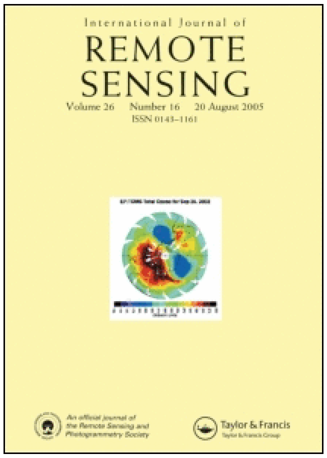

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Multi year satellite remote sensing of particulate matter air quality over Sydney, Australia

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Particulate matter (PM) air-quality information is usually derived from ground-based instruments. These measurements, while valuable, are not well suited to provide air-quality information over large spatial scales. In this study, using 4 years of satellite aerosol optical thickness (AOT) at 0.55 μm derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) on board NASA's Terra and Aqua satellites, we present a multi-year air analysis of PM air quality over Sydney, Australia. We then compare the satellite data with $PM_{2.5}$ mass concentration measurements from six ground-based stations in the area. Our results indicate significant diurnal variations and an overall increase in $PM_{2.5}$ during Southern Hemisphere spring and summer seasons due to bush fires. The air quality in Sydney, Australia is good throughout the year except during major bushfires when $PM_{2.5}$ mass loading can increase from normal ($<20\,\mu g\,m^{-3}$) to unhealthy conditions ($>70\,\mu g\,m^{-3}$). The satellite data also show corresponding AOT changes from less than 0.1 to greater than 1.0 during bushfire events. We conclude that satellite data are an excellent tool for studying PM air quality over large areas, especially when ground measurements are not available. While this is the first multi-year combined satellite and ground-based air quality analysis over Sydney, ancillary information from lidars, sun photometers, and size-resolved chemistry measurements will further enhance our capability to monitor and forecast air quality in and around Sydney.

1. Introduction

Urban air-quality monitoring and forecasting have become an important issue for many environmental protection agencies (EPA) around the world. Particulate matter (PM) or aerosols with aerodynamic diameter less than 2.5 μm ($PM_{2.5}$) is especially of concern to human health because they can be inhaled into the lungs and cause premature death (Krewski *et al.* 2000). PM is strongly associated with daily mortality in Australia and around the world (Dockery and Pope 1994). Increased PM was associated with 2400 deaths per year in Australia with an associated health cost of $17.2 billion (Morgan *et al.* 1998, Simpson *et al.* 2000). Sydney has around 400 premature mortalities each year due to increased levels of pollution, and asthma is also common in this area (Barusch 1997).

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Atmospheric aerosols have natural as well as anthropogenic sources. Natural sources include wind-blown dust, sea salt, large-scale dust storms, naturally occurring forest fires, and volcanic eruptions. Anthropogenic aerosols are primarily from emissions from motor vehicles, industries, power plants, and biomass burning due to agricultural practices. PM pollution is one of the major air-quality issues in Australia, and during the cooler months, in some parts of Australia, smoke from wood-heaters results in elevated pollution levels that are a high health risk (Gras *et al.* 2002). Temperature inversions can further slow down the removal of PM from the atmosphere, thereby quickly degrading air quality. According to the National Ambient Air Quality Status and trend report in 2004, Australia has only 15 $PM_{2.5}$ monitoring stations located in major cities, and so they are not sufficient for providing air-quality information in areas where measurements are not available. The New South Wales Environmental Protection Authority (NSW-EPA) has several ground-based $PM_{2.5}$ measurements stations in Sydney and surrounding areas. Each station measures the $PM_{2.5}$ mass concentration and reports the air quality based on these measurements.

