CHAPTER 4. **Satellite Remote Sensing of Global Air Quality**.

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ABSTRACT

Good air quality is critical for human health. With increasing population and a demand for fossil fuel resources, air quality has degraded in many nations. Before sound policies can be enacted on how to monitor and regulate air pollution, monitoring is a necessary first step. Although ground measurements of air pollution are important, they lack the spatial coverage that is necessary for monitoring global air pollution. In this chapter we demonstrate how satellite remote sensing can be an effective tool for monitoring global particulate matter air pollution.

4.1 INTRODUCTION

Urban air quality has gained critical public health concern in many parts of the globe as urbanization and industrialization have amplified many folds during the last few decades. Almost half of the world's population now lives in the urban areas, and their number will increase to four billion by the end of this decade. Particulate matter (PM) (or aerosols) and ozone are among the two major pollutants affecting the air quality in urban areas throughout the world. Particulate matter is a complex mixture of solid and liquid particles that vary in size and composition and remain suspended in the air. Many chemical, physical, and biological components of atmospheric aerosols are identified as being potentially harmful to respiratory and cardiopulmonary human health effects. Aerosols have many sources from both natural and anthropogenic activities, naturally occurring processes such wind blown dust and episodic activities such as forest fires/agricultural burning (mostly anthropogenic), and volcanic eruptions. Increasing human activities also contribute to this, such as combustion from automobiles, industries, and emissions from power plants. Apart from direct emissions, PM is also produced by other processes such as gas to particle conversion in the atmosphere.

4.1.1 AEROSOLS AND HUMAN HEALTH

Atmospheric aerosols are one of the most important components of the earth-atmosphere system and play important role in climate and weather related processes (Kaufman et al., 2002). Air pollution has both short-term and long-term effects. Short-term impacts include, respiratory infections, irritation to the eyes, nose and throat, headaches, nausea, and allergic reactions. Short-term air pollution can intensify the medical conditions of individuals with asthma and emphysema. In 1952 London experienced one of the worst smog disasters, which killed more than four thousand people in few days due to very high concentration of particulate matter in the air. Long-term effects include lung cancer, heart disease, chronic respiratory disease, and even damage to the brain, nerves, liver, or kidneys.

Particulate matter with aerodynamic diameters less than 2.5 µm (PM2.5) can cause respiratory and lungs disease and even premature death. The World Health Organization (WHO) estimates that 4.6 million people die each year from causes directly attributable to air pollution. A medical study (Pope, 2000) concludes that fine particles and sulfur oxide related pollution are associated with causes such as, lung cancer and cardiopulmonary mortality. The same study also states that an increase of 10 µgm^{-3} in fine particulates can cause approximately a 4%, 6%, and 8% increased risk of all cause, cardiopulmonary, and lung cancer mortality, respectively. Indirectly, air pollution significantly affects the economy by increasing medical expenditures and expenditure for preserving the surrounding environment and therefore monitoring particulate matter air quality is critical.

4.1.2 MONITORING PARTICULATE MATTER POLLUTION

Various agencies around the world are using ground monitors for measuring air pollution. For example, the US Environment Protection Agency (EPA) monitors air quality by measuring PM and ozone concentration at thousands of ground based monitoring stations across the country. At the majority of the stations, PM2.5 is measured using a Tapered-Element Oscillating Microbalance (TEOM) instrument. A vibrating hollow tube called the tapered element is set in oscillation at resonant frequency and an electronic feedback system maintains the oscillation amplitude. When the ambient air stream enters the mass sensor chamber and particulates are collected at the filter, the oscillation frequency of the tapered element changes and the corresponding mass change is calculated as the change in measured frequency at time t to the initial frequency at time t_0. The mass concentration is then calculated from dust mass, time and flow rate. Ideally, only the collection of aerosol mass on the filter should change the tapered element frequency. However, temperature fluctuations, humidity changes, flow pulsation and change in filter pressure could affect the TEOM performance. Even in best-case scenarios when the operational parameters can be held constant, the heat-induced loss of volatile material could pose serious errors in the $PM_{2.5}$ mass. However, various correction factors are usually applied to adjust for these factors although the $PM_{2.5}$ mass usually represents the lower limits of a true value (Grover et al, 2005).

