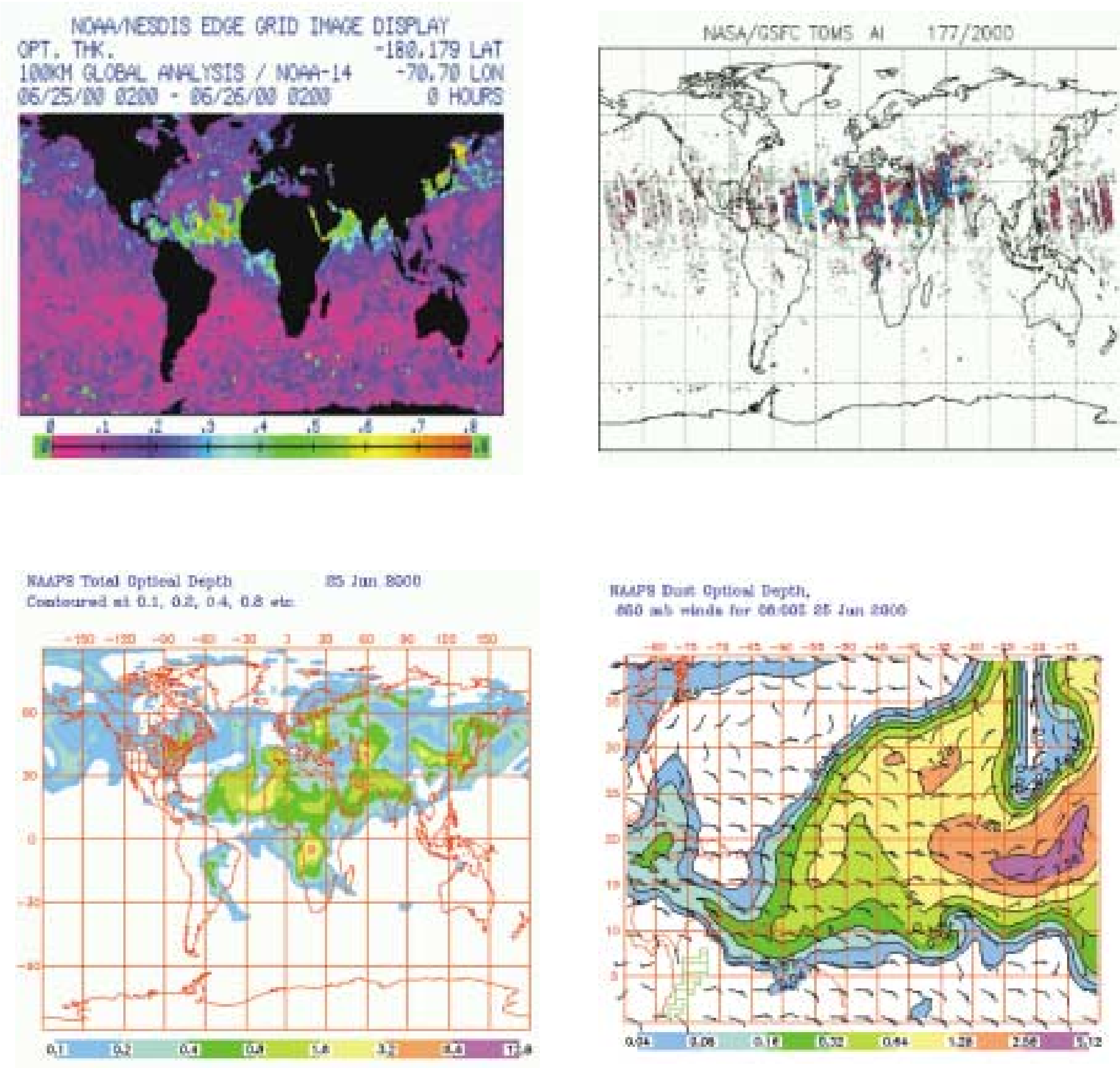

Figure 4-10. June 25, 2000 images of Trans-Atlantic African dust plume reaching Florida. Top left is an image from AVHRR data and top right is from TOMS. The bottom two images are NAAPS models, the bottom left is a NAAPS World model, the bottom right a NAAPS Tropical Atlantic model. Images courtesy of the Naval Research Laboratory, as well as NASA Goddard Space Flight Center and NOAA NESDIS.

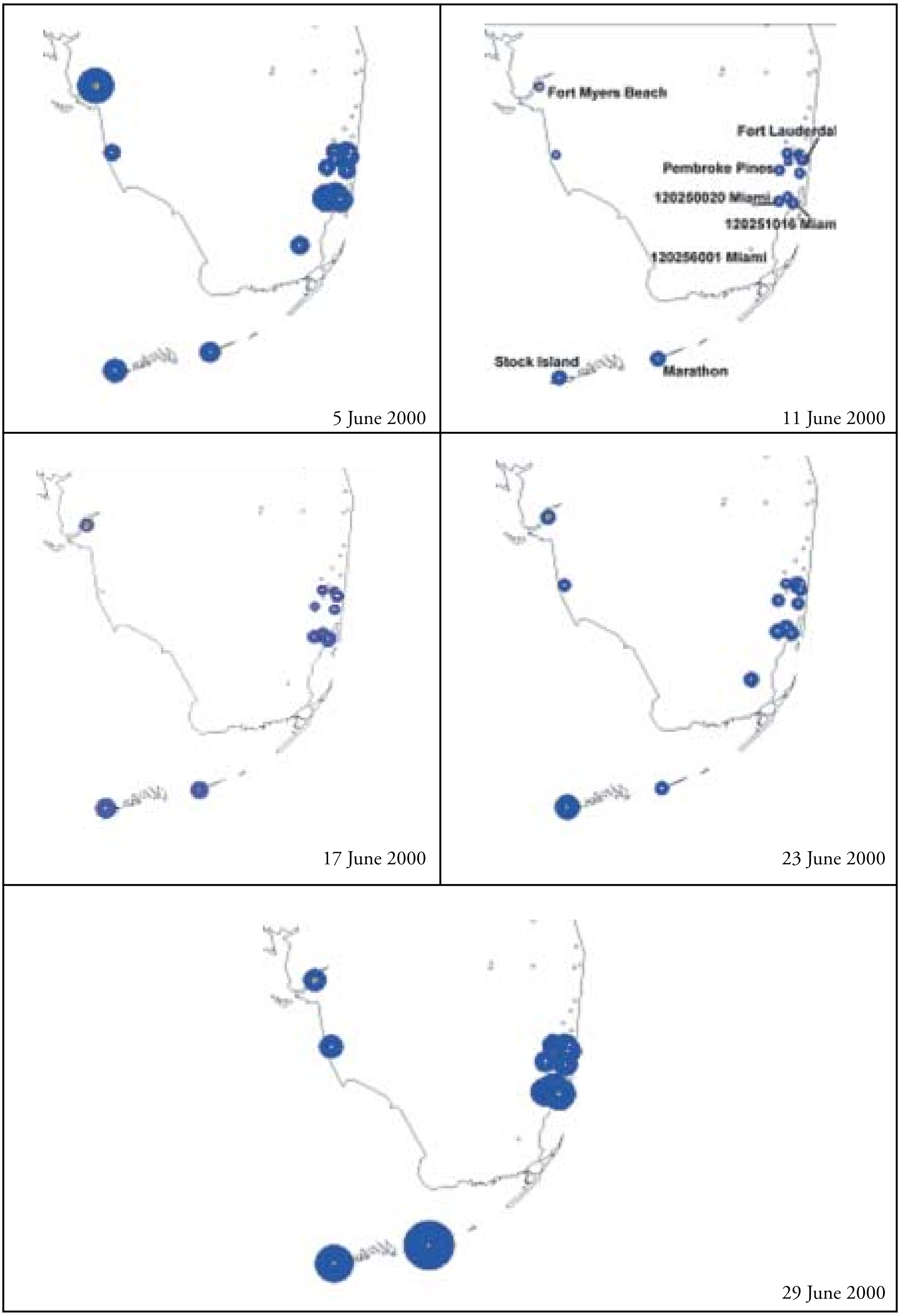

Figure 4-11. EPA AIRS PM_{10} Concentrations across South Florida for June 5, June 11, June 17, June 23, and June 29, 2000. Lowest concentrations are on June 11 and highest on June 29 at Stock Island and Marathon.