Advancement in satellite remote-sensing techniques has opened new corridors for Environmental Protection Agencies (EPA) and other scientific communities (Al-Saadi *et al.* 2005). Polar orbiting satellites make reliable and repeated measurements over the globe with high spatial resolution when compared with surface instruments, which are limited because they are point observations. The MODerate resolution Imaging Spectroradiometer (MODIS) and Multi-angle Imaging SpectroRadiometer (MISR) onboard the Earth Observing System (EOS) satellites provide high-quality aerosol information over the globe (Remer *et al.* 2005). AOT is one of the important properties retrieved from satellite observations that represents columnar aerosol loading from the surface to the top of the atmosphere, while the $PM_{2.5}$ mass concentration measured from ground based instruments represents the dry mass of pollutants near the surface. Several studies over the past few years have demonstrated the relationship between satellite-derived AOT and ground-based measurements of $PM_{2.5}$ mass (Chu *et al.* 2003, Wang and Christopher 2003, Engel-Cox *et al.* 2004, Al-Saadi *et al.* 2005, Liu *et al.* 2005). Although these studies demonstrated the capabilities of satellites to derive PM air-quality information, they are mainly focused over the United States. For example, Wang and Christopher (2003) showed that the MODIS AOT is well correlated with $PM_{2.5}$ mass over the South-eastern United States, and concluded that the satellite-derived AOT can be a useful tool for monitoring air quality over large scales. However, ancillary information such as vertical distribution of aerosols and meteorological information is needed to further refine the analysis (Gupta *et al.* 2006).

This study will present PM air quality observed from ground- as well as space-based sensors over Sydney and surrounding areas during 2000–2004. §2 describes the area of study and the data sets used. The methodology is presented in §3 along with a brief discussion of air-quality standards. Results begin in §4 of the paper with a short overview of aerosols and air quality in Australia. We then present an analysis of $PM_{2.5}$ mass concentrations, AOT derived from Terra-MODIS at different locations in the Sydney basin before, during, and after the December 2001–January 2002 fire episode. We then provide analysis of day-to-day variations in $PM_{2.5}$ mass and AOT over a 1-month period at two selected stations. This is followed by a weekly analysis of air quality and a 4-year analysis of $PM_{2.5}$ mass and AOT over Sydney.

2. Area of study and data

The data used in this research study include the MODIS AOT and $PM_{2.5}$ mass concentration. The MODIS sensors onboard Terra and Aqua satellites observe the Earth–atmosphere system in 36 different spectral bands. Measurements taken in these channels are then used to derive different geophysical parameters related to Earth, atmosphere and oceans. The MODIS provide this information with moderate spatial (ranging from 250 m to 1 km) and temporal (1–2 days) resolution.

We use the daily AOT at $0.55\,\mu$m wavelength from the MODIS from two satellites, Terra (MOD04, version V004) and Aqua (MYD04, version V004), from 2000–2004. Since Aqua was launched in May 2002, data from this satellite are only available after July 2002. The AOT land algorithm uses observed radiance in two wavelengths (0.47 and $0.67\,\mu$m) and pre-computed look up tables to retrieve AOT (Remer *et al.* 2005). The MODIS AOT at $0.55\,\mu$m is not a direct retrieval, but an interpolation technique is used to obtain values from 0.47 and $0.67\,\mu$m. Over land, the reported accuracy of MODIS AOT is $\pm 0.05 \pm 0.20\tau$ when compared with several ground based AERONET measurements, except in situations with possible cloud contamination, over surfaces with subpixel surface water such as coastal areas and marshes, and over surfaces with subpixel snow or ice cover. In clean environments like Sydney, when AOT values are very low (<0.1) the uncertainty in MODIS AOT value could be very large. On a global basis, about 68% of the AOT retrievals fall within the expected errors (Remer *et al.* 2005).

The MODIS L3 monthly mean AOT data in 1×1 degree grid resolution are also used for qualitative analysis since they are not recommended for rigorous quantitative analysis over land (Remer *et al.* 2005). Monthly mean AOT data for 49 months (April 2000 to April 2004) are used to discuss the seasonal variations and background aerosol loading in the area. Also, these monthly mean values are used to obtained a 5-year mean (January 2001 to December 2005) to show the spatial distribution of long-term mean aerosol loading over Australia.