The ground monitors have several advantages. The measurement techniques can be standardized and applied across all ground monitors. They can measure pollution throughout the day and provide hourly to any type of time average. They can measure pollution regardless of clouds since these are filter-based measurements that are usually located at the surface. They also have some disadvantages. The obvious one is that they are point measurements and are not representative of pollution over large spatial areas.

The United States EPA issues National Ambient Air Quality Standards (NAAQS) for six criteria pollutants namely ozone, particulate matter, carbon monoxide, sulfur dioxide, lead and nitrogen oxides. Standards for particulate matter was first issued in 1971 then revised in 1987 and 1997 by EPA. In September 2006, EPA revised its 1997 standards to tighten the criteria. The 2006 standards reduced the 24-hour mean PM2.5 mass concentration standard from 65 µgm^{-3} to 35 µgm^{-3}, and retain the current annual PM2.5 standard at 15 µgm^{-3}. The EPA reports an Air Quality Index (AQI) based on the ratio between 24-hour averages of the measured dry particulate mass and NAAQS, and it can range from nearly zero in a very clean atmosphere to 500 in very hazy condition. In recent years, other countries in Europe, Australia, Japan, and China have also started monitoring PM2.5 mass as measure of air quality conditions.

4.1.3 SATELLITE REMOTE SENSING OF PARTICULATE MATTER POLLUTION

Satellite data have tremendous potential for mapping the global distribution of aerosols and their properties (Chu et al., 2003). Particulate matter air pollution from space-borne sensors are obtained by largely using passive remote sensing such as reflected solar radiation or emitted thermal radiation. Hoff and Christopher (2009) provide a thorough review of the various satellite sensors available for studying PM2.5 Here we describe the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard NASA's Terra (morning satellite with equatorial over cross time is 10:30 AM) and Aqua (afternoon satellite with equatorial over cross time is 1:30 PM) satellites that provides systematic retrieval of cloud and aerosol properties over land (King et al., 1992). The MODIS has 36 channels and provides near daily global coverage due to its large swath width. Its spatial resolution is from 250-1000m. MODIS provides the spectral information on aerosol optical properties in seven different wavelengths with good accuracy (Remer et al., 2005). Aerosol optical depth (AOD) is an important aerosol parameter, retrieved from satellite observations representing columnar loading of aerosols in the atmosphere along with the fraction of fine mode aerosol which is an indicator of anthropogenic pollution. Several studies conducted over land reveal that MODIS AOD retrievals are within expected uncertainty levels (Remer et al., 2005).

In the absence of clouds, the reflected solar radiation, for an aerosol layer, from the sun to the earth-atmosphere and back to the satellite-sensor is a function of surface reflectance, molecular scattering and absorption. The top of atmosphere reflectance is a function of sun-satellite viewing geometry and can be related to aerosol optical depth (AOD), which is the columnar value of aerosol extinction (absorption plus scattering). Figure 1 shows the seasonal distribution of MODIS AOD at 550 nm. In the Northern hemisphere spring and summer, pollution over Asia, Africa and other parts of the globe are readily seen. Dust is prevalent in Africa during the summer months and these dust aerosols can be transported several hundred miles to the Atlantic Ocean. Biomass burning is observed from satellites in the Southern hemisphere during August-September and has significant impacts on air quality and climate. This columnar satellite-derived AOD can be related to ground level PM2.5 using the following equation:

$$AOD = PM_{2.5}\, H\ f(RH)\, \frac{3Q_{ext,dry}}{4\rho\, r_{eff}}$$

Where *f(RH)* is the ratio of ambient and dry extinction coefficients, ρ = aerosol mass density (g m^{-3}), $Q_{ext,dry}$ is the Mie extinction efficiency and r_{eff} is the particle effective radius that is an area weighted mean radius of the particle, and H is boundary layer height. This equation indicates that if the boundary layer height and other information about the atmosphere and aerosols are known, the satellite-retrieved AOD can be converted to ground level PM2.5. During clear sky conditions and well mixed boundary layer situations (typical during Terra and Aqua overpasses) AOD can be related to surface PM2.5.

This relationship was explored in Wang and Christopher (2003) who correlated ground level PM2.5 with AOD and found an excellent correlation between the two measures. This relationship was then used to calculate air quality indices for the Southeastern United States.

