Utilizing a New Aerosol Data Display and Dissemination Tool to Analyze Aerosols over the Northern Indian Subcontinent Region

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Abstract

Aerosol emissions originating from the Northern Indian Subcontinent (NIS) region have a significant effect on local and regional climate. Although the level of scientific understanding for aerosol radiative forcing is very low, an aerosol analysis using a new aerosol data display and dissemination tool (BAMGOMAS) showed significant changes in aerosol loading over the NIS region. A number of widely distributed aerosol data sets such as ground-based (AERONET, MPLNET) and satellite-based (MODIS, GIOVANNI) measurements as well as model data (back trajectory analyses, GOCART) were integrated into one web analysis tool. Using this tool, an aerosol analysis was conducted over the NIS region for 2004. This analysis found that 500nm daily average aerosol optical depth (AOD) values as high as 1.6 AOD consisted primarily of fine mode particles during the dry monsoon phase, while the wet monsoon phase produced much lower 500nm daily average values near 0.2 AOD with coarse mode particles. Satellite imagery and retrieved data, back trajectory analyses, and model output provided supporting information on aerosol source regions, transport, and chemistry. These data sources confirmed the seasonality of aerosol loading and estimated aerosol particle constituents over the NIS region.

1. Introduction

Atmospheric aerosols can impact the local and regional radiation heat budget. Black carbon aerosols absorb incident solar radiation and heat the atmosphere more effectively than dust, sulfates, and organic carbons, which reflect more radiation and cool the atmosphere. However, the scientific understanding of the aerosol radiative forcing magnitude remains very low (Albritton and Filho 2001). Although the lifespan of aerosols is about one week, persistent meteorological phenomena and anthropogenic activities can provide an environment of greater climate impact (Rasch 2001). Aerosols influenced by these conditions can be observed by visible satellite images and verified by ground-based observations over the Northern Indian Subcontinent (NIS) region (Chu 2003).

The population 1.08 billion in India (CIA World Fact Book, July 2005 estimate) has led to a significant demand on natural resources (i.e., water, land, and fossil fuels). Biofuels such as wood fuel, dung, and crop waste are the primary contributors of aerosols in rural areas of India (Habib 2004). Aerosol emissions in urban regions result from fossil fuel sources such as diesel and kerosene mixed-fuel vehicles, industrial processes, and coal-fired power generation (Dickerson 2002, Prasad 2006). Industrialization and population expansion with agricultural and fuel-use practices induce high aerosol loading over the NIS (Lelieveld 2001, Prasad 2006). However, the anthropogenic influence is not entirely responsible for persistent aerosols. Meteorological phenomena induced by local geography (i.e., Himalayan Mountains and the Indian Ocean) exacerbate smog conditions by prolonging the lifetime of aerosols and clouds to further impact climate.

A number of methods can be used to determine aerosol properties including ground-based, satellite, and *in situ* measurements as well as modeling used to estimate aerosol chemistry. In an effort to improve aerosol data access, these data sources were integrated into a web data display and dissemination tool. This tool was used to identify aerosol loading, sources, and potential types over the NIS region in 2004. This paper provides background on the NIS region, a discussion of previous work, a summary of aerosol data sources, a description of the analysis tool, and a case study of aerosols over the NIS region.

2. Regional Meteorological Effects on Aerosols

The Indian subcontinent geography creates unique conditions that often result in prolonged aerosol lifetime. The Indian subcontinent is bordered by the Himalayan Mountains and the Tibetan Plateau to the north. This elevated landmass provides a mechanism to uplift warm, moist air from the south or enhance subsidence induced by northerly winds (Figure 1). The Arabian Sea and Bay of Bengal of the Indian Ocean lie to the south and provide a source of moisture especially during the summer monsoon. The Thar Desert in western India provides is a local source of dust for the NIS region (Sagnik 2004).

Figure 1 Northern Indian Subcontinent Region (Google Earth).

The seasonal changes in wind are controlled by the heating of the elevated terrain with warm air rising during the "wet" monsoon phase and cool air sinking during the "dry" monsoon phase (Webster 1998, McIlveen 1992). As the Himalayan and Tibetan Plateau warm in the summer, southwest winds supply moisture to the region from the Indian Ocean typically from June to September (Figure 2). Winds shift to the north during the fall months when heating of the elevated surfaces wanes with decreasing mean solar intensity. This cool, dry air suppresses convective cloud formation and precipitation during the winter months (Webster 1998). The subsidence inversion caps the vertical mixing with the free troposphere and retains aerosols for extended periods within the well-mixed layer. The dry monsoon phase is a key regional-scale meteorological process that promotes increased aerosol lifetimes in the atmosphere over the northern Indian subcontinent, while the wet monsoon phase tends to reduce aerosol concentrations.

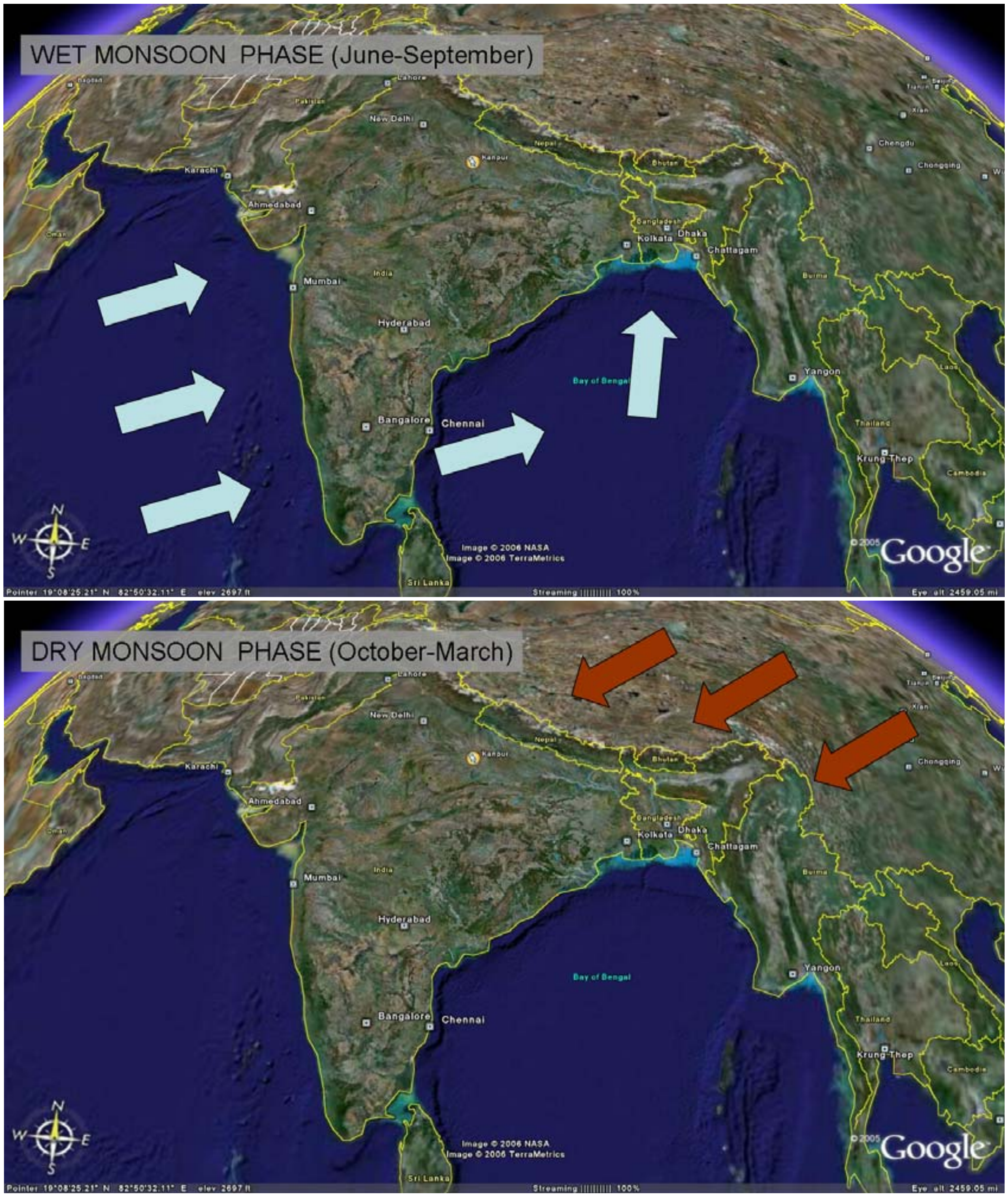

Figure 2 Typical Indian subcontinent "wet" and "dry" monsoon periods (Google Earth).