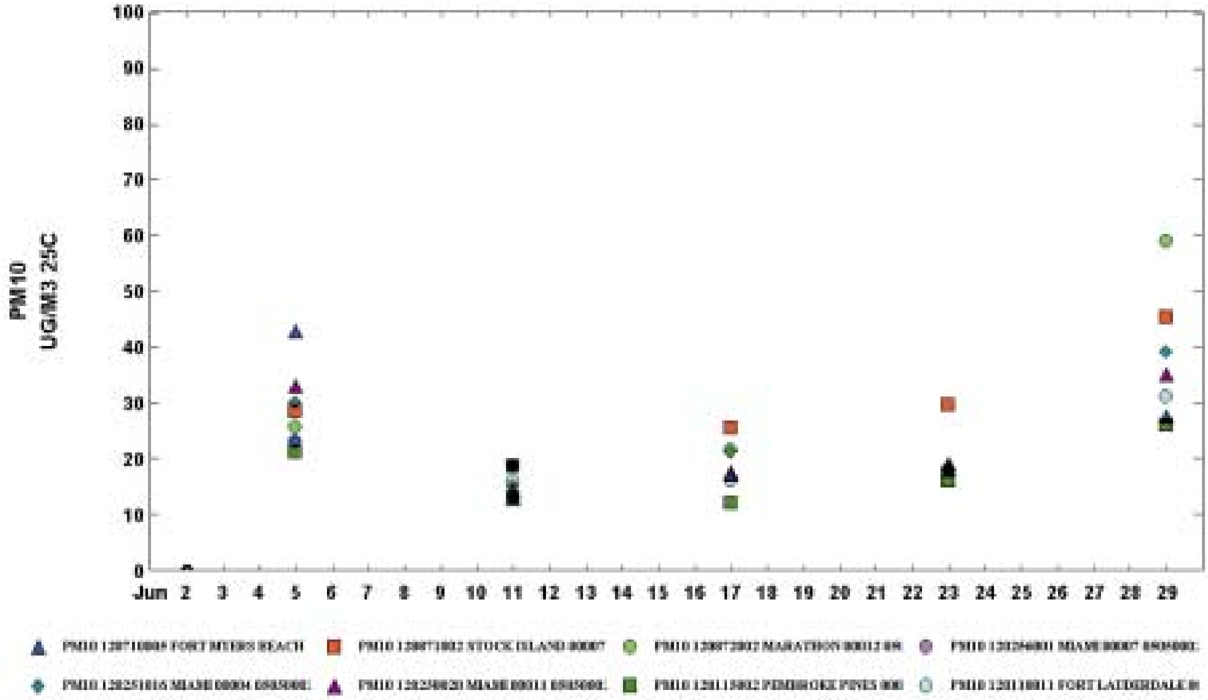

Figure 4-12. EPA AIRS PM_{10} concentrations at selected sites in Southern Florida in June 2000. Concentrations are most uniform across the region on June 11 and are most variable on June 29.

a non-urban source. The June 23 Stock Island data might be the onset of this event. Figure 4-13 is the HYSPLIT model run that indicates a southern Pacific-side arrival of the Saharan dust to the Everglades, which correlates with the satellite images and AIRS data.

When reviewing AIRS data from January to June 2000, the PM_{10} concentrations on June 29,

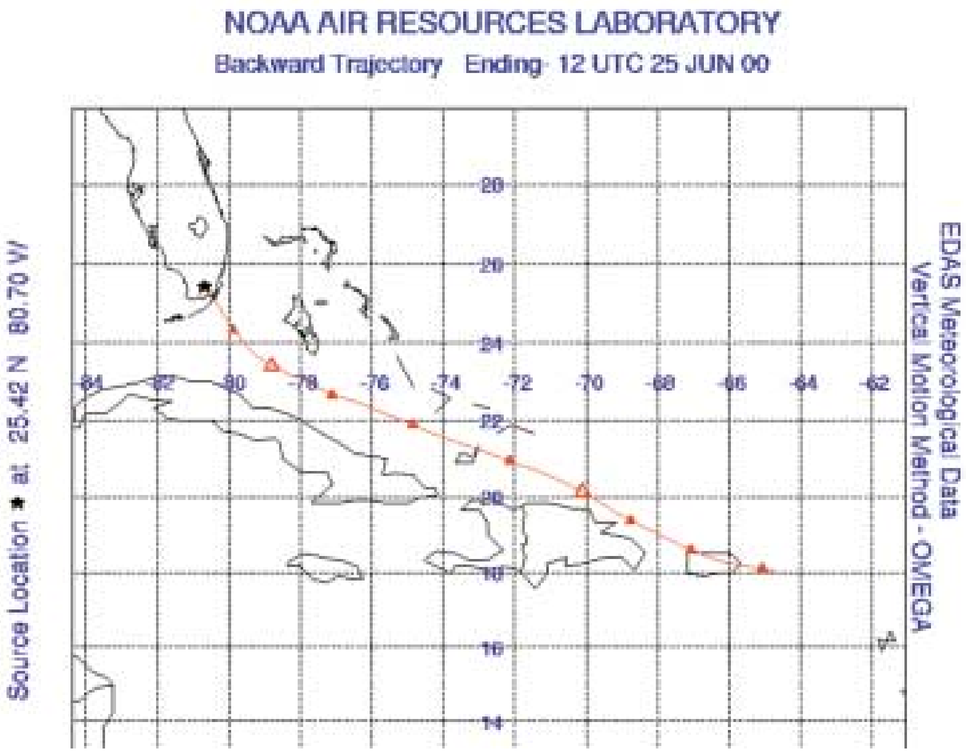

Figure 4-13. HYSPLIT model data indicating southern arrival of Saharan dust to Southern Florida. The triangles represent 6-hour intervals. HYSPLIT courtesy of the NOAA Air Resources Laboratory.

2000 are the highest for that period. The concentrations on June 29, 2000 are substantially higher than the AIRS 1995-2000 data average and are part of a consistent pattern of peak PM_{10} concentrations in southern Florida during June and July. June 2000 values however are not as high as some of the multi-year peak concentrations for the region Figure 4-14 shows the comparison of TOMS aerosol index data with AIRS data for the period May 25-June30, 2000. This chart shows a possible correlation between the TOMS satellite data and the ground-based data. These datasets are not directly comparable without additional data. This is primarily due to the low resolution of TOMS data as well as its limited ability to accurately portray ground-based levels.

4.7 PILOT PROJECT CONCLUSIONS

Three types of events impacted Florida during the sampling period: local fires, entrainment of U.S based pollution, and African dust storms. Other possible influential events – volcanos or fires in the Caribbean, Mexico, and Central America – were not observed. Satellite images and models based on satellite data were successfully used to determine the most likely dates of these influences on southern Florida. When combined with the EPA AIRS ground-based data, the satellite images provided a better picture (both literally and figuratively) of the general types of pollution sources in the Florida Everglades.

In order to make any conclusions about mercury sources specifically, further data from the aircraft sampling done by the EPA-NOAA team are required. This includes direct mercury sampling data, as well as particulates and other pollutants that help identify the types of mercury sources (such as, stationary combustion sources or mobile sources). By using satellite images to determine the general direction of pollutants at any particular time and combining this knowledge with aircraft and monitoring data of mercury, particulates, and other pollutants, scientists will be able to clarify if mercury in the Everglades comes from local, U.S., or trans-Atlantic sources.

This pilot project was successful since it demonstrated that satellite data integrated with ground-based data provide more information about an environmental phenomenon that either dataset alone. In general, we conclude that using satellite imagery can provide significant and useful information to a ground-based monitoring project. Additionally, the methodology that had been developed was successfully used to complete this pilot project, thereby validating the methodology.

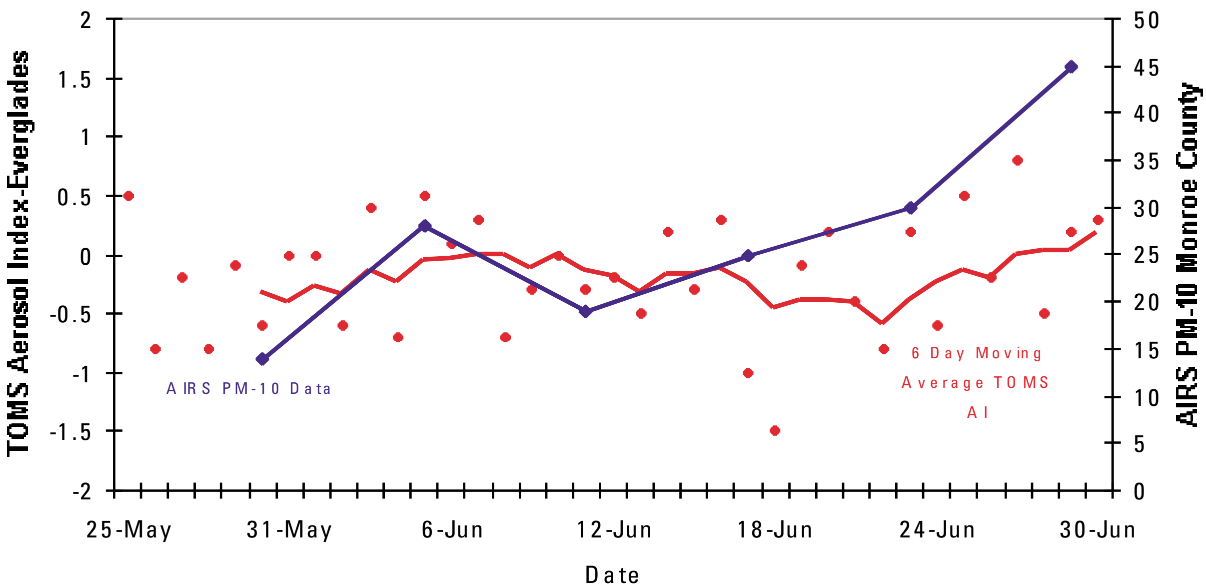

Figure 4-14. EPA AIRS PM_{10} Data compared to TOMS Aerosol Index. Blue diamonds are 24-hour average PM_{10} values as collected every 6th day by EPA and stored in the AIRS database. Red dots are daily TOMS aerosol index values and the red line is a moving 6 day average.