The $PM_{2.5}$ mass concentration is measured using a Tapered-Element Oscillating Microbalance (TEOM) instrument with an accuracy of $\pm 1.5\,\mu g\,m^{-3}$ for hourly averages. The hourly $PM_{2.5}$ mass concentration data from several ground stations in Sydney and surrounding areas were collected for selected months during 2000–2004 (table 1). Also, monthly mean $PM_{2.5}$ mass data during April 2000 to April 2004 were

Table 1. List of PM2.5 stations in Sydney area.

Station no.	Station name	Altitude (m)	Latitude	Longitude	Station type
1	Richmond	21	33.62° S	150.74° E	Inside the campus of University, residential and semi-rural area
2	Westmead	12	33.80° S	150.99° E	Golf course, residential area
3	Lidcombe	40	33.88° S	151.04° E	Central of Sydney basin, mixed of residential and commercial area
4	Liverpool	22	33.92° S	150.90° E	Central of the Sydney basin in a mixed residential and commercial area
5	Earlwood	7	33.92° S	151.13° E	Park, residential area
6	Woolooware	6	34.04° S	151.14° E	Road side, residential area

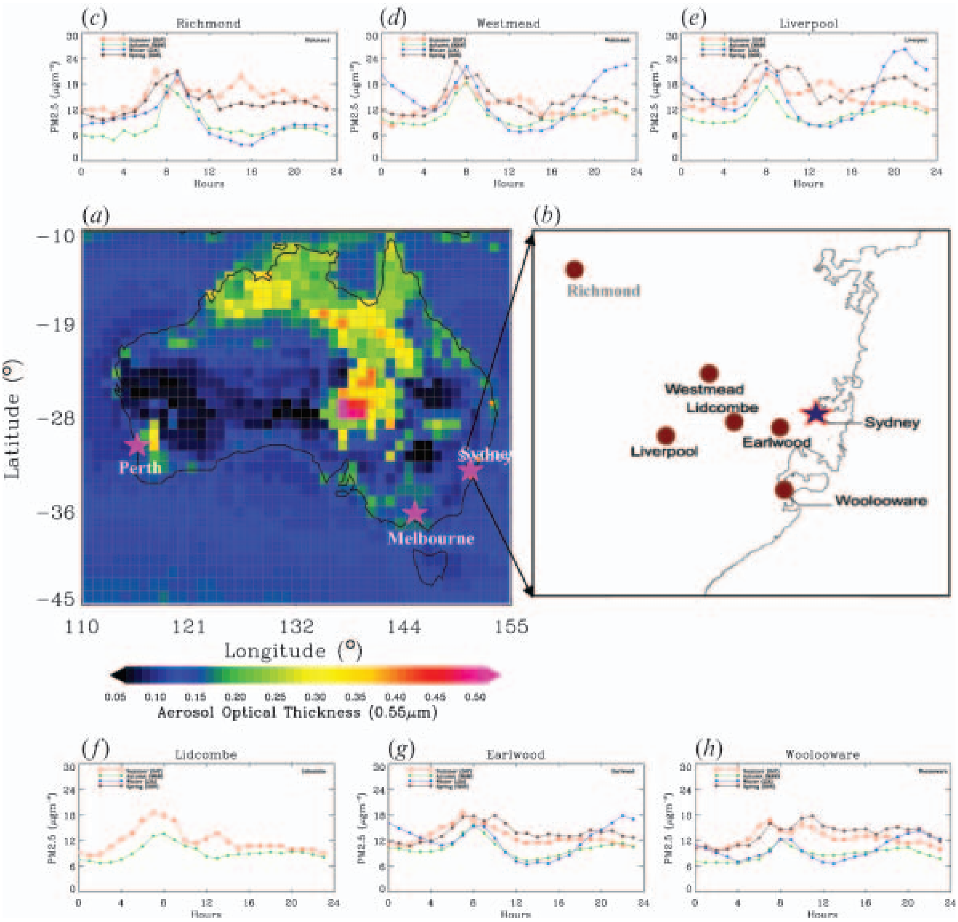

Figure 1. (*a*) Spatial distribution of the 5-year (2001–2005) mean of MODIS AOT over Australia and location of $PM_{2.5}$ monitoring stations, which are mainly located in the major cities of Australia. (*b*) Ground-based $PM_{2.5}$ station network in Sydney and surrounding area used in this study. (*c–h*) Seasonal mean diurnal pattern in $PM_{2.5}$ mass from six locations during 2002.

collected from NSWEPA quarterly air quality reports. Figure 1(*a*) shows the 5-year mean (December 2000 to January 2006) AOT from Terra-MODIS. The purple stars denote the major cities where most of the $PM_{2.5}$ ground stations are located (total of 17 stations). Figure 1(*b*) shows the zoomed area around Sydney with $PM_{2.5}$ measurement locations. Figure 1(*c*)–(*h*) shows the diurnal variation of PM2.5 from the ground stations and will be discussed in detail in §4.

3. Methodology