Aerosols (e.g., sulfates, black carbon, and organic carbon) in this region originate from agriculture, industry, urban, domestic, and power generation sources. All of these sources contribute to the aerosol loading in the atmosphere. The AQUA-MODIS satellite image from February 2003 shows an example of aerosols trapped in the stagnant conditions over NIS (Figure 3). Biomass burning occurs in Pakistan and northwestern India rural regions. Industry, urban, and power generation pollution result from Kanpur and other cities along the Ganges River Basin. Figure 3 shows fog and aerosols over the central Ganges River Basin. A sharp aerosol gradient exists to the north over the Himalayan Mountains where aerosols do not reach much higher than the foothills. The linear edges of the fog layer are mainly a function of altitude. In comparison, a cloud has formed to the southeast and above the aerosol layer. Cloud formation may have resulted from aerosols acting as cloud condensation nuclei. Satellite observations confirm that these persistent aerosols can have a significant effect on the atmosphere by changing cloud shape, concentration, and lifetime.

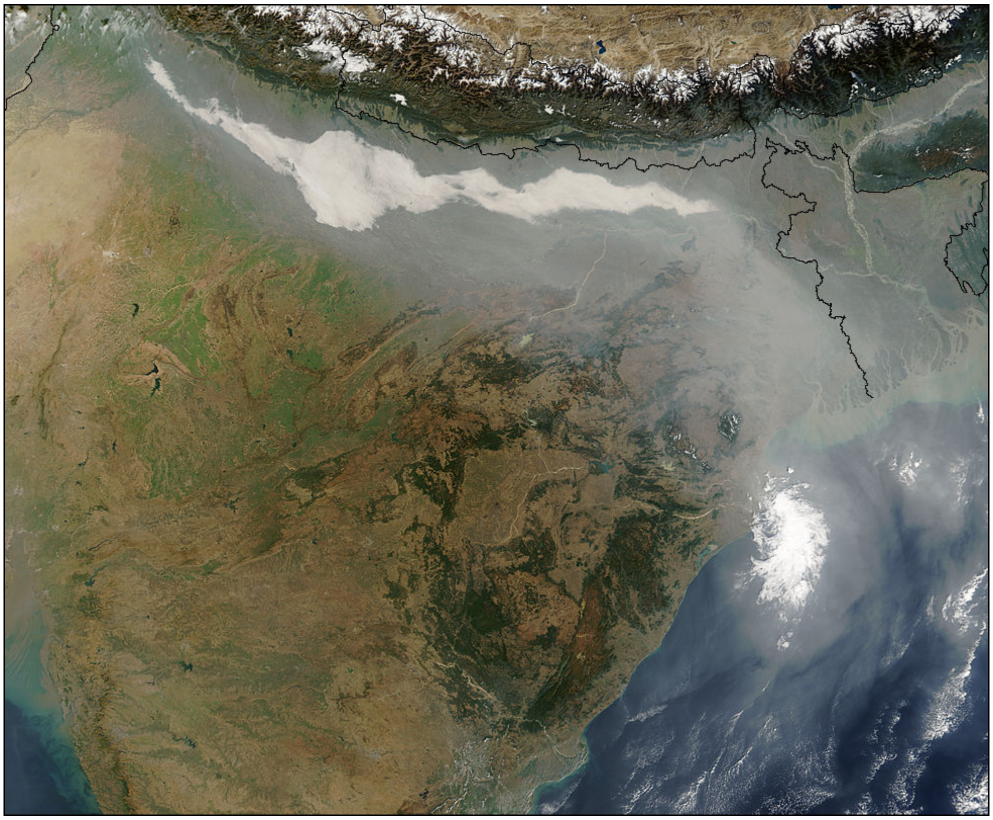

Figure 3 TERRA-MODIS true color image depicting a high concentration of aerosols over Northern India on December 17, 2004.

3. Aerosol Measurements and Modeling Techniques

A number of observation platforms have been used to measure aerosols. These platforms include the use of ground-based, satellite, and *in situ* measurements. Each measurement technique has its advantages and disadvantages, but when integrated simultaneously, these data provide information key to understanding the aerosol forcing on the atmosphere through model simulations. A number of field campaign experiments have been conducted to collect data to be used in calibration, validation, and modeling activities. While several studies have assessed aerosol effects in other regions of the world, none have characterized the aerosols in the NIS region where aerosols are continually produced by anthropogenic activities.

In the late 1990s, the Indian Ocean Experiment (INDOEX) attempted to characterize the effects of Indo-Asian haze over the Indian Ocean (Ramanathan 2001). The experiment included an array of observations including ground- and ship-based surface measurements, satellite retrievals, and *in situ* aircraft observations. These measurements and assimilated data were ingested to the Climate Community Model (CCM). The CCM results showed that aerosols transported from the Indian subcontinent and Southeast Asian region increased the heating at the surface in the northern tropical Indian Ocean. The increased heating led to enhanced precipitation in the Intertropical Convergence Zone (ITCZ), and this enhanced upward motion perturbed the east-west Walker circulation. The general circulation model (GCM) showed that the modified Walker circulation suppressed rainfall in the western Pacific and enhanced rainfall in the eastern Pacific: two regions significantly affected by El Niño/Southern Oscillation (ENSO) variability. This extensive study provided insight into the Indian subcontinent aerosol impact on regional and global climate.

A number of other experiments in the late 1990s also attempted to characterize aerosols in other regions of the world. The Aerosol Characterization Experiments (ACE-1) and (ACE-2) attempted to reduce the uncertainty in the calculation of climate forcing by aerosols by sampling the Southern Hemisphere and subtropical northeast Atlantic marine atmosphere (Bates 1998, Raes 2000). The Tropospheric Aerosol Radiative Forcing Observational Experiment (TARFOX) was conducted over the coastal eastern United States with a similar goal (Hobbs 1999). The Smoke, Clouds, Aerosols, Radiation-Brazil (SCAR-B) experiment attempted to characterize the effect of biomass burning, smoke, aerosol, and trace gases and their climate effects (Kaufman 1998). Although these experiments have reduced some uncertainty with respect to the climate impact of aerosols, a significant amount of uncertainty still remains (Albritton and Filho 2001).

3.1 Ground-based Remote Sensing Networks

Ground-based measurement networks have been established to validate and calibrate satellite measurements and models as well as to establish a long-running record of meteorological and atmospheric aerosol conditions. These networks have been established regionally and globally. A dense surface meteorological network (e.g., temperature, pressure, wind speed and direction) was established by the National Weather Service (NWS) Automated Surface Observing System (ASOS) program and Federal Aviation Administration (FAA) Automated Weather Observing System (AWOS) program in the United States. The NWS and FAA sites presently total about 1000 with a majority of the measurement stations located at or near airports (http://www.faa.gov/asos/hist-aos.htm). Similar networks measuring atmospheric and oceanic conditions (e.g., sea surface temperature, pressure, winds, etc.) have been established over the ocean through the use of moored buoys, drifting buoys, and platforms along the coastal United States by the National Data Buoy Center in addition to an observation network over the equatorial oceans to track changes in ENSO (McFadden 1998).