5. CONCLUSIONS AND FUTURE DIRECTIONS

5.1 CONCLUSIONS

This project completed an intensive literature and project review on integrated spaceborne images and ground-based data from available and developing technologies, developed a general methodology for using integrated datasets for environmental monitoring, and validated this methodology through a pilot project in the Florida Everglades. Based on these activities, we can make the following conclusions.

Integrating satellite images and ground-based data can be beneficial toward understanding environmental issues. The literature and project review found several published studies and on-going projects as evidence that using integrated datasets can increase our ability to understand both the local and the long-distance influences and consequences of environmental events. However, we also found that the satellite and ground-based monitoring science and policy communities do not communicate or collaborate on a regular basis. This lack of collaboration is a result of institutional barriers, but it is also due to the fact that the tools to use integrated datasets were developed very recently.

Recent technological advances make the integrated use of satellite images and ground-based data possible. Three technological advances within the last 5-10 years have made using integrated datasets relatively easy. These are: the launch of new satellite technologies; the growth of ground-based monitoring networks; and the increased on-line accessibility of satellite sensor images and surface-based observations. Since these advances are so new, very few projects exist that have used these data in an integrated fashion and there was no standard methodology to do so.

The general methodology for integrating satellite images and ground-based data is valid. Following on the literature and project search, a general methodology for integrating satellite images and ground-based data was developed. This methodology includes five basic steps: define the project; find appropriate partners and resources; select data sources; apply techniques for electronic communication; and conduct the project. The steps of the methodology were validated through the pilot project on airborne sources of mercury.

Satellite images integrated with ground-based data provide more information about an environmental phenomenon than either dataset alone. The pilot project analyzed the sources of pollutants in the Florida Everglades over several sampling dates and was able to provide imagery that supplemented ground-based data on the sources of pollutants. Therefore, in addition to validating the methodology, the pilot project confirmed the basic premise that integrating satellite images and ground-based data is possible and beneficial.

5.2 FUTURE DIRECTIONS

The work conducted thus far to develop the methodology should be continued through additional applications and projects. Future projects should build on the work and partnerships developed so far, as well as expand the use of integrated data to address international environmental issues. Additionally, new satellite sensors that offer better views of the Earth's atmosphere, water, and land are becoming available and future projects should make use of this new technology. We have developed criteria for selecting projects for potential future applications of the methodology. Recommended projects would:

- Benefit from integrated use of satellite images and ground-based data.
- Be specific in scope for a current environmental issue with global applicability.

- Leverage existing studies and/or use existing datasets.
- Consist of cross-agency/organization teams.
- Continue to help validate the methodology.
- Use the new generation of satellites.

A possible next step would be to apply the methodology to other regions around the globe and to a wider range of pollutants. Logical new projects include: the study of air pollution at a local level; transboundary transport of air pollution such as smoke from forest fires; and water pollution such as oil spills and algae blooms. Many other possible new projects would offer support to policy-makers on specific environmental issues of interest.

The benefits to implementing such projects include:

- Increased understanding of specific environmental issues due to the combined use of satellite imagery and ground-based data.
- Integrated analysis and visualization of the data in order to present a more complete and clear picture of environmental information to the public and policy-makers.
- Development of a body of work in the combined use of spaceborne images and ground-based datasets that supports further applications.
- Improved cross-agency/organization partnerships.

Ultimately, the development of a larger program that would use data integration and visualization to provide information to the public and policy-makers over a wide range of environmental issues could be considered.

ANNOTATED REFERENCES

Organizations and Projects

ACE-Asia

http://saga.pmel.noaa.gov/aceasia/

This is a NOAA and NSF funded program to combine ground-based monitors, aerial flights, and satellite remote sensing to monitor aerosols and their transport in and from Asia. This is a multi-year project aimed at a long-term understanding of the issue. A project to observe for methodology development and to partner with for long-term implementation.

AErosol RObotic NETwork (AERONET)

http://aeronet.gsfc.nasa.gov:8080/

AERONET is an optical ground based aerosol monitoring network and data archive supported by NASA's Earth Observing System and expanded by federation with many non-NASA institutions. It consists of sun-sky scanning radiometers, or sun photometers, that measure the direct sunlight in specific spectral bands and from which the aerosol optical thickness can be determined.

Canadian Centre for Remote Sensing

http://www.ccrs.nrcan.gc.ca/ccrs/

A Canadian national program for remote sensing that is responsible for the acquisition of Earth observation data and for the development of remote sensing applications, related methodologies, and systems.

The CEO (Centre for Earth Observation) Project

http://www.ceo.org/

The CEO project is a European initiative to encourage the wider use of information generated by Earth Observation satellites.

Committee on Earth Observation Satellites (CEOS)

http://www.ceos.org/

An international organization that consists of providers and users of spaceborne images and data for Earth observation. CEOs has an project called the *Integrated Global Observing Strategy (IGOS)*, that seeks to manage the spaceborne piece of the integrated use of in situ and spaceborne images, in order promote more effective use of satellite technologies. It is anticipated that in situ and user components will be added to an overall strategy. Additional Partners in the IGOS development process will be actively sought. The project has selected 6 pilot projects that are currently on-going: global ocean data assimilation experiment, upper air measurement, long-term continuity of ozone measurements, ocean biology, global observations of forest cover, and disaster management support.

CEOS also maintains the *Disaster Information Server* (http://disaster.ceos.org/) that is the result of one of the IGOS pilot projects. This project is seeking to develop partnerships and useful tools with the disaster management community. They have completed a baseline report with recommendations for further progress. The 8 kinds of disasters they are focusing on are: drought, earthquake, fire, flood, landslide, oil spill, tropical cyclones, and volcanic hazards. For more information, see Wood (1999).

Data Fusion Server

http://www-datafusion.cma.fr/welcome.html

An organization that promotes the combined use of multiple types of satellite data. They focus primarily on the use of different spectral bands, however, they have some combined uses of satellite and point source data. They define data fusion as “a formal framework in which are expressed means and tools for the alliance of data originating from different sources”. It aims at obtaining information of greater quality.

Ecole des Mines de Paris, Center for Energy Studies, Remote Sensing and Modeling Group

http://www-cenerg.cma.fr/eng/tele/welcome.html

http://www-cenerg.cma.fr/eng/tele/air/qualaireng.html

Groupe Télédétection & Modélisation conducts research and education activities related to Earth observation from space. They have a specific project related to using satellite data for mapping urban air quality, primarily to substitute for a lack of ground measurements, or to fill in areas that do not have sufficient ground stations. They have been conducting studies to determine the correlation between satellite measurements (Landsat, SPOT, ERS SAR, and others) and ground based measurements. They have seen excellent correlation with particulates, NO_X and SO_2. Their current measurements are over long time periods and are used more for model development than for tracking quick changes in air quality.

Based on their initial research, they submitted a proposal for mapping air quality in Nantes, France. The abstract is: “Atmospheric pollution, particularly in urban areas, has a strong impact upon daily life. Recent research indicates that periodic observations made by current satellites might efficiently complement ground measurements. For the city of Nantes, high correlation was found between Landsat data and measurements of air quality, such as black particles, sulfur dioxide or nitrogen dioxide. In addition, ERS synthetic aperture radar images allow a good discrimination between residential areas, industrial areas, large groups of buildings, and open areas. Hence, SAR imagery will lead to an aerodynamic roughness mapping, and optical imagery will lead to the pollution layers mapping.”

ECOLEX

http://www.ecolex.org/

ECOLEX is a gateway to environmental law sponsored by IUCN, UNEP and the Dutch Government. ECOLEX is designed to use IUCN’s Environmental Law Information System (ELIS) as its core archival system and link this data to full text information available with UNEP’s Computerised Environmental Law Information Base (CELIB) and other authoritative sources. Among the treaties cataloged are 41 treaties dealing with the atmosphere.

Users can search using subject area, keyword, country, or date. The list of subjects includes, for example: climate/atmosphere; fresh water; marine environment; soils; forests; biodiversity; energy; protected areas; hazardous substances; and wastes. ECOLEX includes information on multilateral treaties; national legislation; European Union instruments; international “soft law” and related documents; law and policy literature; and judicial decisions.