To compare satellite derived AOT values with $PM_{2.5}$ mass concentrations at the ground, the two parameters were collocated in space and time. Since the spatial resolution of the level 2 AOT product is $10 \times 10\,km^2$, a single MODIS AOT pixel represents a spatially averaged value of $100\,km^2$, whereas $PM_{2.5}$ mass measurements are representative of only a few square metres surrounding the measurement location. Also, the TEOM could observe different air masses over a period of time, whereas the MODIS AOT is an instantaneous value during the time of the satellite overpass. Therefore, the MODIS pixels over a horizontal scale will be sampled by a surface $PM_{2.5}$ station over a period of time. All the hourly $PM_{2.5}$ mass concentration values within ±30 min of MODIS overpass time were averaged over $50 \times 50\,km^2$ (5×5 pixels) MODIS AOT values based on methods outlined in Ichoku *et al.* (2002). The MODIS AOT values were obtained only when three or more MODIS pixels were found for a $PM_{2.5}$ mass measurement. Possible cloud contamination in AOT values were removed if the standard deviation is more than 0.5 (Wang and Christopher 2003).

3.1 *Air-quality monitoring and standards*

The Australian National Environment Protection (Ambient Air Quality) Measurement (AAQ NEPM) standard has only daily and annual advisory reporting standards for $PM_{2.5}$ mass. According to these standards, the $PM_{2.5}$ mass should be less than $25\,\mu g\,m^{-3}$ over a 1-day period, whereas the annual mean should be less than $8\,\mu g\,m^{-3}$ (NAAQSTR 2004). In the absence of AAQ NEPM standards for $PM_{2.5}$ mass for specific health categories, the USA $PM_{2.5}$ mass standards are taken as a reference in this study. The United States Environment Protection Agency (USEPA) evaluates daily air quality based on the National Ambient Air Quality Standard (NAAQS) using the 24-h mean $PM_{2.5}$ mass concentration. Table 2 presents details on air-quality categories as defined by NAAQS for different categories and the corresponding $PM_{2.5}$ mass values. According to these standards (USEPA), the 24-h mean value of $PM_{2.5}$ mass should be less than $65\,\mu g\,m^{-3}$ and $15\,\mu g\,m^{-3}$ for annual mean. In December 2005, the EPA has proposed lowering the 24-h mean $PM_{2.5}$ mass standard to $35\,\mu g\,m^{-3}$ while keeping the annual mean values the same (Federal Register 2006).

Table 2. US EPA categories for $PM_{2.5}$ mass concentration, air-quality category, corresponding 24-hourly mean $PM_{2.5}$ mass ($\mu g\,m^{-3}$), and their potential effects on human health.