In addition to meteorological conditions, other ground-based networks attempt to measure aerosols in the atmosphere. For example, the NASA Aerosol Robotic Network (AERONET) provides information on aerosol atmospheric optical properties such as aerosol optical thickness, single scattering albedo, and size distributions (Holben 1998, Dubovik 2000). The network includes over 240 sites globally with 160 sites operating in 2006 (Figure 4). Futhermore, the Mircropulse Lidar Network (MPLNET) is comprised of approximately 10 instruments with a majority of these lidars collocated with AERONET sites. These instruments measure the aerosol and cloud vertical distribution using an eye-safe laser at the 532nm wavelength (Spinhirne 1993).

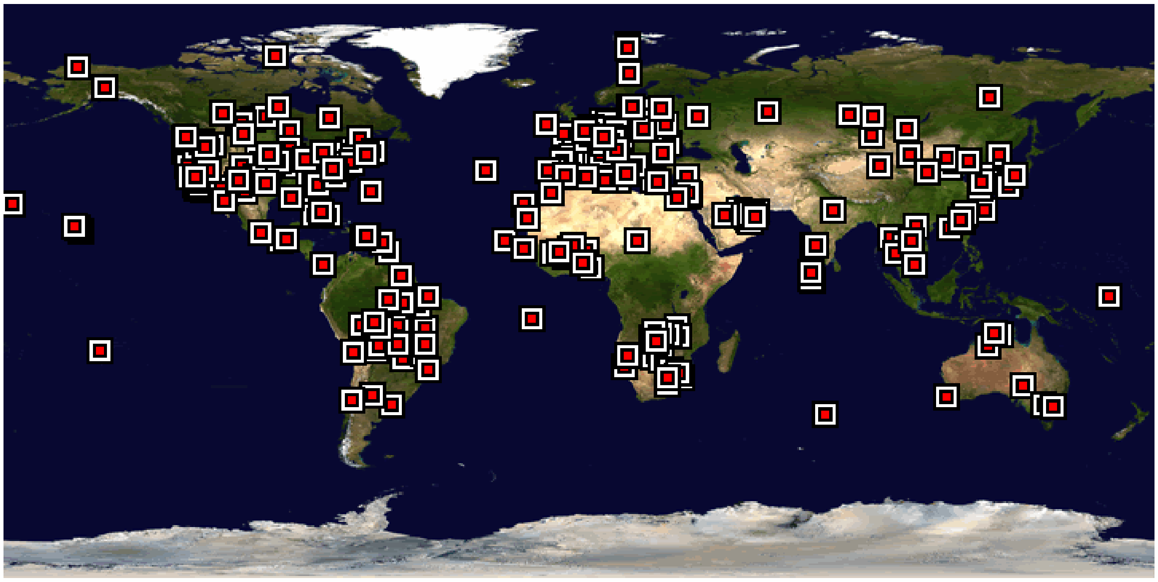

Figure 4 AERONET Site Distribution.

Balloon-based meteorology and chemistry networks can be used to understand the vertical profile of an atmospheric parameter in addition to the surface conditions. Meteorological information is collected twice daily using radiosondes at sites throughout the world. These measurements provide altitude, pressure, wind direction and speed, temperature, and dew point near the balloon launch site. Regional balloon-based networks have also been established to measure the concentration of ozone. The NASA Southern Hemisphere Additional Ozonesonde (SHADOZ) network was established to validate total ozone measurements from the Total Ozone Mapping Spectroradiometer (TOMS) instrument (Thompson 2003). The network is comprised of 14 sites in the southern hemisphere to monitor the concentrations of ozone and meteorological parameters in a measurement-sparse region of the world. The peak ozone concentration tends to be decoupled with peak aerosol concentrations; however, these maximum concentrations may coincide during some biomass burning episodes (Thompson 2001).

3.2 Satellite Remote Sensing

Geostationary satellites and polar orbiting satellites are the primary mechanisms for satellite remote sensing. Geostationary satellites maintain an orbit over a certain area of the globe near the equator. Instruments on these satellites can observe cloud characteristics (e.g., type and coverage) as well as water vapor and brightness temperatures continuously from 65°S to 65°N. Polar orbiting satellites fill the data void not observed by geostationary satellites. These low-orbiting satellites move from pole to pole passing over the north and south poles several times per day, while regions near the equator only experience up to two overpasses per day. These polar orbiting satellites can provide data similar to geostationary satellites but with a higher spatial resolution.

While satellites were primarily focused on collecting meteorological parameters for weather forecasting and analysis in the late 1900s, aerosol measurements from satellites have increased in the last six years. In 2000, the first Moderate Resolution Imaging Spectroradiometer (MODIS) sensor was launched aboard the TERRA satellite to measure Earth science parameters such as aerosol optical depth, size distribution, and cloud extent (Chu 2002). MODIS data products have been available from TERRA since February 2000 and from the AQUA platform since July 2002. In addition to MODIS, other satellite sensors such as the Multispectral Imaging SpectroRadiometer (MISR) provide global coverage of aerosol optical depth. Due to the polar orbiting nature of these Earth-observing satellites, measurement parameters are collected twice daily (in the morning and in the evening) from the tropics to the mid-latitudes. Temporal resolution can be improved using data from multiple satellite platforms. For example, TERRA-MODIS satellite observations are followed by AQUA-MODIS a few hours later. These measurements offer a distinct advantage by providing supplementary aerosol data to the ground-based networks. However, these data do have some uncertainty due to calibration and reflectance characteristics of the Earth surface. MODIS land uncertainty for aerosol optical depth is ±0.05 (Remer 2005). Nonetheless, MODIS data provides important information on the spatial aerosol loading and source regions needed for proper modeling and analysis.

3.3 *In Situ* Observations

Research aircraft can sample specific points in the atmosphere above measurement campaign regions. These aircraft can be equipped with a number of probes and instruments to collect aerosol (e.g., particle size and chemistry), meteorological (e.g., temperature and pressure), and aviation (e.g., position and altitude) data. Aircraft missions can be flown at various altitudes to sample the aerosol size distribution, shape, and chemical composition and observe the interactions between aerosols and clouds. Mission assessments conducted each morning determine if meteorological and aerosol conditions are appropriate for sampling. Flight plans will typically consider ground-based and balloon-based sites as critical observation points to simultaneously collect information over these sites. The aircraft samples various altitudes over each site to obtain a vertical distribution of aerosols and clouds. These aircraft missions provide *in* *situ* measurements of particle type, chemical composition, and size distribution, which can only be inferred by other observation techniques.

3.4 Implementing Aerosol Measurements in Atmospheric Models

A General Circulation Model (GCM) coupled to ocean, biosphere, and chemical models can provide a more realistic prediction of the future Earth system state. The Geophysical Fluid Dynamics Laboratory (GFDL) uses a coupled GCM to provide climate predictions from the seasonal to multi-century timescales. Chemical transport models can ingest these data from the GCMs to predict the concentration of the constituent trace gases such as CO_2 over the next 100 years. GCMs can also be used to assess the global impacts of the aerosols in the NIS region. The aerosol-induced regional and global effects may include modification of the Asian monsoon and changes in the magnitude of ENSO events. A two-tiered forecasting approach could be implemented by using an atmospheric-chemical transport model [e.g., Georgia Tech/Goddard Global Ozone Chemistry Aerosol Radiation Transport (GOCART)] to determine and substantiate the aerosol component (Chin 2002). The GOCART model produces information on modeled aerosol properties (e.g., optical depth, size distribution, and aerosol type). These results can be applied to the GFDL GCM with coupling among the atmosphere, ocean, and biosphere. Running a model simulation with and without aerosol inputs is one method to determine regional and global climate sensitivity.