U.S. EPA Office of Air and Radiation, Office of Air Quality Planning and Standards

http://www.epa.gov/airs/
(Aerometric Information Retrieval System, AIRS Website)

http://www.epa.gov/ttn/uatw/
(Unified Air Toxics Website)

OAQPS (a Division of EPA’s OAR) maintains databases of air monitoring data collected by EPA and the States for compliance purposes. An excellent source of ambient data, updated on a monthly basis is AIRS (Aerometric Information Retrieval System). OAQPS is in the process of establishing a network of approximately 1,000 particulate monitors (2.5 microns or less) that will be in place by the end of the year, including two initial “supersites” in Fresno and Atlanta collecting very detailed data.

German Remote Sensing Data Center (DFD), part of the German Aerospace Center, Deutsches Zentrum für Luft- und Raumfahrt (DLR)

http://www.dfd.dlr.de/

The German Remote Sensing Data Center (DFD), which is part of the German Aerospace Center, Deutsches Zentrum für Luft- und Raumfahrt (DLR), develops and operates German and international satellite earth observation programs, including data reception, processing, archiving and distribution activities. DFD provides timely products like ocean and land surface temperatures, vegetation indices and chlorophyll maps, as well as ozone density maps.

Indian Ocean Experiment (INDOEX)

http://www-indoex.ucsd.edu/index.html.

The Indian Ocean Experiment (INDOEX) was designed to study regional consequences of global warming due to the cooling effect of aerosols. These tiny particles, about a micron or smaller in diameter, scatter sunlight back to space and cause a regional cooling effect. These aerosols consisting of sulfates, soot, organic carbon and mineral dust are produced both naturally and by human activities. Results of numerous global warming models suggest that the aerosol cooling is one of the largest, if not the largest, sources of uncertainty in predicting future climate. Still, the complex influence of aerosol cooling on global warming is not clearly understood.

INDOEX's goal is to study natural and anthropogenic climate forcing by aerosols and feedbacks on regional and global climate. This issue is at the core of the International Global Change Research Program and has been identified by IPCC as a major gap in the science of climate change prediction.

INDOEX field studies occurred where pristine air masses from the southern Indian Ocean including Antarctica and not-so-clean air from the Indian subcontinent meet over the tropical Indian Ocean to provide a unique natural laboratory for studying aerosols. Scientists collected data from the water surface through the lower stratosphere, on the aerosol composition, reactive atmospheric gases, solar radiation fluxes, wind and water vapor distribution. These data collections involved multiple aircraft, ships and island stations over the Arabian Sea and the Indian Ocean. Building on data collected in 1995 – 1998, an intense field campaign was undertaken during January to April 1999. The field data were used to calibrate the National Aeronautics and Space Administration's Earth Observing System instruments to obtain a regional map of the aerosol cooling effect. In conjunction with the regional scale satellite data, the field data were used to include aerosol effects in global warming prediction models.

NASA Earth Observatory and Visible Earth

http://earthobservatory.nasa.gov/

http://visibleearth.nasa.gov/

The purpose of NASA's Earth Observatory is to provide a freely-accessible publication on the Internet where the public can obtain new satellite imagery and scientific information about our home planet. Visible Earth provides searchable directory of images, visualizations, and animations of Earth. The Goddard Space Flight Center runs both programs.

NASA Goddard Space Flight Center

http://www.gsfc.nasa.gov/

Goddard is the lead Center in NASA's Mission to Planet Earth program. Mission to Planet Earth is NASA's long term, coordinated research effort to study the Earth as a global environmental system.

NASA Langley Research Center

http://eosweb.larc.nasa.gov/

Langley does a variety of Earth monitoring activities, including air quality and ozone. The NASA Langley Atmospheric Sciences Data Center focuses on radiation, clouds, tropospheric chemistry, and aerosols. For aerosols they look particularly at biomass burning and volcanoes. They have done some other air quality work, notably CO monitoring from the space shuttle. And, they even plan to have Aerosol Trading Cards (http://eosweb.larc.nasa.gov/EDDOCS/Trading.html).

NOAA Air Resources Laboratory
(one of the Environmental Research Laboratories)

http://www.arl.noaa.gov/

http://www.erl.noaa.gov/

The Air Resources Laboratory, managed by Bruce Hicks, has many projects of interest. They have real-time environmental applications available on the Internet at their READY site. They also have chemical monitoring stations throughout the U.S. and accurate transport models with which they predict the dispersion of aerosols. They are actively involved with the PARTS project.

NOAA NESDIS Organization

http://psbsgi1.nesdis.noaa.gov:8080/PSB/EPS/EPS.html

http://www.saa.noaa.gov

anonymous ftp: aries.nesdis.noaa.gov

The NOAA/NASA AVHRR Pathfinder Atmosphere (PATMOS) project is developing a climatology of aerosol optical thickness (AOT) with AVHRR (imager) data from polar satellites (one observation per day), from 1981 to the present. AOT is a measure of the effect of aerosol particles on the transmission of solar radiation to the earth's surface - the larger it is, the less solar radiation reaches the ground. They have already developed such climatology over oceans (Husar et al 1997), where the background reflectance is much lower and more stable than that of land, making the retrieval of AOT more reliable (this data is available via ftp and at one point was available in near real-time). Cloud-free radiance statistics exist for each day on a global 110 km grid for all five channels of AVHRR. Ocean grid cell data have been processed with the NOAA operational aerosol retrieval algorithm to create the most extensive record of AOT ever compiled. They are now beginning a similar project using the AVHRR data over land. It will take 1-2 years to develop a remote sensing algorithm for land applications with AVHRR polar data. Another group in NESDIS has been working on fire and smoke detection algorithms with GOES data at the University of Wisconsin.

NOAA Operational Significant Event Imagery Server

http://www.osei.noaa.gov/

The purpose of this group is to produce daily detailed imagery of significant natural or human events that are visible by remote sensing. These events include dust storms, fires, floods, oil spills, volcanoes, severe weather, and others. They produce a daily imagery report 5 times a week and have a listserver that will e-mail these reports daily. They also do some long-term analysis of special events, such as volcanoes. Their images include multiple satellites and often describe how the analysis was done using different satellite bands.

NOAA Satellite Active Archive

http://www.saa.noaa.gov/

Digital archive of real-time and historical satellite data. The information is in data not image format, thus remote sensing analysis software is needed to use most of this data. Data is free.

NOAA National Weather Service, International Activities Office

http://www.nws.noaa.gov/ia/home.htm

The NOAA National Weather Service International Activities Office, in conjunction with NOAA NESDIS and other offices has a project called Program to Address ASEAN Regional Transboundary Smoke (PARTS), which will install an integrated forest fire monitoring network in southeast Asia. The goal is to enhance the capability within southeast Asia to monitor and respond to forest fires (and some other causes of episodic pollution events) and the resulting transboundary air pollution. This network will include access to polar orbiting satellite imagery, ground-based atmospheric monitoring (meteorology, air sampling, optical depth), and a computer-based model to provide access to real-time monitoring and modeling information about aerosol events.

NOAA National Climatic Data Center (NCDC)

http://www.ncdc.noaa.gov/ol/climate/climatedata.html

Contains data that are derived from the World Meteorological Organization (WMO) World Weather Watch Program, including visibility data and imagery. Data are accessible through the NCDC web server.

United Nations Environment Program

http:// www.unep.org

http://www.unep.net

The United Nations Environment Programme (UNEP) serves as the environmental voice of the United Nations. UNEP's is an advocate of environmental concerns within the international system. In this, it makes a particular effort to nurture partnerships with other UN bodies possessing complementary skills and delivery capabilities and enhancing the participation of civil society in the achievement of sustainable development.

UNEP's areas of concentration include: environmental monitoring, assessment, information and research including early warning; enhanced coordination of environmental conventions and development of environment policy instruments; freshwater; technology transfer and industry; and support to Africa.

UNEP Chemicals Persistent Organic Pollutants

http://www.chem.unep.ch/pops/

UNEP Chemicals is the center for all chemicals-related activities of the United Nations Environment Programme. Their goal is to make the world a safer place from toxic chemicals. They do this by helping governments take needed global actions for the sound management of chemicals, by promoting the exchange of information on chemicals, and by helping to build the capacities of countries around the world to use chemicals safely.

Among their responsibilities are the treaties and conventions on Persistent Organic Pollutants (POPs). POPs are chemical substances that persist in the environment, bioaccumulate through the food web, and pose a risk of causing adverse effects to human health and the environment. With the evidence of long-range transport of these substances to regions where they have never been used or produced and the consequent threats they pose to the environment of the whole globe, the international community has now, at several occasions called for urgent global actions to reduce and eliminate releases of these chemicals.

UNEP GRID Sioux Falls

http://grid.cr.usgs.gov/

The North American node of UNEP's Global Resource Information Database (GRID), designated as GRID-Sioux Falls, located at the EROS Data Center of the United States Geological Survey in Sioux Falls, South Dakota. UNEP GRID Sioux Falls, has been operational since 1991 as a partnership between UNEP, the Geological Survey (USGS), the National Aeronautics and Space Administration (NASA), Environmental Protection Agency (EPA) and the Forest Service (USFS).

