SATELLITE REMOTE SENSING OF AIR QUALITY OVER AUSTRALIA

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Abstract

Using case studies from the 2002 bush fires in New South Wales, Australia we examine the potential of using satellite data for air quality research. We compare ground based $PM_{2.5}$ mass with satellite derived aerosol optical thickness. Our preliminary analysis shows that due to their large spatial coverage, satellite data sets can be used for monitoring air quality during episodic bush fire events. However several outstanding issues remain including the vertical structure of aerosols, hygroscoposcity and the use of satellite data for *forecasting* air quality.

Keywords: Air pollution, Satellite Remote Sensing, Particulate matter, aerosols.

1. Introduction

Particular matter (PM), or aerosol, is the general term used for a mixture of solid particles and liquid droplets found in the atmosphere. Monitoring natural (dust and volcanic ash) and anthropogenic aerosols (biomass burning smoke, industrial pollution) has gained renewed attention because they influence cloud properties, alter the radiation budget of the earth-atmosphere system, affect atmospheric circulation patterns and cause changes in surface temperature and precipitation [*Kaufman et al., 2002*]. Aerosols also reduce visibility and induce respiratory diseases when sub-micron sized aerosols penetrate the lungs thereby affecting air quality and health [*Krewski et al.,* 2000]. Increased exposure to particular matter with aerodynamic diameters[1] less than 2.5µm ($PM_{2.5}$) can cause lung and respiratory diseases and even premature death [*Wilson and Spengler*, 1996].

Based on particular matter observations, different countries set their own levels for what healthy air quality should be. For example, the United States Environment Protection Agency (EPA) evaluates air quality by comparing 24-hour averages of the measured dry particulate mass with the National Ambient Air Quality Standard (NAAQS). The ratio of particulate mass between the measured and NAAQS (expressed as a percent of NAAQS) is called air quality index (AQI) and can range from nearly zero in a very clean atmosphere to about 500 in very hazy conditions. The U.S. EPA further classifies air quality into five broad categories based on the computed AQI values [good (AQI<50; corresponding 24hourly mean $PM_{2.5}$ 0~15.4μgm^{-3}), moderate (AQI:51~100; $PM_{2.5}$:15.5~40.4μgm^{-3}), unhealthy for certain groups such as children or people with asthma (AQI 101~150; $PM_{2.5}$:40.5~65.4μgm^{-3}), unhealthy (AQI 151~200; $PM_{2.5}$:65.5~150.4μgm^{-3}), very unhealthy (201-300; $PM_{2.5}$:150.5~250.4μgm^{-3}), and hazardous (AQI:301-500; $PM_{2.5}$:250.5~350.4μgm^{-3} for AQI 301~400; $PM_{2.5}$ 350.5~500.4μgm^{-3} for AQI 401~500). Also, for healthy conditions, the 24-hour averaged $PM_{2.5}$ concentration must be less than 65.5μgm^{-3}. However these thresholds are different for different countries. Australia mandates that for healthy air quality, the 24-hour mean $PM_{2.5}$ should not exceed 25 μgm^{-3} where as for Japan it is 100 μgm^{-3}

Several ground measurement networks are currently in operation to monitor aerosols for different purposes including the Aerosol Robotic Network (AERONET) [*Holben et al.*, 2001], and routine $PM_{2.5}$ monitoring sites throughout the world. Although these point measurements are well calibrated, and have tremendous potential for examining aerosol-related climate and air quality issues, there are only a limited number of measurements, and are inadequate to provide health alerts on large spatial scales, especially when the pollution comes from sources outside the area of interest. Examples of transported aerosols include smoke from Central American biomass burning fires to southern U. S. [*Peppler et al., 2000*], dust aerosols from the Saharan

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[1] Aerodynamic diameter (d_a) is the diameter of a unit-density sphere having the same gravitational settling velocity as the particle (with diameter d_p) being measured. Approximately, $d_a \cong (\rho_p)^{0.5} d_p$, where ρ_p is the density of the particle.

desert to South America. [*Prospero*, 1999] and pollution due to bush fires from one state to another in Australia.

Compared to ground measurements, satellite imagery, due to their large spatial coverage and reliable repeated measurements, provide another important tool to monitor aerosols and their transport patterns. Most aerosols in the atmosphere, due to their submicron sizes (except large dust and sea salt particles), are very efficient at scattering solar radiation and therefore, the visible portion of the electromagnetic spectrum is often used to retrieve aerosol information from satellite sensors [*Kaufman et al*., 2002]. One important and common parameter that is retrieved from satellite sensors is aerosol optical thickness (AOT), which is a measure of aerosol extinction of atmospheric radiative transfer. *Kaufman and Fraser* [1983] expressed AOT (also denoted by τ) as:

$$\tau=\int_0^{TOA}\beta_{ext}(z)dz=\beta_{ext}(0)\times H_{eff}=f(rh)\times \mathrm{Q}_{\mathrm{dext}}(0)\times \mathrm{m}_{\mathrm{daer}}(0)\times \mathrm{H}_{\mathrm{eff}} \quad (1)$$

$$H_{\mathrm{eff}}=\int_0^{\mathrm{TOA}}\beta_{\mathrm{ext}}(z)\,dz\Big/\beta_{ext}(0) \quad (2)$$

where TOA is top of atmosphere, β_{ext} is the volume extinction efficiency (m^{-1}), H_{eff} is effective scale height, $Q_{dext}(0)$ is the mass extinction efficiency (m^2g^{-1}) of dry particles at the surface, $m_{daer}(0)$ is the mass concentration (gm^{-3}) of dry aerosol particles at the surface, and *f(rh)* is a hygroscopic growth factor that considers the change of aerosol extinction efficiencies due to the solubility (hygroscoposcity) of aerosols. For simplicity, wavelength dependence is not shown in the above equations. Generally, a higher AOT value indicates higher column aerosol loading and therefore low visibility. However, such positive correlations could vary depending upon the vertical distribution of aerosol mass concentration or β_{ext} [*Bergin et al.*, 2001] as shown in equation (1).

Several studies have attempted to use the AOT retrieved from satellite imagery to monitor aerosol loading and the associated air quality effects [*Kaufman and Fraser*, 1983] . Until recently, the use of satellite remote sensing data for air quality studies has been hampered largely due inadequate spatial, radiometric and spectral resolutions [*King et al.,* 1999]. However new data sets from the recently launched Moderate Resolution Imaging Spectroradiometer (MODIS, on Terra and Aqua satellites) provide an unprecedented opportunity to monitor aerosol events and examine the role of aerosols in the earth-atmosphere system [*Kaufman et al*., 2002]. The Terra and Aqua are both polar-orbiting satellites, with equatorial crossing times of 10:30A.M and 1:30 P.M., respectively. For a given area, the MODIS instruments provide two daytime observations, one during the morning (from Terra) and one in the afternoon (from Aqua). While several studies have applied the MODIS AOT to study the aerosol radiative forcing [e.g., *Christopher and Zhang*, 2002], the application of the MODIS AOT product for air quality studies is still largely unexplored. This paper will explore the potential of using the MODIS AOT product for air quality studies over Australia. A comparison of MODIS AOT with $PM_{2.5}$ mass is presented, for selected locations in Australia followed by a discussion of the uncertainties in this approach and recommendations for further research.

2. Methods and Results

The data used in this study includes the MODIS (version 4-Level 2), aerosol product, and hourly particular matter data collected at several locations in NSW, Australia (Table 1). The $PM_{2.5}$ observations are widely utilized by several nations for monitoring particulate matter. Only hourly averaged $PM_{2.5}$ data is available for these sites. The MODIS aerosol product is at 10km spatial resolution and contains aerosol characterization parameters such as aerosol optical thickness derived from two independent algorithms for retrievals over ocean and land, respectively [*Remer et al.,* 2002]. When compared against ground-based AERONET measurements the MODIS AOT values are within uncertainty levels of ±0.03 ±0.05AOT over ocean [*Remer et al.*, 2002] and ±0.05±0.20 AOT over land [*Chu et al.*, 2002].

To compare the MODIS AOT with $PM_{2.5}$, a suitable spatio-temporal window size for the collocation must be carefully considered. Since the $PM_{2.5}$ measurements have a temporal resolution of 1 hour; for each day, we first find two continuous time periods *t* and *t+1* so that the MODIS overpass is between these two observation times. Then we average the $PM_{2.5}$ at *t* and *t+1* and compare this value with the MODIS AOT. Since all $PM_{2.5}$ measurements are located in proximity and the distance between these sites is small, we compared the $PM_{2.5}$ mass with the MODIS pixel that is centered over the observation site. During the comparison, potential cloud contamination of a pixel (i.e., centered at the PM observation site) is evaluated based on the AOT availability in a group of 3X3 pixels centered at that pixel. Only the pixel whose surrounding eight pixels have valid AOT values are considered in the comparison, thereby reducing the possibility of using the AOT retrieved near the cloud edges [*Chu et al*., 2002].

We present preliminary results from a case study from January 2002 when bush fires destroyed more than a million acres around Sydney. Figure 1 shows a satellite image taken on January 1, 2002 over Eastern Australia clearly showing the fire locations and the smoke plumes. We obtained $PM_{2.5}$ data for January 2002 over five locations in NSW, Australia including Earlwood, Lidcombe, Liverpool, Richmond, and Woolooware to examine the $PM_{2.5}$ levels during the bush fire events (Table 1).