Data assimilation is the synergism of observations and model output. The assimilated data are used in research to provide the best estimate of past meteorological conditions using the best observations and model algorithms and parameterizations to produce products such as back trajectory analyses. Data assimilation can have uncertainty (e.g., measurement errors or cloud parameterization) but the analysis scheme implemented by the NCEP/NCAR and GEOS Data Assimilation System reanalysis has been accepted for scientific analysis (Kistler 2001, Schubert 1995).

4. Developing Aerosol Analysis Tools

As ground-based network, satellite, and model data have been collected and stored over the past decade, these data have been maintained on various web sites and stored in different data formats (e.g., NetCDF and HDF). In 2002, NASA allotted funds through Research, Education and Applications Solutions Network (REASoN) Comprehensive Agreement Notice (CAN) to attempt to improve data accessibility and analysis of NASA Earth science datasets. This effort titled, "**B**ack Trajectories, **A**ERONET, **M**ODIS, **GO**CART, and **M**PLNET **A**erosol **S**ynergism (BAMGOMAS)," proposed to provide aerosol ground-based (AERONET and MPLNET), satellite-based (MODIS), and model output (GOCART and Back trajectories) at one user-friendly web site for use by researchers, students, and the general public (Table 1).

The data access and analysis tool (**Figure 5**) developed by the author and collaborators as a result of this project is called the BAMGOMAS Interactive Data Display (BIDD).

Table 1 BAMGOMAS Interactive Data Display (BIDD) Product Description and Availability

Product	Frequency	Availability	Resolution	Source
AERONET	Every 15 minutes during the solar day	Near real-time; starting in 1993	Globally-distributed sites	http://aeronet.gsfc.nasa.gov
Back Trajectory Analyses	Twice daily at 00UTC and 12UTC	Within 3 weeks of real-time; starting in 2000	2° by 2.5°	http://croc.gsfc.nasa.gov/aeronet/
MODIS (AQUA and TERRA)	Daily	Near real-time; starting in 2003	2km, 1km, 500m, 250m	http://rapidfire.sci.gsfc.nasa.gov/
GOCART	3-Hour intervals	July-September 2004	2° by 2.5°	http://code916.gsfc.nasa.gov/People/Chin/gocartinfo.html
MPLNET	Every minute	Near real-time; starting in 1998	Regionally-distributed sites	http://mplnet.gsfc.nasa.gov/
GIOVANNI-MODIS	Monthly	TERRA - starting February 2000 AQUA - starting July 2002	1° by 1°	http://disc.sci.gsfc.nasa.gov/techlab/giovanni/

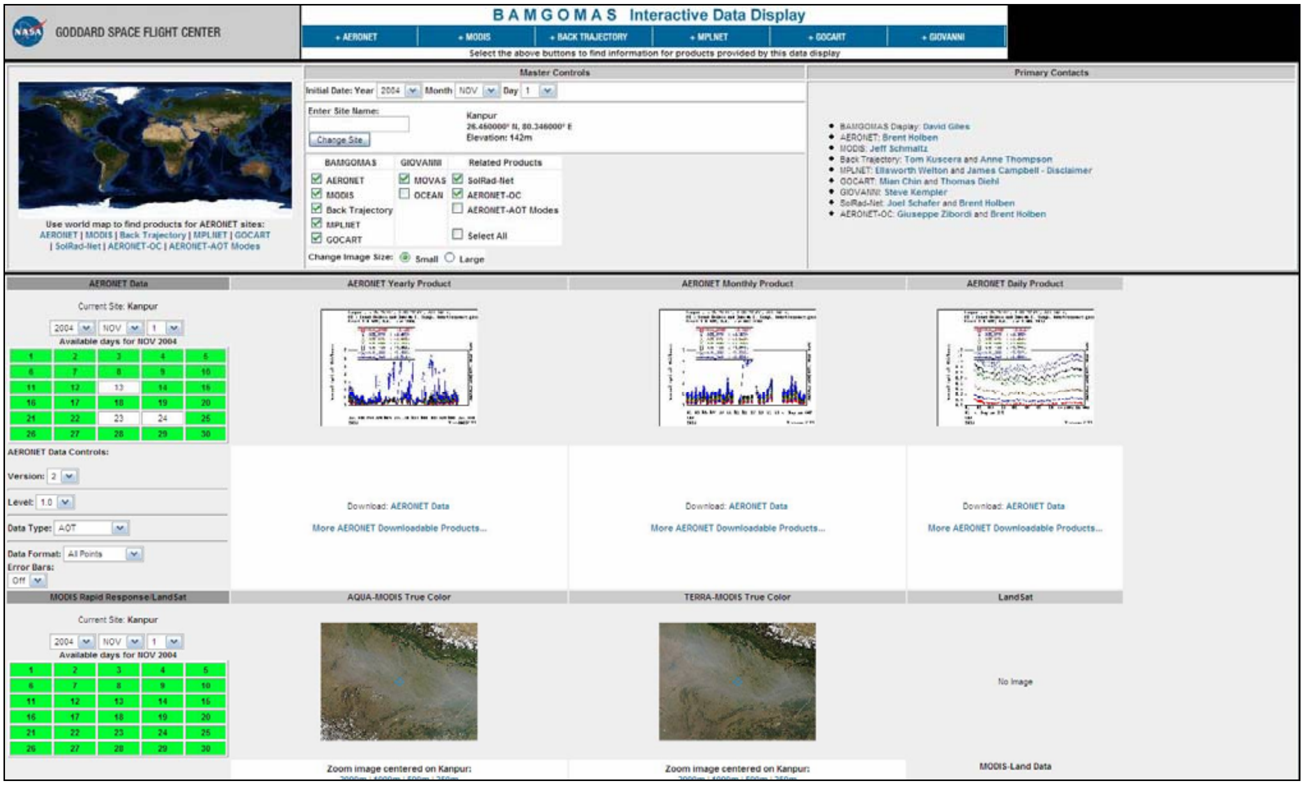

Figure 5 BAMGOMAS Interactive Data Display (BIDD) – http://aeronet.gsfc.nasa.gov/BAMGOMAS/.

AERONET data products are currently the most robust part of BIDD because AERONET has the longest data record with over 13 years of collecting data. AERONET uses Cimel sun photometers to measure irradiance and radiance in generally cloud-free conditions during the solar day. The AERONET database provides aerosol optical depth (AOD) derived from direct sun measurements at 340, 380, 440, 500, 675, 870, 1020, and 1640nm wavelengths; Ångstrom parameter computed from the 440, 500, 675, and 870nm wavelengths; and Precipitable Water (PW) derived from the 940nm wavelength (Holben 1998). These products are assigned quality levels 1.0 (unscreened), 1.5 (cloud-screened), and 2.0 (quality assured). In addition, the database provides aerosol optical properties derived from radiance measurements. These radiance products include the complex index of refraction, single scattering albedo, phase functions, and size distributions (Dubovik 2000).

Seven-day back trajectory analyses show the kinematic trajectory of air parcels over the past seven days. These analyses are produced for approximately 125 AERONET sites twice per day at 0 and 12 UTC using the GEOS data assimilation at NASA GSFC (Thompson 2003, Schoberl 1995). These data are computed at eight pressure levels from 950 to 200hPa. The product provides both a graphical representation of four preset pressure levels (950-500hPa) and all eight pressure levels (950 to 200hPa) in addition to text data that provides all of the eight pressure levels. These data are available daily starting from January 2000 to three weeks prior to present day.

The MODIS Rapid Response creates MODIS subset images centered on over 100 AERONET sites. These images are currently available starting in late 2003 for both TERRA and AQUA satellite platforms. TERRA and AQUA images are provided in true color with the MODIS fire product overlaid as red dots on the images in the presence of fires. These images are subset over AERONET sites at four spatial resolutions: 2km, 1km, 500m and 250m. These MODIS images provide visual information on the state of fires, aerosols, and clouds over the measurement domain.