UNEP GRID Sioux Falls analyses data and information about people and the environment using space and computer technologies. This information is used to respond to questions about human population, fresh water, biodiversity, food security, climate change, wild fires and other global population-environment issues.

GRID Sioux Falls has an active program dealing with development, analysis and dissemination of environmental information to worldwide users.

USGS EROS Data Center

http://edcwww.cr.usgs.gov/

The Earth Resources Observation Systems (EROS) Data Center (EDC) is a data management, systems development, and research field center for the U.S. Geological Survey's (USGS) National Mapping Division. Since its opening, the EDC has stored, processed, and distributed a variety of data, including cartographic data, satellite data, and aircraft data.

The EDC's archives also hold the world's largest collection of civilian remotely sensed data covering the Earth's land masses, housing millions of satellite images and aerial photographs. As part of its role as a data archive, the EDC operates the National Satellite Land Remote Sensing Data Archive, a legislatively mandated program designed to maintain a high quality data base of space-acquired images of the Earth for use in studying global change and other related issues.

The EDC is designated as a World Data Center for Remotely Sensed Land Data and is a cooperator in many domestic and international programs. EDC is a distributed active archive center associated with NASA's Earth Observing System (EOS) Program, NASA's Earth Science Enterprise initiative, and NASA's launching of the Landsat-7 satellite.

Washington University St. Louis, Center for Air Pollution Impact and Trend Analysis (CAPITA)

http://capita.wustl.edu

http://capita.wustl.edu/Asia-FarEast/
(dust storm from China)

http://capita.wustl.edu/Central-America/
(fires in Central America)

The Center of Air Pollution Impact and Trend Analysis (CAPITA) specializes in global aerosol research and the impact of air pollution on the atmosphere. CAPITA has a staff composed of faculty, permanent technical staff, visiting scientists, postdoctoral research assistants, and graduate students. They coordinated the monitoring and public reporting of dust from dust storms in China that traveled to the west coast of the U.S. and the transport of smoke from fires in Central America into eastern U.S. These projects were in real-time (they called it "just in time scientific input"), through real-time images put regularly onto the Internet. They used images from NASA's SeaWiFS program and also used normal NASA and NOAA satellite imagery with ground-truthing and limited particulate ground monitoring.

References

Chami, M., and R. Santer, 1998. "Aerosol Remote Sensing using Ground-Based Measurements and POLDER Airborne Sensor above Coastal Waters." *Remote Sensing of the Environment*, Vol. 66, pp. 203-221.

Chavez, F.P., et al, 1999. "Biological and Chemical Response of the Equatorial Pacific Ocean to the 1997-1998 El Niño." *Science*, Vol. 286, No. 5447, pp. 2126-2131.

The article describes the use of in situ and satellite systems to analyze the effect of the El Niño on the equatorial region of the Pacific. Specifically, they looked at the phytoplankton levels, sea surface temperatures, and chemical nature of the ocean as the El Niño ended in 1998. For satellites, they used AVHRR sea surface temperature measurements and SeaWiFS chlorophyll levels. These were combined with readings from sensors on ocean moorings. The results were significant enough for a major *Science* publication and the images striking enough to be on the cover. In the conclusions, the authors state: "The dramatic biological and chemical perturbation associated with the 1997-98 El Niño would not have been captured had it not been for in situ sensors on moorings, regular ship visits to service the moorings, and remote sensing of chlorophyll."

Christopher, S.A., J. Chou, R. M. Welch, D. V. Kliche, and V. S. Conners, 1998. "Satellite investigations of fire, smoke, and carbon monoxide during April 1994 MAPS mission: Case studies over tropical Asia." *Journal of Geophysical Research*, Vol. 103, pp. 19,327-19,336.

Crippen, Robert. 1999. Personal communication.

Crippen, R.E. and R.G. Blom, 2000. "Unveiling the lithology of vegetated terrains in remotely sensed imagery." *Photogrammetric Engineering & Remote Sensing*, in press.

Deschamps, P. and N. Sifakis, 1992. "Mapping of Air Pollution using SPOT Satellite Data." *Photogrammetric Engineering and Remote Sensing*, Vol. 58, pp. 1433-1437.

The authors determined the variation in optical depth by comparing multiple satellite images to a "pollution-free" reference image. A pollution free, or reference, image is found by comparing multiple images to find the cleanest ones. The cleanest of the clean images is determined through support of ground-based pollution observations. After correcting the images for natural atmospheric optical effects, any extra optical depth degradation in images compared to the reference image can be attributed to air pollutants. This type of analysis requires the underlying surface to be relatively constant over time so that the surface reflectance does not change among images. In this case an urban area was used and it was felt that this criterion was met since urban areas generally have stable spectral signals due to lack of biomass content. The dates used for this analysis were March 5, 1986 (polluted), January 5, 1987 (polluted), September 23, 1986 (clean) and May 22, 1986 (clean).

Three spectral channels from the SPOT sensor are used in the analysis and range from 0.5-0.89 um. The SPOT XS1 channel (0.5-0.59 um or green/yellow on the color spectrum) was found to be most sensitive to changes in optical depth over land.

Conclusions from the paper included future benefits of satellite mapping of air pollution, such as its use in complementing ground-based measurements in filling in concentrations where no ground-based stations are located and in aiding the ground-based network design.

De la Sierra, Ruben U., John F. Vesecky, and William Drake, 1995. "A preliminary approach to the examination of population-environment dynamics in the United State/Mexico border region using integrated remote sensing and field data." *International Geoscience and Remote Sensing Symposium*, Institute of Electrical and Electronic Engineers.

This study was undertaken in order to analyze changes to the U.S.-Mexico border region as a result of changes in trade and economic laws, in particularly, NAFTA. Remote sensing data was used to review land use change primarily, using Landsat Channel 2 images from 1983 and 1992 in the El Centro, California region. This was a very simple, qualitative study. However, they identified the need for higher resolution images and combination with environmental data to get a better picture of the environmental changes in the region as it develops.

Derr, V.E., 1972. *Remote Sensing of the Troposphere*, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Boulder, Colorado.

1999 EOS NASA Reference Handbook: A Guide to NASA's Earth Science Enterprise & the Earth Observing System.
http://eos.nasa.gov/.

Fishman, J. and A.E. Balok, 1999. "Calculation of daily tropospheric ozone residuals using TOMS and empirically improved SBUV measurements: Application to an ozone pollution episode over the eastern United States." *Journal of Geophysical Research*, Vol. 104, No. D23, pp. 30,319-30,340.

An estimate of tropospheric ozone is made using TOMS aerosol optical thickness data, solar backscattered ultraviolet (SBUV) data from the Nimbus 7 and NOAA 11 satellites, and ozonesonde data. The SBUV data provide information for 12 layers from the surface to 0.12 mbar. The lowest three levels are used to determine the amount of ozone in the troposphere. Due to measurement errors in the lowest level, the SBUV is corrected using ozonesonde data. The corrected SBUV is then used to determine the ozone in the troposphere as well as in the stratosphere. The SBUV derived stratospheric ozone is then subtracted from the TOMS total ozone amount to arrive at the tropospheric ozone amount.

Fishman, J., and V.G. Brackett, 1997. "The Climatological Distribution of Tropospheric Ozone Derived from Satellite Measurements Using Version 7 TOMS and SAGE Data Sets." *Journal of Geophysical Research*, Vol. 102, pp. 19,275-19,278.

Fraser, Robert F, Yoram J. Kaufman, and R.L. Mahoney, 1984. "Satellite Measurements of Aerosol Mass and Transport." *Atmospheric Environment*, Vol. 18, No. 12, pp. 2577-2584.

These scientists derived aerosol optical thickness over land from GOES satellite measurements of the radiance of scattered sunlight. They were looking at the transport of sulfur-containing aerosols and its horizontal transport through use of wind vectors. Their measurements corresponded well with published estimates. The limitation to this data is that the GOES satellite can only measure APT under cloud-free conditions and other required data for the calculations are sparse. They state that "A large uncertainty exists in the accuracy of the values of particulate mass and transport based on satellite observations. The accuracy of these data have to be validated with independent data measured on well designed field experiments that are coordinated with satellite observation."

Guentzel, J.L. 1997. *The Atmospheric Sources, Transport, and Deposition of Mercury in Florida*. Doctoral Dissertation in Oceanography, Florida State University.

Hanna, Adel F., Rohit Mathur, Kiran Alapaty, and Joseph Pinto, 1999. "Modeling the Episodic Transport of Air Pollutants from Asia to North America." Available at North Carolina

Supercomputing Center (NCSC) Environmental Programs group website, http://envpro.ncsc.org/projects/MITP/, Version: December 22, 1999.

The goal of this study is to "determine the mechanisms and the meteorological conditions associated with the transport of tracers from hypothetical sources in Asia to the United States… [in order to] give some insight into the physical mechanisms that are responsible for the long-range transport of pollutants." The study modeling studies on hypothetical transport of tracers from Asia to North America.