However, satellite remote sensing of particulate matter (PM) air quality is relatively new area of research. As shown in Table 1, many research studies have shown the potential of using satellite derived AOD information as surrogate for air quality conditions. The two main conclusions from table 1 indicate that; 1) most of studies have used MODIS derived AOD products except few studies by Liu et al. (2004, 2005), and Donkelaar et al. (2006), which used AODs from both MISR and MODIS, 2) Area of study for most of the studies have been in some part of United States except studies by Gupta et al. (2006), Koelemeijer et al. (2006), and Donkelaar et al. (2006). One of the reasons is that MODIS gives much better spatial and temporal coverage as compared to MISR and measurements of PM2.5 mass concentration in other part of the world are limited. The first study by Wang and Christopher (2003) used PM2.5 mass and MODIS AOD data over seven stations in Alabama and presented very good correlation (>0.7) between these two parameters. This study also concluded that although deriving exact PM2.5 mass from satellite could have uncertainties but satellites can provide daily air quality indices with sufficient accuracies. Chu et al. (2003) was more focused on qualitative analysis of MODIS product as alternative for air pollution in the regions where surface measurements are not available. It also shows the potential of satellite monitoring of transport of air pollution from source to near and far urban areas. Hutchison et al. (2004, 2005) mainly focus on air quality over Texas and Eastern United States, and use of satellite imaginary in detecting and tracing the pollution.

The first comprehensive study by Engel-Cox, et al. (2004) presented a thorough correlation analysis between MODIS AOD and PM2.5 mass over entire United States. The correlation pattern shows high values in eastern and Midwest portion of the United States whereas correlations are low in western United States. This study also concludes that high space and time resolved observations from satellites can provide synoptic information, visualization of the pollution, and validation of ground based air quality data and estimations from models. Engel-Cox and other co-authors also published other studies in 2004, 2005 and 2006 which further emphasizes the use of satellite derived aerosol products in day to day air quality monitoring and even in policy related decision making. One of these papers (Engel-Cox, et al., 2006*)* also presented the application of LIDAR derived vertical aerosol profiles to improve PM2.5-AOD relationship. MODIS aerosols and clouds data are now being used in IDEA (Infusing satellite Data into Environmental Applications, http://www.star.nesdis.noaa.gov/smcd/spb/aq/) program to monitor air quality over United States. IDEA is a joint effort by various federal agencies including NASA, NOAA and EPA to improve air quality assessment, management, and prediction by infusing satellite measurements into analysis for public benefit (Al-Saadi et al., 2005). MISR derived aerosol products were first used by Liu et al. (2004), which shows similar potential for air quality applications. This study also used chemistry transport models and to derive meteorological fields to examine their relative effects on PM2.5-AOD relationships. Gupta et al. (2006) compared PM2.5-AOD relationship in different parts of the world such as Europe, Australia, USA, and Asia. This study shows applications of satellite derived air quality products at global scales and in the regions where surface PM2.5 measurements are not available. Correlations analysis varies in different part of the world depending on accuracies of MODIS retrieval, cloud contamination in AOD and height of aerosol layer in the atmosphere. Donkelaar et al. (2006) published a study, which used GEOS-CHEM (a chemistry transport model) derived vertical extinction profiles and basic mass formula to calculate mass of fine particles and compared the results over several locations in USA and Canada. This study also presented a global picture of MODIS and MISR derived PM2.5 mass concentration and results looks more promising. More recently Gupta and Christopher (2009a, b) used multiple regression and neural network techniques to improve surface PM2.5 mass estimations from satellite-derived AOD.

All these studies mainly concluded that the MODIS and MISR AODs are important to define air quality over large spatial domains and to track and monitor aerosol sources and transport. These studies are based on correlation and linear and multi-variant regression between MODIS AOD, ground based PM2.5 mass and model derived meteorological parameters. The MODIS derived AOD which is measure of column aerosol loading cannot be used alone to derive PM2.5 mass concentration, which is an indicator of the mass of the dry PM2.5 near the surface (Wang and Christopher, 2003). Meteorological factors such as surface temperature (T_s), relative humidity (rh), wind speed (WS) and direction (WD), variations in sunlight due to clouds and seasons are important parameters which affect the relationship between the two parameters. Changes in these processes, which affects the variability in pollution, is primarily governed by the movement of large-scale high and low-pressure systems, the diurnal heating and cooling cycle, and local and regional topography. The vertical profile of aerosol mass extinction (β_{ext}) and f(RH), which are not always uniform within the boundary layer height (H) are also are also very important parameters that must be accounted for while deriving relationships between PM2.5 and AOD (Wang and Christopher, 2003, Gupta et al., 2006).