The GOCART model data is provided on the data display for over 240 AERONET sites at 2° latitude by 2.5° longitude resolution. This data product currently provides the total integrated column AOD for each AERONET site at 350, 550, and 900nm wavelengths. The model also estimates constituent aerosols such as organic carbon, black carbon, sea salt, dust, and sulfates. GOCART model results are currently available from July 1, 2004 to September 30, 2004.

The Micropulse Lidar Network (MPLNET) instruments measure the aerosol and cloud vertical distribution using an eye-safe laser at the 532nm wavelength (Spinhirne 1993). MPLNET is comprised of approximately 10 instruments with a majority of these lidars collocated with AERONET sites. Importantly, AERONET measurements are used to provide total column aerosol optical depth to calibrate lidar products (Campbell 2003). Lidar instruments operate and collect continuous data, providing aerosol and cloud distribution at night, whereas passive remote sensing instruments require solar radiation. MPLNET Level 1 and 1.5a data availability depends on the site and measurement campaign.

BIDD has also utilized a link into the GES-DISC Interactive Online Visualization and Analysis Infrastructure (GIOVANNI) tool developed by the Goddard Earth Sciences-Data and Information Services Center (GES-DISC). This link provides multiple resolution maps and data over each AERONET site for TERRA and AQUA-MODIS collection 4 products. These monthly average products include aerosol optical depth, fine mode fraction, clear sky water vapor, and cirrus cloud fraction.

The BIDD tool will continue to evolve as new aerosol-related products become available. For example, the solar flux data from the Solar Radiation Network (SolRad-Net), normalized water-leaving radiances from AERONET-Ocean Color, and AQUA-MODIS and SeaWiFS ocean data from GIOVANNI-Ocean have been added recently to the data tool. The versatility of the data tool allows for incorporation and expansion of new Earth Science datasets in the future.

5. Using BIDD to Analyze Aerosols over the NIS Region

The BAMGOMAS Interactive Data Display (BIDD) tool was used to acquire and analyze data over the NIS region for 2004. Precipitable water (PW) and aerosol optical depth (AOD) Version 2, Level 2.0 data were downloaded for the Kanpur, India AERONET site. Figure 6 shows reduced PW values mostly below 1.75cm with aerosol optical thickness values between 0.5 and 5.8 during the 2003 dry monsoon phase. At the onset of the wet monsoon in late May, PW significantly increases and AOD decreases at the same time as winds turn southerly providing a source of moisture. Through cloud and precipitation processes, the aerosols are precipitated out, leading to a significant reduction in AOD. As the wet monsoon ends in late September, PW values decrease and AOD values increase as the subsidence returns over northern India, trapping the aerosols along the foothills of the Himalayan mountains.

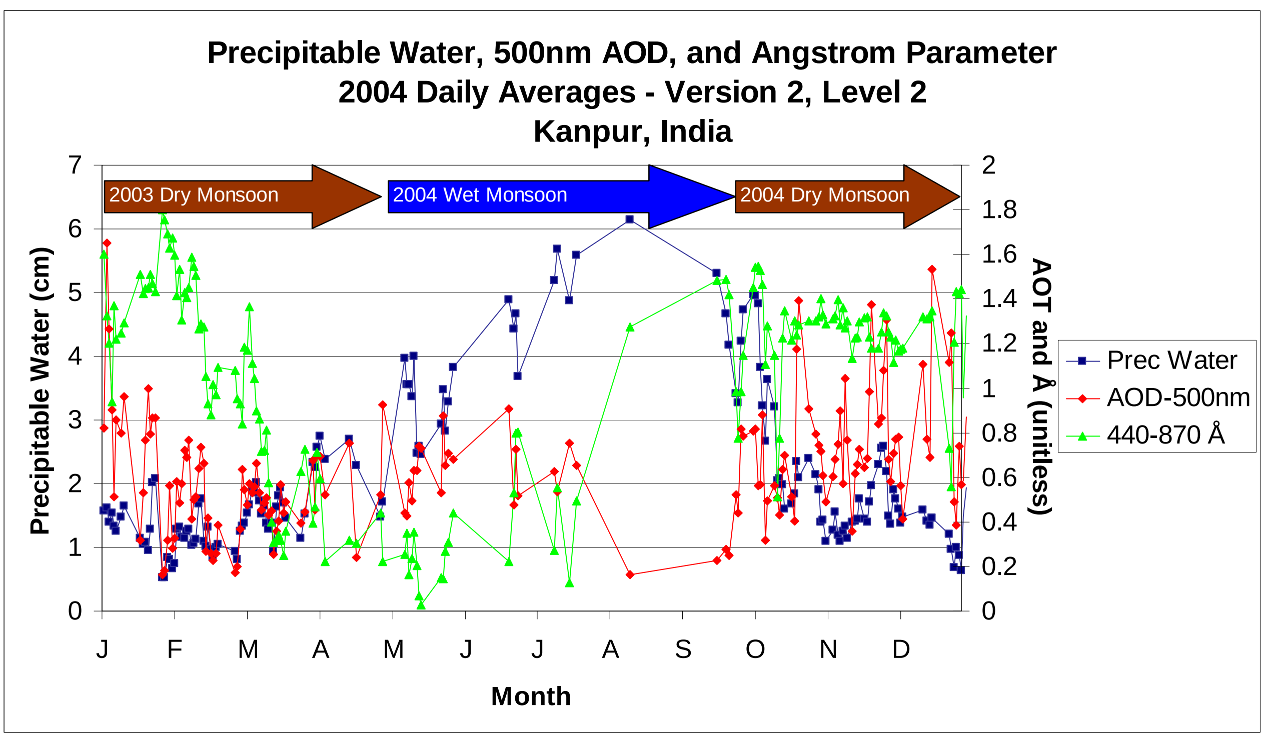

Figure 6 AERONET Version 2, Level 2.0 Precipitable Water, 550nm AOD, and 440-870nm Ångstrom Parameter for Kanpur, India in 2004.

Ångstrom parameters calculated from 440 to 870nm provide an estimate of the aerosol size distribution. Pure fine-mode aerosols can have Ångstrom parameter values near 2, while pure coarse-mode aerosols can have values near 0 (Eck 1999). Figure 6 shows that the Ångstrom parameter is typically greater than 1 during the dry monsoon phase where sulfate and carbon-based aerosols likely dominate the fine mode. However, low values during the wet monsoon phase indicate the presence of coarse mode dust from the Thar Desert (Sagnik 2004, Singh 2004).

In support of this analysis, BIDD provides satellite imagery from AQUA-MODIS over the Kanpur, India AERONET site. Figure 7 images show the existence of aerosols and clouds over the NIS region. The MODIS satellite images are shown for each period, 2003 dry monsoon (January 27, 2004), 2004 wet monsoon (July 17, 2004), and 2004 dry monsoon (November 11, 2004). The 2003 and 2004 dry monsoon phase images depict a typical aerosol loading event over the NIS region. The 2004 wet monsoon phase image shows that aerosols have been scavenged by clouds and precipitation or have become obscured by clouds.