Helfert, M. R., and K.P. Lulla, 1990. "Mapping Continental-Scale Biomass Burning and Smoke Palls over the Amazon Basin as Observed from the Space Shuttle." *Photogrammetric Engineering and Remote Sensing,* Vol. 56, pp. 1367-1373.

Over 2,000 NASA photographs taken between 1961 and 1989 were reviewed, filtered and analyzed to map the spatial pattern of Amazon Basin smoke palls. The photographs were taken during Space Shuttle, Skylab, Mercury, Gemini, and Apollo missions.

The early work illustrates the ability to integrate images from multiple space sensors for identifying and analyzing tropospheric air pollutant activity. The texture, tonal homogeneity, and associated morphology of the images were used to distinguish between smoke and clouds. Clouds were identified as very bright (saturated) patches whereas smoke plumes were seen as whitish/greyish cylindrical or funnel shaped puffy masses.

Hotz, Robert Lee, 1998. "Fire Towers in Space, Satellite Images Give Emergency Crews an Edge in Detecting and Battling Blazes Around the Globe." *Los Angeles Times*, July 16.

Article on the use of satellite imagery to monitor forest fires, based on work done at NASA Goddard. Of most interest is the list of satellites and their websites, in particular, TOMS that can detect smoke, GOES-8 that detects thermal changes, and SeaWiFS that images fire fronts. Also, the article states that "experts hope to combine satellite data with information gathered by aircraft and by researchers at the fire front on the ground to better understand how fires around the world affect the health of the atmosphere or contribute to potential climate change."

Husar, R., J. Prospero, L.L. Stowe, 1997. "Characterization of Tropospheric Aerosols over the Oceans with the NOAA/AVHRR Optical Thickness Operational Product." *Journal of Geophysical Research*, Vol. 102, D14, pp. 16,889-16,910.

Study using AVHRR data to review the radiatively equivalent aerosol optical thickness over a 2 year period from July 1989 to June 1991. The data revealed high AOT values related to wind-blown dust and biomass burning in certain areas, including Africa, Middle East, and the Asian subcontinent. The northern hemisphere had average higher AOT than the southern hemisphere. Major dust sources were noted (northern Africa and the Middle East) as well as biomass burning (southern Africa).

Husar, R.B., J.D. Husar, and L. Martin, 2000. "Distribution of Continental Surface Aerosol Extinction Based on Visual Range Data." *Atmospheric Environment*, Vol. 34, pp. 5067-5078.

Husar, R.B., D. M. Tratt, B. A. Schichtel, S. R. Falke, F. Li , D. Jaffe, S. Gassó, T. Gill, N. S. Laulainen, F. Lu, M. Reheis, Y. Chun, D. Westphal, B. N. Holben, C. Geymard, I. McKendry, N. Kuring, G. C. Feldman, C. McClain, R. J. Frouin, J. Merrill, D. DuBois, F. Vignola, T. Murayama, S. Nickovic, W.E. Wilson, K. Sassen, and N. Sugimoto, 2001. "The Asian Dust Events of April 1998." *Journal of Geophysical Research-Atmospheres*, Vol. 106, No. D16, pp. 28, 317.

Keating, Terry, 1999. "Hemispheric Transport of Air Pollutants," unpublished presentation and notes for the EPA Office of Air and Radiation Hemispheric Transport Meeting, November 19.

Discusses interest of OAR in the cross-border transport of air pollutants. Summarizes the imports and exports of air pollution to North America, including U.S. contribution of 50% of NO_X over North Atlantic, 30% of global NO_X from fossil fuel combustion, and 36% of O_3 production in northern latitudes. Included preliminary image from Joe Pinto, U.S. EPA, showing concentrations of a hypothetical tracer released in China and stretching across the Pacific in varying colors according to a logarithmic scale.

Kester, Dana R., Mary F. Fox, and Andrea Magnusen, 1996. "Modeling, Measurements, and Satellite Remote Sensing of Biologically Active Constituents in Coastal Waters." *Marine Chemistry*, Vol. 53, pp. 131-145.

Mostly a review of work done in the Narragansett Bay in the northeastern US. They did not actually use any satellite data since this preceded major second-generation ocean color satellites (such as SeaWiFS). However, they conducted some historical analysis of surface water chlorophyll levels in order to evaluate possibilities for combining in situ and remote sensing data in the future.

King, M. D., Y. J. Kaufman, D. Tanre, and T. Nakajima, 1999. "Remote Sensing of Tropospheric Aerosols from Space: Past, Present, and Future." *Bulletin of the American Meteorological Society*, Vol. 80, pp. 2229-2259.

This article provides an excellent overview of the state of the art in aerosol remote sensing. It discusses existing methods of retrieving aerosols from satellite images and describes currently operating and future sensors.

Leon, J. F., P. Chazette, and F. Dulac, 1999. "Retrieval and monitoring of aerosol optical thickness over an urban area by spaceborne and ground-based remote sensing." *Applied Optics*, Vol. 38, pp. 6918-6926.

Levy, G., C. Pu, and P.D. Sampson, 1999. "Statistical, physical, and computational aspects of massive data analysis and assimilation in atmospheric applications." *Journal of Computational and Graphical Statistics*, Vol. 8, pp. 559-574.

Mobley, David and Sally Shaver, 1999. "Air Toxics Monitoring Concept Paper," internal EPA Memorandum, Office of Air Quality Planning and Standard, Research Triangle Park, North Carolina, April 19.

Memorandum from two Directors in OAQPS defining planned activities to increase toxics monitoring at EPA. Available at http://www.epa.gov/ttnamti1/files/ambient/airtox/transmit.pdf.

Nguyen, Hung V., S.M. Bhandari, A. Jayaraman, V. Ramanathan, L.V.G. Rao, S.T. Rupert, G. Viswanathan, S.F. Williams, and K.S. Zalpuri, 1998. "INDOEX 1998 First Field Phase Operations Summary January 1 - April 1, 1998." INDOEX Publication #19, INDOEX International Project Office, August. Available at http://www-indoex.ucsd.edu/ffp98opssum/.

NOAA, 1999. *Hysplit User's Guide*. NOAA Tech Memo ERL ARL-230, June.

NRL, 2000. Naval Research Laboratory/ Monterey, Marine Meteorology Division, Aerosol Page, http://www.nrlmry.navy.mil/aerosol/.

Ott, S.-T., A. Ott, D.W. Martin, and J.A. Young, 1991. "Analysis of a Trans-Atlantic Saharan Dust Outbreak Based on Satellite and GATE Data." *Monthly Weather Review*, Vol. 119, pp. 1932-1850, August.

This paper reviewed a Saharan dust event in 3-11 September 1974. They used satellite data from the Visible Spin Scan Radiometer (VISSR) on the Synchronous Meteorological Satellite (SMS-1) and combined it with ground gathered information from a project called GARP Atlantic Tropical Experiment (GATE). GATE was a project to take various soundings from ships across the Atlantic. These two datasets were combined with wind and weather data through an algorithm to simulate the motion of the aerosols from Africa to North America.

Otterman, Fraser and Bahethi, 1982. "Characterization of tropospheric desert aerosols at solar wavelengths by multispectral radiometry." *Journal of Geophysical Research*, 87C, pp. 1270-1278.

This paper describes the characteristics of tropospheric desert aerosols by comparing nadir spectral reflectivity computed from radiative transfer models with reflectivity measured from Landsat over both land and ocean.

Pohl, C., and J. L. van Genderen, 1999. "Multisensor image fusion in remote sensing: concepts, methods and applications." *International Journal of Remote Sensing*, Vol. 19, No. 5, pp. 823 -854.

Prospero, Joseph M., 1999. "Long-term measurements of the transport of African mineral dust to the southeastern United States: Implications for regional air quality." *Journal of Geophysical Research*, Vol. 104, No. D13, pp. 15,917-15,927, July 20.

This study used ground-based sampling data of airborne aerosols collected since 1974 from a university station on the campus of the University of Miami, Rosenstiel School of Marine and Atmospheric Sciences, located on a small island 4 km east of the mainland. They focused on data from 1989-1997 when they adjusted their sampling to minimize the effect of sources from the mainland and focus on collecting samples that would be coming from the east. Their data indicated a peak during June, July, and August, consistent with an African source. This data was combined with qualitative studies from the literature using AVHRR and TOMS data. The study concludes with a discussion of how this could impact EPA's administration of the new $PM_{2.5}$ regulation.

Retalis, A., C. Cartalis, and E. Athanassiou, 1999. "Assessment of the distribution of aerosols in the area of Athens with the use of Landsat Thematic Mapper data." *International Journal of Remote Sensing,* Vol. 20, No. 5, pp. 939-945.