To forecast air quality, numerical modeling actually requires a system of models and observations including satellite and ground-based data that work together to simulate the emission, transport, diffusion, transformation, and removal of air pollution and these models include meteorological models, emission models and air quality models. Figure 2 shows various examples of regional pollution events from around the world including agricultural burning in South America/Australia, dust events in China/Africa, haze events in Eastern United States and Asia. These large scale pictures provide critical information on episodic events for the air quality community. Furthermore, satellite-derived information can be of tremendous use to air quality modelers. For example fire locations and emissions derived from satellites are an important for forecasting PM2.5 mass due to agricultural events (e.g. Christopher et al., 2009). Satellite-based AOT can be used to constrain the fire emissions (Wang et al., 2006) and update the aerosol mass fields through the data assimilation (Zhang et al., 2008). However, an algorithm targeted for global retrieval of aerosols may have large errors at regional scale that is of high interest for air quality applications (Drury et al., 2008). Hence, an integrated use of satellite aerosol product, in particular, the radiance/reflectance data and fire emission data with air quality models can be designed and calibrated with ground-based data at regional-to-continental scales to improve the air quality forecast and studies (Christopher, 2009; Drury et al., 2010)

4.2 CONLCUSIONS

Satellite remote sensing is the only viable method for monitoring global air pollution. While ground monitors are useful, space borne sensors can readily map columnar aerosol concentrations. These columnar values can be related to ground-based particulate matter mass if the vertical distributions of aerosols or boundary layer heights are known. Research studies have shown the promise and potential for monitoring global pollution from space and future sensors will continue to improve our capabilities. Moreover, satellite information (e.g. fire locations and emissions) can be used in numerical models to forecast air quality which is an exciting area of research.

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Table 1 Relevant Literature survey on satellite remote sensing of particulate matter air quality.

#	Reference	Data & Study Area	Key conclusions/Remarks
1	*Wang and Christopher, 2003*	MODIS, 7 stations, Alabama	Quantitative analysis with space and time collocated hourly PM2.5 and MODIS AOD. Demonstrated the potential of satellite data for PM2.5 air quality monitoring. (R=0.7)
2	*Chu et al., 2003*	AERONET, MODIS, PM10, 1 station, Italy	Show relationship between PM10 and AOD. More qualitative discussion on satellite capabilities to detect and monitor aerosols globally. (R=0.82)
4	*Engel-Cox et al., 2004*	MODIS, PM2.5 Continental United States	First study, which present correlation analysis over entire USA and discuss difference in relationship over different regions. Qualitative and qualitative analysis over larger area, demonstrated spatial distribution of correlation. Range of R.
5	*Hutchinson et al., 2004*	MODIS AOD maps, Ozone, Eastern USA	Used few MODIS AOD maps and discussed the hazy conditions, no correlation analysis, and more emphasis on ozone pollution.
6	*Liu et al., 2004*	MISR, GEOS-CHEM GOCART, USA	First used MISR data for air quality study and have emphasis on seasonal and annual mean correlation analysis and forecasting. (R=0.78)
7	*Liu et al., 2005*	MISR , GEOS-3 Meteorology, USA	Regression model development and forecasting of PM2.5, model generated coarse resolution meteorological fields are used and focused only in Eastern United States. 48% explanation of PM2.5 variations.
8	*Al-Saadi, J., et al., 2005*	MODIS, USA	More descriptive paper on IDEA program, which provides online air quality conditions from MODIS and surface measurements over several locations in the USA
9	*Hutchinson et al., 2005*	MODIS, Texas	Correlation analysis in Texas. Correlation varies from 0.4 to 0.5 and long time averaging can make correlation greater than 0.9
10	*Engel-Cox et al., 2005*	MODIS, USA	Potential of satellite data for monitoring transport of PM2.5 over state boundaries and event specific analysis.
11	*Gupta et al., 2006*	MODIS, Meteorology, Global 21 locations	Correlation varies from 0.37 to 0.85 over different part of the world. Cloud fraction, relative humidity and mixing height information can improve relationship significantly. First study covered several global locations.
12	*Engel-Cox et al., 2006*	MODIS, LIDAR, USA	Weak correlation can be significantly improved by using vertical aerosol information from