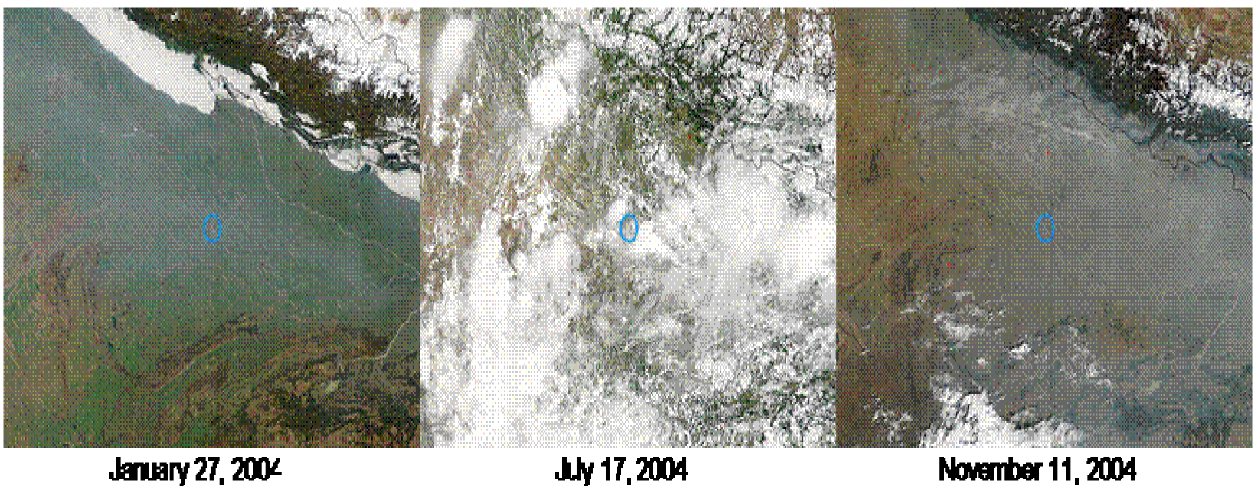

Figure 7 AQUA-MODIS Rapid Response imagery centered over the AERONET site in Kanpur, India. These images show the coverage of aerosols and clouds in each monsoon regime.

Back trajectory analyses show the kinematic trajectory of air parcels over the past seven days. A representative day in each monsoon phase was chosen to show the wind flow patterns at different pressure levels and provide information on the transport of aerosols from other source regions. Figure 8 shows that the low level flow originates from Pakistan and western India where dust may be transported from the Thar Desert during the 2003 dry monsoon. The 2004 wet monsoon phase shows low-level winds mainly originating from the Indian Ocean responsible for moisture advection into the region during the wet monsoon phase months. In the 2004 dry monsoon, biomass burning in northeastern Pakistan and northwestern India generate fine mode aerosols and these aerosols move southeastward over the Ganges River Basin.

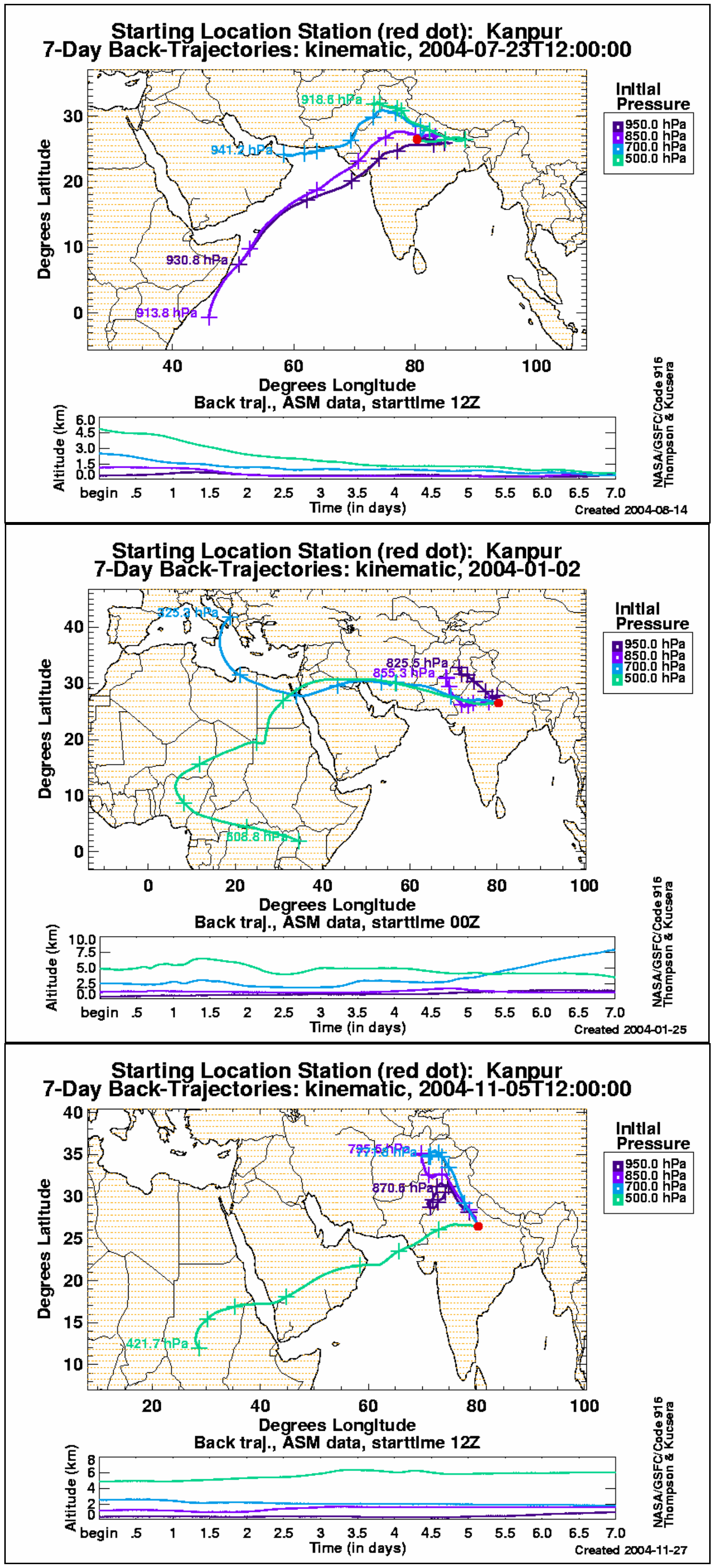

Figure 8 Seven-day back trajectory analyses for each monsoon regime.

GOCART model data were available from July 2004 through September 2004. Figure 9 indicates aerosols composed mainly of sulfates and dust. As back trajectory analyses showed in Figure 8, the winds originated from the southwest with trajectories over the deserts where some dust may have been captured by the monsoon winds. The total optical depth of 0.5 for the three-month period would be expected during significant cloud and precipitation processes in the region as the aerosols would be readily removed from the atmosphere.