This study used Landsat images of Athens, Greece, from one clear and one polluted day to quantitatively determine the aerosol distribution in the city. They used a spectral interval of 0.45-0.52 micrometers. They also compared the satellite derived aerosol values to a network of ground-based air monitors that measure CO, NO_2, O_3, SO_2, and particulates. They found a correlation between the satellite-measured optical density and both the SO_2 and particulate ground-based measurements.

Limitations of the study included the fact that Landsat only images the Athens area every 15 days. Their ground-based data were also limited due to the fact that their particulate measurements were 8-hour averages, instead of real-time. However, overall, the satellite images were determined to be useful in supplementing a very limited ground-based monitoring network. They propose that temporal resolution could be resolved by using NOAA's AVHRR Channel 1, although its spatial resolution would be significantly less than Landsat (1 km versus 30-120 m).

Rud, Ove and Martin Gade, 1999. "Monitoring algae blooms in the Baltic Sea: a multi-sensor approach." *Geoscience and Remote Sensing Symposium, 1999 IEEE International*, IEEE Geoscience and Remote Sensing Society, pp. 1211-1213.

This article talks about the use of a 4 different sensors to analysis the same event, in this case an algae bloom in the Baltic Sea. They used the AVHRR on the NOAA-14 satellite, the

Wide Field Scanner (WiFS) on the Indian IRS-1C satellite, the Thematic Mapper on Landsat-5, and the synthetic aperture radar (SAR) on the Second European Remote Sensing Satellite (ERS-2). Resolution ranged from 25-30 meters for the SAR and TM, to 188 m for the WiFS, to 1.1. km on the AVHRR. They report success in being able to extract different information from each. The only ground-based data they used were wind and sea depth measurements. Importance of this article is that it shows the use of multiple satellite data to monitor a ground level event.

Selinus, Olle, 1996. "Large-scale Monitoring in Environmental Geochemistry." *Applied Geochemistry*, Vol. 11, pp. 251-260.

Sifakis, N.K., N.A. Soulakellis, and D.K. Paronis, 1999. "Quantitative mapping of air pollution density using Earth observations: a new processing method and application to an urban area." *International Journal of Remote Sensing*, Vol. 19, No. 17, pp. 3289-3300.

Landsat-5 satellite images were used to derive the aerosol optical thickness (AOT) over Athens, Greece. The AOT is determined by comparing visible range (0.55 um) reflectances for clean and polluted days. The authors developed code to identify the 'blurring effect' and the 'screening effect' on images compared to a clean image. The blurring effect occurs when incoming short wavelength is scattered by aerosol particles resulting. The screening effect occurs due to the attenuation of long wavelength surface reflected radiation by particles.

Sulfur dioxide concentrations measured from a local ground-based network were correlated with the calculated AOT and resulted in a coefficient of correlation of 0.76.

Stowe, L.L., A.M. Ignatov, R.R. Singh, 1997. "Development, validation and potential enhancements to the second generation operational aerosol product at the National Environmental Satellite, Data, and Information Service of the National Oceanic and Atmospheric Administration," *Journal of Geophysical Research*, Vol. 102. pp. 16,923-16,934

Tømmervik, H., M.E. Johansen, J.P. Pedersen, and T. Guneriussen, 1998. "Integration of Remote Sensed and In-situ Data in an Analysis of the Air Pollution Effects on Terrestrial Ecosystems in the Border Areas Between Norway and Russia." *Environmental Monitoring and Assessment*, Vol. 49, pp. 51-85.

This paper analyzed an area in northeastern Norway to determine the effects of cross-border air pollution from nickel smelters in neighboring Russia. The study integrated several types of data collection including: a physical field inventory and study of field sample plots to determine vegetation cover; analysis of lichens from these field plots for Ni and S contamination; modeled estimates of SO_2 concentration at ground level that interpolated data from a limited number of monitoring stations and known emission measurements from the smelters; and Landsat data from 1973, 1979, 1985, and 1988 to determine land cover and land cover change. They placed these values into a GIS (Arc/Info) and conducted association analyses between the 1988 land cover conditions and the SO_2 air concentrations, between the 1988 land cover conditions and the Ni and S concentrations in the lichens, and the range and change of land cover conditions with the total pollutant exposure to Ni, S, and SO_2.

The satellite imagery results showed a reduction of sensitive lichen land cover areas and an increase in barren landscape and pollution tolerant grasses and other plants. During this time, pollutant levels increased significantly. A strong correlation was found between increased SO_2 levels and decreased lichen cover. There was also a correlation between increased S and Ni levels and decreased lichen cover.

The researchers felt the combined use of remote sensing and ground-based field studies gave them greater insight into the pollutant issue than would have been achieved with only field studies and ground monitoring. They anticipated better results in the future as new satellites with better spatial, temporal, and spectral resolution were launched.

Veefkind J.P., G. de Leeuw, P.A. Durkee, P. B. Russell, P. V. Hobbs, and J. M. Livingston, 1999. "Aerosol optical depth retrieval using ATSR-2 and AVHRR data during TARFOX." *Journal of Geophysical Research,* Vol. 104, pp. 2253-2260.

Wald, L. 1999. "Some terms of reference in data fusion." *IEEE Transactions on Geoscience and Remote Sensing 37*, 3, pp. 1190-1193.

Wald, L., T. Ranchin, and M. Mangolini, 1997. "Fusion of satellite images of different spatial resolutions: assessing the quality of resulting images." *Photogrammetric Engineering and Remote Sensing,* Vol. 63, pp. 691-699.

Walker, Nan, 1996. "Satellite Assessment of Mississippi River Plume Variability: Causes and Predictability." *Remote Sensing of Environment*, Vol. 58, pp. 21-35.

This study used 5 years (1989-1993) of historical NOAA AVHRR images to investigate the variability of Mississippi sediment plume in the Gulf of Mexico. This was combined with measurements of river speed and discharge and wind speed. The data were calibrated with a limited number of direct water samples. The plume was found to be very reactive to wind speed. The results of this work were the successful use of satellite imagery to understand a water contamination/plume scenario.

Wilson, William, 1999. Personal communication. U.S. Environmental Protection Agency. Office of Research and Development.

Wood, Helen, 1999. "Disaster Management Support Highlights." Packet for a meeting of the Committee on Earth Observation Satellites, National Oceanic and Atmospheric Administration, May.

This document is a "white paper" on how Earth Observation Satellites could be used in disaster warning, response, and management. It discusses each major kind of disaster and the potential for using satellite imagery to support current ground-based observations. They recognize and address the challenge of introducing a new technology to disaster experts who are not familiar with satellite imagery. While it has been done in research and demonstration projects, "the operational application of these data is rare." They also recognize that the two groups often work in a vacuum and do not involve the other in the development and implementation of new monitoring methods. To address this, CEOS formed several hazard teams to analyze the current state of technology, user needs, and gap analysis in order to make recommendations. They mention that NOAA is developing an Internet server (http://disaster.ceos.org) to support disaster management in one single location for ease of use. They are involving many other agencies in its development.

This document also reports that CEOS is engaged in a more general initiative called Integrated Global Observing Strategy (IGOS), that will address both space-based and in-situ data, in order to create "improved higher level products by facilitating the integration of multiple data sets from differ-

ent agencies, national and international organizations." Their goal is improved use of resources, continuity of observations, and transition of research systems to practical operational use through international cooperation. Over several years, they developed a draft strategy and are testing it with 6 pilot projects

See summaries of CEOS Organization for more information. An e-mail exchange with Helen Wood, project lead, indicated that CEOS had not done anything in this area previously, but she felt the idea was worthwhile and of interest in general.

Woodruff, Dana L., Richard P. Stumpf, Julie A. Scope, and Hans W. Paerl, 1999. "Remote Estimation of Water Clarity in Optically Complex Estuarine Waters." *Remote Sensing of Environment*, Vol. 68, pp. 41-52.

This study used AVHRR satellite imagery to measure turbidity in the Pamlico Sound estuary in North Carolina. In situ water data and reflectance imagery were collected to calibrate the satellite-derived reflectance. Results related to the levels of phytoplankton in the rivers versus the bays and the changes in organic matter and suspended sediments. They feel that AVHRR data is useful for historical information and the new (at the time) SeaWiFS satellite will provide better future data (SeaWiFS Band 6 resembles AVHRR Band 1 at 580-680 nm).

APPENDIX A

Potential Relevant Satellites

AVHRR: The most often used sensor for aerosol retrieval to this point is AVHRR. It has flown on NOAA polar orbiting satellites since 1978. It is a five-band radiometer. AVHRR images are received at about 40 stations around the world and the EROS Data Center in Sioux Falls coordinates the archiving of these images.
http://edcwww.cr.usgs.gov/glis/hyper/guide/avhrr

TOMS: Total Ozone Mapping Spectrometer. Used since 1978 on Nimbus-7, it scans at ultraviolet wavelengths and is sensitive to absorbing aerosols.
http://jwocky.gsfc.nasa.gov/

GOES: Covers 1/3 of the Earth, the U.S. and surrounding oceans.
http://rsd.gsfc.nasa.gov/goes/
http://www.goes.noaa.gov/
http://orbit-net.nesdis.noaa.gov/goes/
http://orbit-net.nesdis.noaa.gov/goes/sat/images.html
http://cimss.ssec.wisc.edu/goes/misc

Landsat and Landsat Thematic Mapper (TM): Designed to monitor land on Earth, although images useful for aerosol monitoring. Data available at EROS Data Center.
http://landsat.gsfc.nasa.gov/
http://edcsns17.cr.usgs.gov/EarthExplorer/

ATSR-2: Launched in 1995 on ERS-2 (Europe) and is a multiangle sensor with similar bands to AVHRR.