Figure 2 shows the mean $PM_{2.5}$ over the six locations for January 2002 along with November and December 2001 values as a baseline. The mean $PM_{2.5}$ for November and December 2001 are below 25 ugm^{-3} where as in January 2002 when hourly data became available, the $PM_{2.5}$ values are 4 times larger than due the particulate emissions from forest fires. The $PM_{2.5}$ values through the first 2 weeks of January are much higher than the mandated levels. Figure 2 also shows the MODIS AOT values at 0.55 μm with corresponding scales on the right. While the satellite trends of AOT match the $PM_{2.5}$ trends well over the first week there are some discrepancies starting the second week of January, 2002 and this is probably due to cloud cover over the region of interest. Satellite algorithms can only retrieve AOT during cloud-free conditions. Other reasons for the differences include vertical variation of aerosol properties, hygroscoposcity and choice of aerosol models in satellite algorithms. These issues are still under research and will be discussed during the presentation.

3. Uncertainties and summary

There are several uncertainties that could arise in this type of analysis. First, satellite derived aerosol optical thickness values are column integrated quantities whereas the $PM_{2.5}$ observations are near-surface values. This relationship between satellite AOT and mass $PM_{2.5}$ is applicable when aerosols are in the lower atmospheric boundary layer. If aerosols are lofted in the atmosphere due to synoptic conditions then discrepancies will arise. Therefore independent information on the vertical structure of aerosols is needed either from ground or space borne lidars. Next water uptake by aerosols could influence size and properties thereby requiring adjustments to satellite algorithms. This requires measurements of aerosol hygroscoposcity. Other outstanding issues include cloud contamination and high surface albedos that affect satellite retrievals of aerosol optical thickness.

In summary, our preliminary results indicate that satellite data sets can be used for quantitative monitoring of air pollution levels although several challenges remain for reducing the uncertainties. However satellite data is well suited to obtain air quality indices where $PM_{2.5}$ measurements are not available.

Table 1. Air quality monitoring sites in Sydney with latitude and longitudes.

Monitoring site		Latitude (South)	Longitude (East)
Earlwood	Beaman Park	33° 55' 04"	151° 08' 05"
Lidcombe	EPA Laboratories	33° 53' 09"	151° 02' 30"
Liverpool	Rose St	33° 55' 58"	150° 54' 21"
Richmond	University of Western Sydney	33° 37' 06"	150° 44' 45"
Woolooware	Woolooware Rd	34° 02' 39"	151° 08' 28"

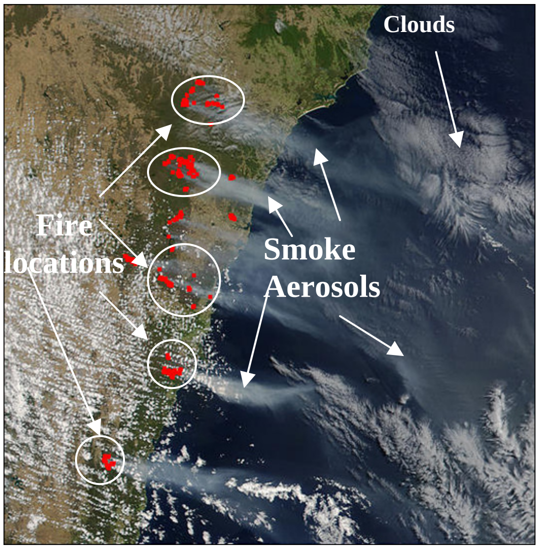

Figure 1. Bush fires and smoke plumes from NASA's Terra satellite on January 1, 2002

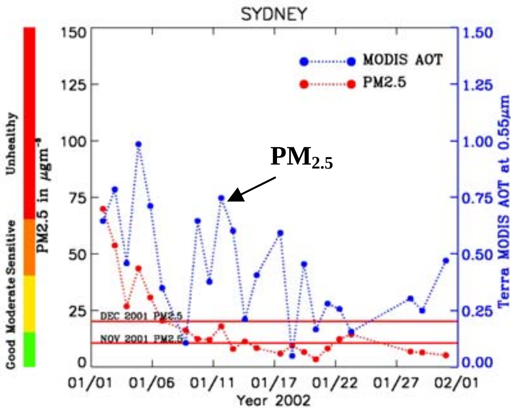

Figure 2. Satellite derived Aerosol Optical thickness and $PM_{2.5}$ mass for January 2002. Also shown are the baseline levels for $PM_{2.5}$ in November and December 2001. Air quality categories are shown on the left as good, moderate, sensitive and unhealthy levels.

Acknowledgements

This research was conducted during Sundar A. Christopher's sabbatical to the University of New South Wales as a Gordon Godfrey Visiting Fellow. We thank Mr. Jayan Karunasinghe of the Department of Environment and Conservation for providing the hourly $PM_{2.5}$ data.

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