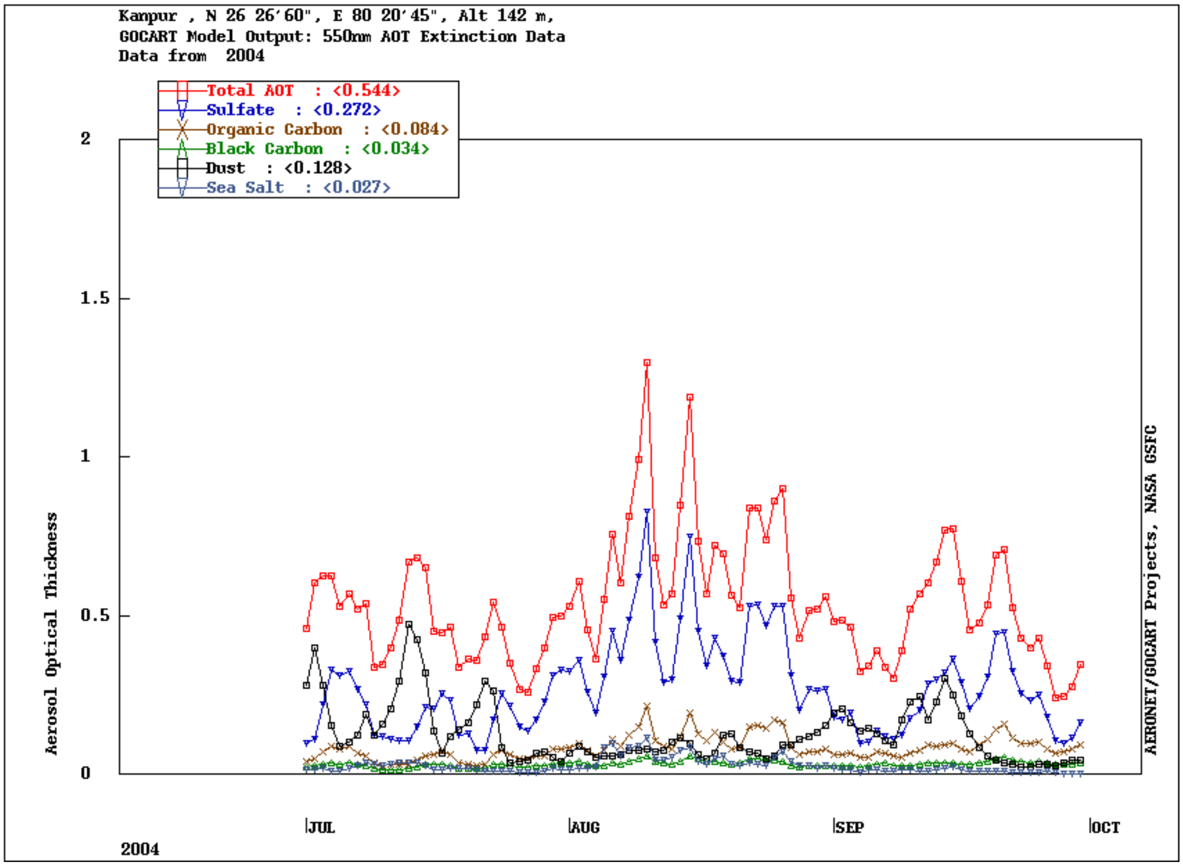

Figure 9 GOCART model data from July through September 2004.

Micropulse lidar data are not available over the northern India subcontinent region. If an MPLNET instrument was present, the lidar would provide a continuous vertical profile of the aerosol and cloud layers for a specific site. This information would be useful in determining the vertical distribution of aerosols and clouds. An example of MPLNET data are provided in Figure 10.

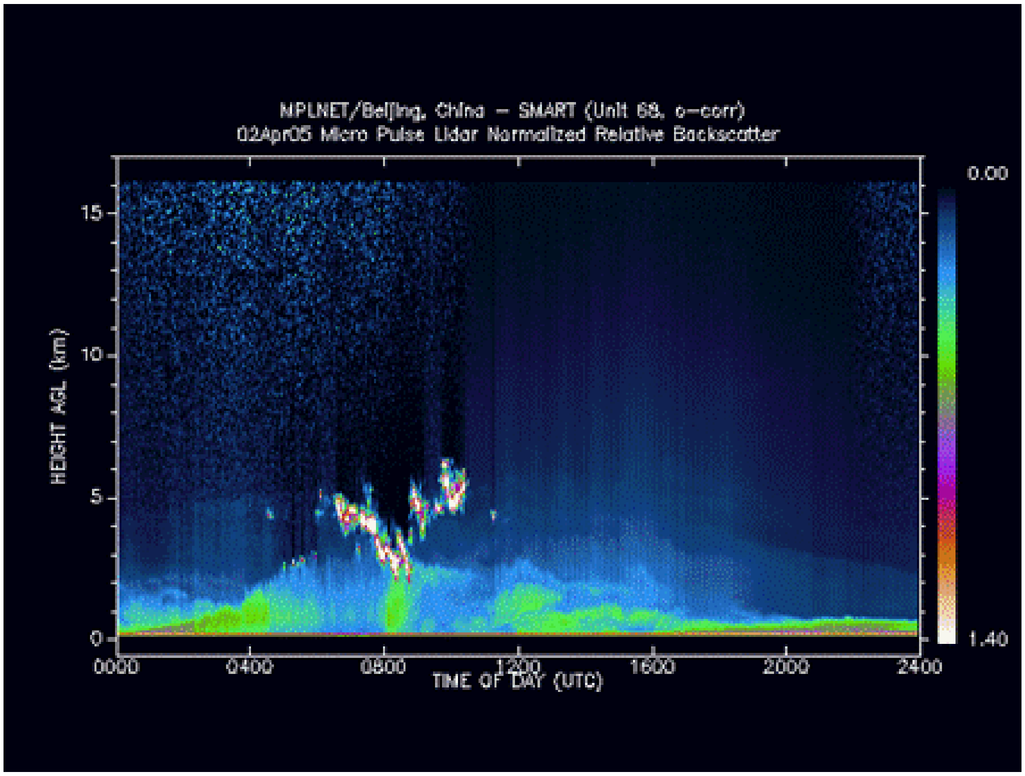

Figure 10 MPLNET Lidar data from Beijing, China in April 2005. This image shows an example of the possible measurements with a lidar, which is not available in the Northern Indian subcontinent region.

The GIOVANNI tool provides MODIS monthly average AOD and clear sky water vapor for the NIS region. In January 2004, AQUA-MODIS monthly average data (Figure 11) over the NIS region show a large swath of 0.7 AOD at 550nm covering most of the Ganges River Basin. Precipitable water using the Clear Sky NIR Method (Figure 12) support AERONET values of PW less than 2.0. However, MODIS monthly average data for July 2004 show AOD at and above 1.0 over the region. These values may indicate issues in retrieving MODIS AOD over land surfaces (Kaufman and Tanre 1998). Since AERONET measurements are collected only during mostly clear sky conditions, *in situ* aircraft measurements would be useful in verifying the satellite retrievals in the presence of clouds. For November 2004, the dry monsoon phase is similar to the January 2004 monsoon period showing high AOD (0.7 to 0.8) and low PW values (less than 2.0 cm).