POLDER: Launched in 1996 on ADEOS (Japan). It is the first space sensor designed with aerosol retrievals in mind and is polarization sensitive.

OCTS: Launched in 1996 on ADEOS. It was designed for ocean color and sea temperature but can be used for aerosol retrieval over water.

SeaWiFS: Launched in 1997 on OrbView-2. An ocean color satellite but also more. Excellent for algae bloom monitoring, tracking oil spills, and other water pollution.
http://seawifs.gsfc.nasa.gov/SEAWIFS.html

RADARSAT: Canadian satellite
http://www.ccrs.nrcan.gc.ca/ccrs/tekrd/satsens/satsense.html

Meteosat: geostationary, earth observation satellite launched by European Space Agency and now operated by Eumetsat.
http://www.nottingham.ac.uk/meteosat/

AATSR: Scheduled for launch in 2000 on Envisat-1. Similar to ATSR-2.

MERIS: Scheduled for launch in 2000 on Envisat-1.

GLI: Scheduled to launch in 2000 on ADEOS II. Similar to MODIS.

OMI: Scheduled for Launch in 2002. A 740-band hyperspectral spectrometer with a spectral band range from 0.27 to 0.5 um.

LASER Atmospheric Sensing Experiment system: Prototype for a future system that will be launched in a few years. Can make LIDAR measurements of water vapor and aerosols from 65,000 feet.
http://larcpubs.larc.nasa.gov/randt/1994/9-SectionA.www12.html

TERRA (was EOS AM1): This satellite was launched in December 1999 and was designed to monitor climate and environmental change. It

Table A-1: Satellite sensors used and potentially used for tropospheric air pollutant monitoring (based on King, et al. 1999)

Sensor	Spacecraft	Start Yr.	Orbit Type
AVHRR	NOAA-7,-9,-11, -14,-L,Metop-1	1978	Polar, Daily Global Coverage
TOMS	Nimbu-1, Met-eor-3, ADEOS, Earth Probe, QuikTOMS	1978	Polar, Daily Global Coverage
Sounder/Imager	GOES,-8, -10	1975	Geo-synchronous
TM	LandSat-5	1984	Polar, 16-day Global Coverage
ETM+	LandSat-7	1999	Polar, 16-day Global Coverage
HRVIR	SPOT, SPOT-4	1986	Polar, 26-day Global Coverage
ATSR-2	ERS-2	1995	Polar
OCTS	ADEOS	1996	Polar, 3-day Global Coverage
POLDER	ADEOS, ADEOS II	1996	Polar
SeaWiFS	OrbView-2	1997	Polar, Daily Global Coverage
MISR	Terra	1999	Polar, 9-day Global Coverage
MODIS	Terra, EOS PM	1999	Polar, 1-2-day Global Coverage
MOPITT	Terra	1999	Polar
AATSR	Envisat-1	2000	Polar
MERIS	Envisat-1	2000	Polar, 3-day Global Coverage
GLI	ADEOS II	2000	Polar, Daily Global Coverage
OMI	EOS CHEM	2002	Polar

Spatial Res. (km).	Swath Width (km)	Comments
1.1 (local mode); 4.4 (global)	2400	Has been used for aerosol optical thickness retrieval.
50	3000	Has been used for aerosol optical thickness retrieval and tropospheric column ozone.
		Have been used to monitor aerosol plume transport.
		Has been used for aerosol optical thickness retrieval.
15-60	115	Can be (has been?) used for retrieval of aerosol optical thickness.
	60	Has been used for aerosol optical thickness retrieval.
1	500	Has not been used for aerosol retrieval but potentially could because of similarity with AVHRR.
0.7	1400	Has been used for aerosol retrieval over the ocean.
7X6	2200	Designed and used for the retrieval of aerosol properties.
1.1 (local); 4.5 (global)	2800	Has been used for aerosol monitoring and aerosol optical thickness retrieval.
1.1	360	Algorithms have been developed for aerosol retrieval. Should be able to retrieve aerosol optical thickness over land and ocean.
0.25-1	2330	Algorithms have been developed for aerosol retrieval. "http://www.eos.ucar.edu/mopitt/home.html"
22		Designed to monitor carbon monoxide and methane.
1	500	Very similar to ATSR-2
0.3-1.2	1150	Designed to retrieve aerosol optical thickness
0.25-1	1600	Similar to MODIS
13 (local); 13X24 (global)	2600	Designed primarily for ozone monitoring but should be able to retrieve aerosol optical thickness using algorithms developed for TOMS

will include several sensors on one platform, including MISR and MODIS, which will enhance and exceed information from AVHRR. The instruments are the:

- Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)
- Clouds and the Earth's Radiant Energy System (CERES) (made up of two identical scanners)
- Multi-angle Imaging Spectroradiometer (MISR), http://www-misr.jpl.nasa.gov/
- Moderate Resolution Spectroradiometer (MODIS)
- Measurements of Pollution in the Troposphere (MOPITT), http://www.atmosp.physics.utoronto.ca/mopitt/home.html
  http://terra.nasa.gov/

See Table A-1 for more information

APPENDIX B

METHODS FOR REMOTE SAMPLING OF AEROSOLS

Aerosol Retrieval Methods

The radiant energy obtained from a earth observing satellite sensor is converted into reflectance or apparent reflectance using information about the atmospheric condition along the path between the ground and the satellite, as well as the viewing geometry and the solar geometry. For those observing land use changes, aerosols block the view. Thus techniques used to remove the aerosols can also be used to highlight or enhance them. The major retrieval methods are summarized below. See Table B-1 for more information.

Single-channel reflectance: This method usually uses a channel in the visual wavelength range. Aerosol optical thickness (AOT) is derived by detecting an increase in reflectance at the chosen wavelength.

Multichannel reflectance: This method is used to derive AOT as well as aerosol size distributions. A ratio of reflectance at two wavelengths is used to estimate the AOT.

Dark targets over dense, dark vegetation: Vegetation usually has low reflectance (dark) in the red (0.6-0.7 um) and blue (0.4-0.5 um) spectral ranges. Aerosols located above these dark surfaces increase the reflectance. The AOT is determined from the difference between the reflectance at the top of the atmosphere and the reflectance at the surface in the red and blue spectral ranges. The limitation of this method is that what appears dark in one image, may not appear as dark in another. Furthermore, the darkest pixel in one image might not be as dark as the pixels in subsequent

Table B-1. Methods for remote sensing of aerosols. (Based on King et al. 1999)

Method	Relevant Sensors
Ocean	
Reflectance-one channel	AVHRR
Reflectance-multiple channels	AVHRR, TOMS, SeaWiFS, POLDER, GLI, MERIS, MISR, OMI
Land	
Reflectance	AVHRR, TOMS, OMI
Reduction in contrast	AVHRR, GLI, MODIS, POLDER
Dark targets over dense, dark vegetation	AVHRR, GLI, MERIS, MISR, MODIS, POLDER, SeaWiFS
Thermal contrast	AVHRR, MODIS, GLI
Land-ocean contrast	AVHRR, POLDER, MODIS, GLI
Angular distribution of reflectance	POLDER, MISR, ATSR-2, AATSR
Polarization	POLDER

images in the same swath. The result is an error in the retrieval of AOT.

Reduction in contrast over land: AOT is determined by taking the difference in reflectance from images on a hazy day and on a clear day. This method requires that the underlying surface is invariant over time. The clear day image is selected based on the relative “sharpness” of multiple images, which can limit the usefulness of this technique.

Thermal contrast: This method is based on emitted thermal radiation (10-12 um) over a period of time. It makes two assumptions: 1) the thermal radiance of the surface is either constant or varies linearly over the time period and 2) one of the days during the time period is clear. During hazy days, surface emitted long-range radiation is reduced and the incoming short-wave radiation is scattered. Both of these aerosol amplified effects cool the surface and increase the thermal contrast between clear and hazy days. Thermal contrast can be related to AOT. This method has only been applied to Saharan dust and may not be applicable for most land cover surfaces or all aerosol types.

Land-ocean contrast: This method uses the radiance of two contrasting surface reflectances on clear and hazy days to estimate the aerosol single scattering albedo and the AOT.

Angular distribution of reflectance: These methods take advantage of the multiple angular measurements of the same location by sensors on some of the new satellites.

Polarization These methods are based on the strong influence that the aerosol particle radius and refractive index have on polarization.