			LIDAR measurements.
13	*Donkelaar et al., 2006*	MODIS, MISR, PM2.5, GEOS-CHEM, USA and Global	Inter-comparison between MODIS and MISR over several locations in Canada and USA. R= 0.69 (MODIS) and R= 0.58 (MISR). Different approach used to calculate the fine mass concentration.
14	*Koelemeijer et al., 2006*	MODIS, PM2.5 and PM10, Europe	Mainly focused on Europe. Correlation varies from 0.5 for PM10 to 0.6 for PM2.5. Use of boundary layer height in analysis improved the relationship.
15	*Liu et al., 2006*	MODIS, MISR, RUC	Inter-comparison between MODIS and MISR in St. Louis area. MISR performed slightly better than MODIS in the region.
16	*Hutchinson et al., 2008*	MODIS, LIDAR	An attempt is made to improve AOD-PM2.5 relationship by refining MODIS AOD product, optimizing averaging area for MODIS pixels around surface station.
17	*Gupta and Christopher, 2009a*	MODIS, RUC meteorology, South East USA	Multi-regression analysis using model-derived meteorology shows improvement to PM2.5-AOD relationships
18	*Gupta and Christopher, 2009b*	MODIS, South East USA	A novel neural network method for assessing PM2.5 using satellite, ground-based and meteorological information.

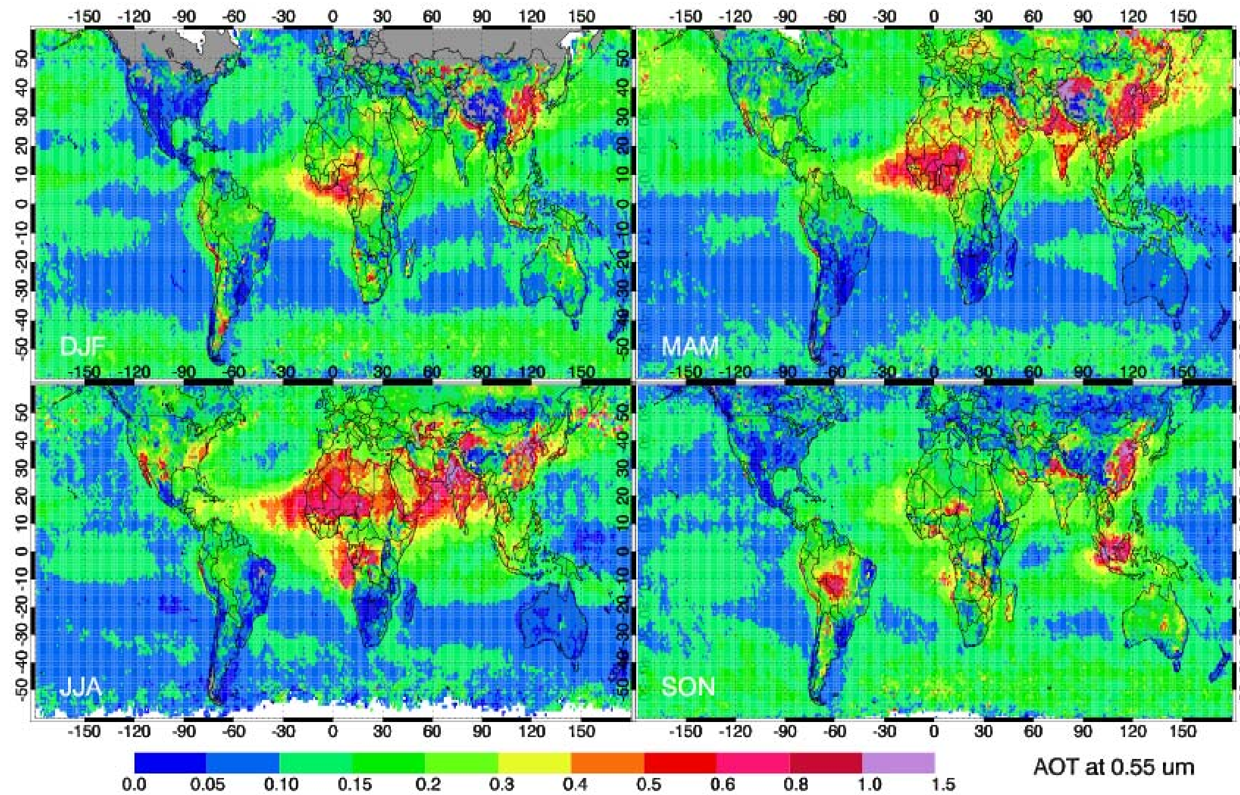

Figure 1. Seasonal distribution of MODIS mid visible aerosol optical depth where DJF is December, January, February, MAM is March, April, May, JJA is June, July, August, and SON is September, October, November for 2006.