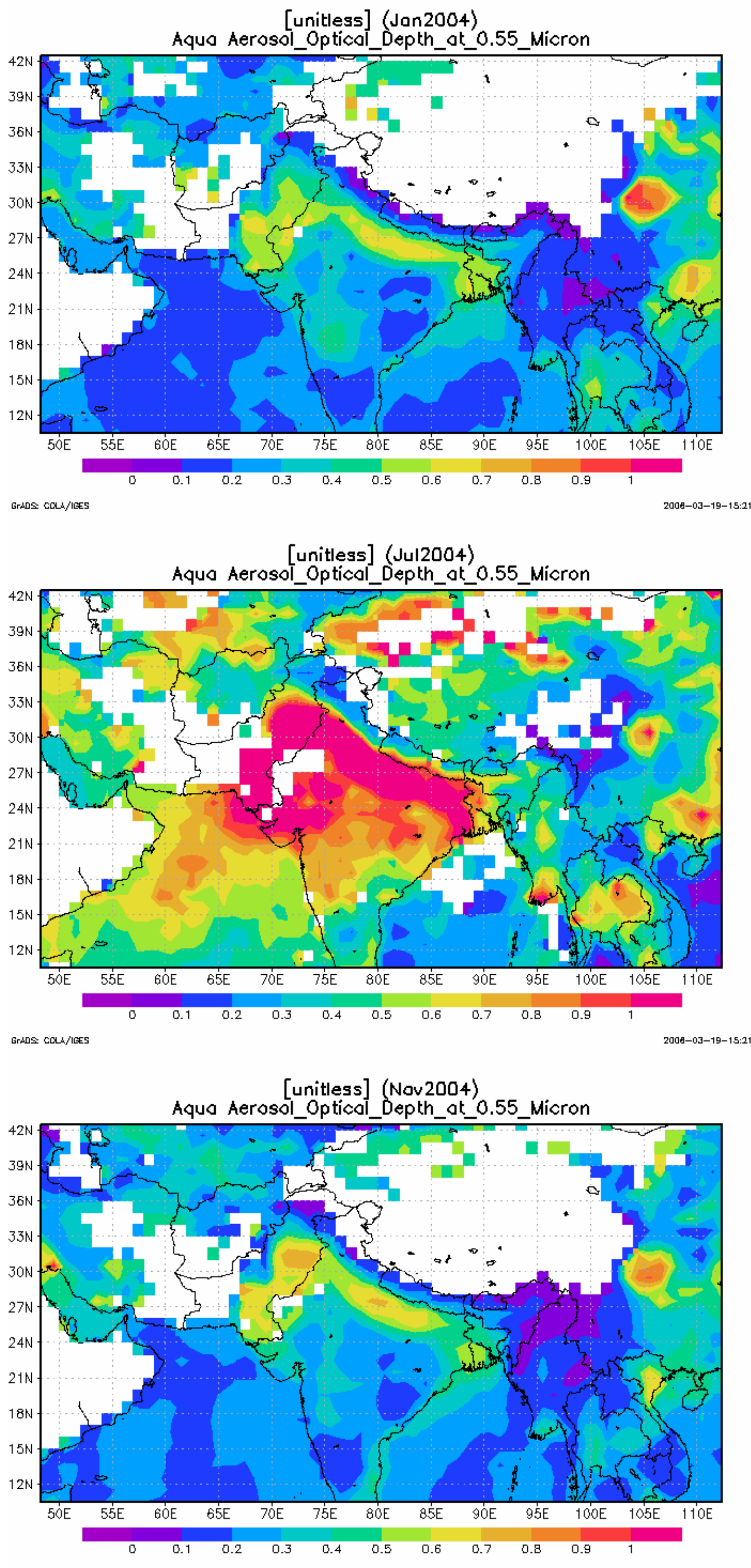

Figure 11 GIOVANNI MODIS-AQUA (collection 4) monthly average AOD at 550nm for each monsoon regime in 2004.

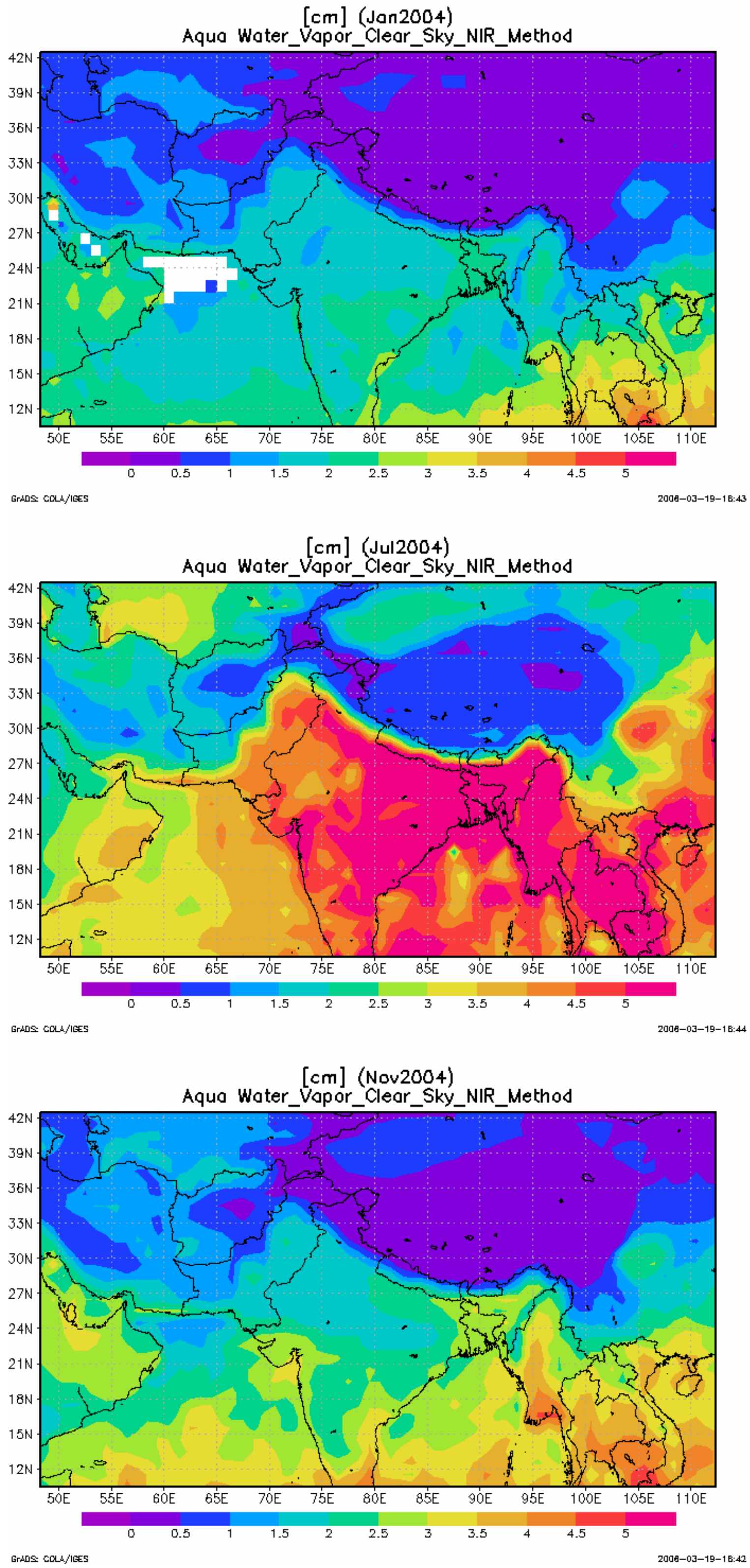

Figure 12 GIOVANNI MODIS-AQUA monthly average Clear Sky Water Vapor using the NIR method for each monsoon regime in 2004.

6. Conclusions

Persistent aerosols over the Northern Indian Subcontinent (NIS) region were analyzed using a recently-developed data display and dissemination tool called the BAMGOMAS Interactive Data Display (BIDD). This tool provides instant access to several different aerosol and aerosol-related databases. The BIDD tool provides access to aerosol data through a user-friendly web site for researchers, students, and the general public.

The BIDD tool provided key aerosol data products needed to analyze aerosols over the NIS region in a one-year period. AERONET measurements from the Kanpur, India AERONET site showed that the precipitable water and aerosol optical thickness were inversely related where moisture increased and aerosol loading decreased and vice versa; this relationship was attributed to the presence or lack of clouds and precipitation. Periods of low Ångstrom parameter occurred due to coarse mode dust before the onset of the wet monsoon phase. MODIS imagery and data showed typical aerosol regimes over the NIS region for the dry and wet monsoon phases; back trajectory analyses indicated potential source regions for aerosols; and GOCART output provided an estimation of aerosol type. The combination of these products showed that persistent aerosols occurred mainly during the dry monsoon phase, while aerosols were readily scavenged by clouds and precipitation during the wet monsoon phase. Although most of the data products showed agreement, MODIS AOD data for the wet monsoon phase showed monthly values of about 1 AOD. The high value may indicate aerosols above the cloud level (e.g., dust) or cloud contamination. Further inspection of daily MODIS AOD data may provide greater insight on the increased AOD during the wet monsoon phase.

The BIDD tool provided access to ground-based, satellite-based measurements as well as model data; however, some additional products would be useful to perform a more complete analysis. For example, GOCART data and other chemical model data could be used to determine aerosol constituents over several years. Additional lidar instrumentation or inclusion of other lidar networks would be beneficial to determine the vertical distribution of aerosols. Although *in situ* data were not available, these data may be added as new campaigns occur in the NIS region and other regions of the world. BAMGOMAS Interactive Data Display remains a powerful data display and dissemination tool which provides data from multiple aerosol measurement and modeling sources to the user community through one web portal.

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