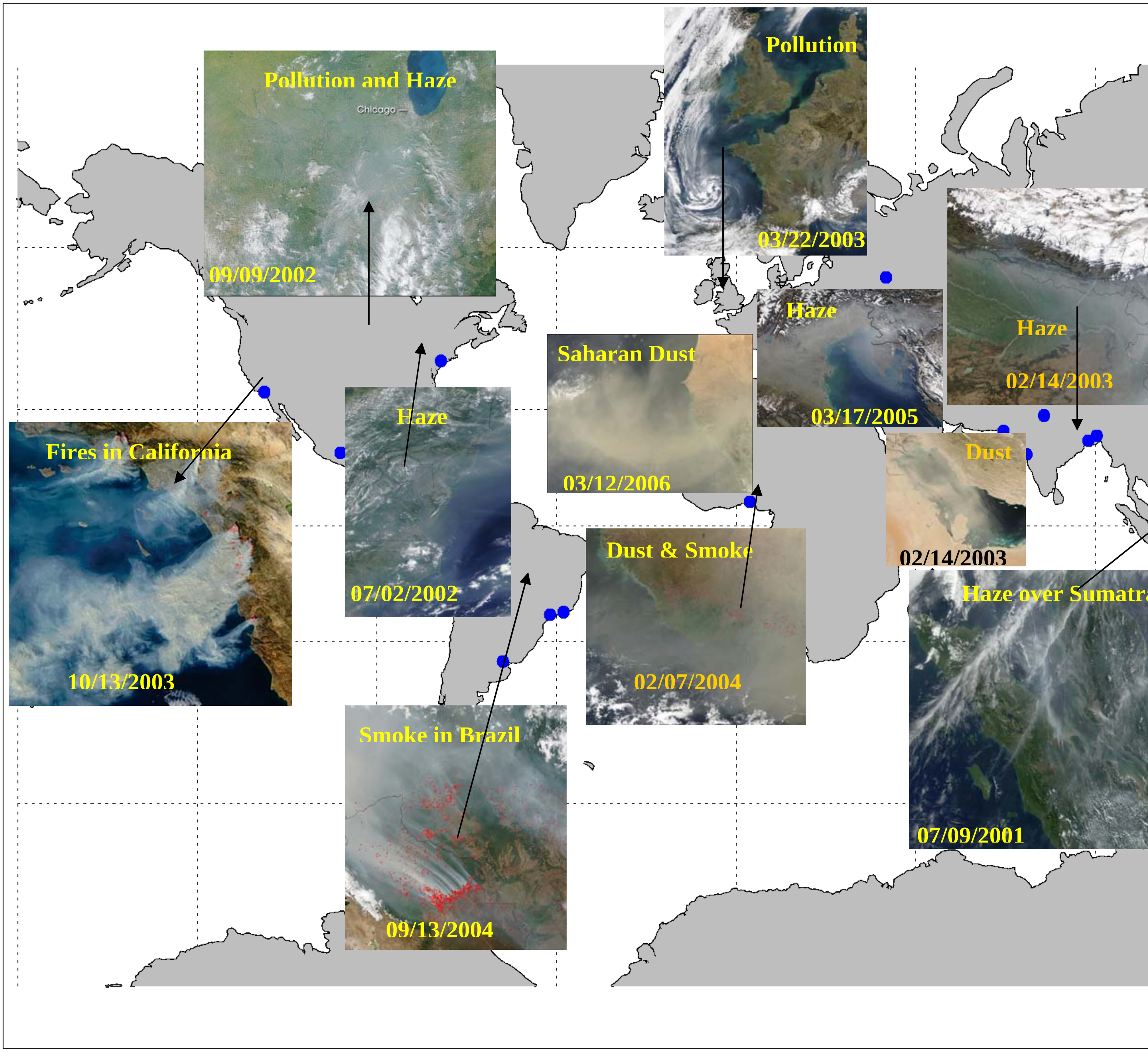

Figure 2. MODIS satellite imagery of regional pollution events from around the earth.