Air-quality category	Description	24-h mean $PM_{2.5}$ mass ($\mu g\,m^{-3}$)
Good	None	0~15.4
Moderate	Unusually sensitive people should consider reducing prolonged or heavy exertion	15.5~40.4
Unhealthy for sensitive groups	People with heart or lung disease, older adults, and children should reduce prolonged or heavy exertion	40.5~65.4
Unhealthy	People with heart or lung disease, older adults, and children should avoid prolonged or heavy exertion; everyone else should reduce prolonged or heavy exertion	65.5~150.4
Very Unhealthy	People with heart or lung disease, older adults, and children should avoid all physical activity outdoors; everyone else should avoid prolonged or heavy exertion	150.5~250.4

4. Results and discussion

4.1 *Aerosols and air quality in Australia: an overview*

The Southern Hemisphere seasons are classified as summer (December, January, and February), autumn (March, April, and May), winter (June, July, and August), and spring (September, October, and November). The Australian urban areas are more susceptible to photochemical smog because of local meteorological conditions, higher solar radiation, and emission of local pollutants (Manins 2001). Sydney is a classic closed basin, bounded by high-altitude land to the south, west, and north, and pollution may accumulate and circulate inside the city for several days, exacerbated by relatively frequent temperature inversions.

Sydney is Australia's largest city with a population of about 3.5 million according to the 2001 census. The PM emissions in the greater Sydney metropolitan area are largely from industries and motor vehicles. Mobile sources contribute around 18%, compared with 40% from industries and 42% from commercial and domestic usage (Corbyn 2004). Measurements made near the University of New South Wales (UNSW) indicate that fine particles comprise 30% (±15%) inorganic species, 23.4% (±15.4%) organic species, 27.6% (±12.9%) elemental carbon, 5% (±2.1%) windblown dust, and 1.3% (±0.7%) trace elements, and the remainder could be water and nitrate (Box *et al.* 2002).

Apart from these anthropogenic sources, bushfires may also contribute to the $PM_{2.5}$ mass during the summer months. For example, 264 270 ha of land burned in a short time period of 5 h during the severe Tasmanian fire of 7 February 1967. The human death toll from this fire was 62 with the destruction of 1400 dwellings and other buildings, and was the largest loss of life and property on a single day in Australian history. Similar bushfires surrounding Sydney during December 2001–January 2002 were seen from the vast smoke plumes from the south-eastern coastline of Australia in satellite imagery. Poor visibilities were reported due to thick smoke haze along the coast for over a 2-week period during which Sydney's worst air quality was recorded by NSW-EPA on 28 December 2001. Severe fires have also been reported in January 2003 in south-eastern Australia around Canberra, Australia (Mitchell *et al.* 2006).

4.2 *Bushfires and particulate-matter air quality*

In this section, we present detailed analysis of the effects of a bushfire event on $PM_{2.5}$ emission, AOT, and air quality. The top four panels in figure 2 show a series of true-colour (RGB composite) images (figure 2(*a*)–(*d*)) from Terra-MODIS. These images were generated using MODIS level-1B (MOD021KM, V004) calibrated and geolocated radiances. The bottom four panels (figure 2(*e*)–(*f*)) are the corresponding AOT at 0.55 μm. These images and AOT maps represent conditions before (December 23 2001), during (25 and 27 December 2001) and post-fire (12 January 2002) days. The red-coloured vertical bars in the AOT maps indicate the hourly $PM_{2.5}$ mass concentration obtained from the six stations during the MODIS overpass time. Note the tremendous advantage in using satellite data to infer air quality in areas where ground measurements are not available. The image taken on 23 December does not show any fire activity or smoke plumes in the area, which is also reflected in low satellite-derived AOT values for the day. The MODIS is able to capture the smoke plumes from the bushfire starting on December 25 and can be seen very clearly in figure 2(*b*), and these smoke aerosols were responsible for the

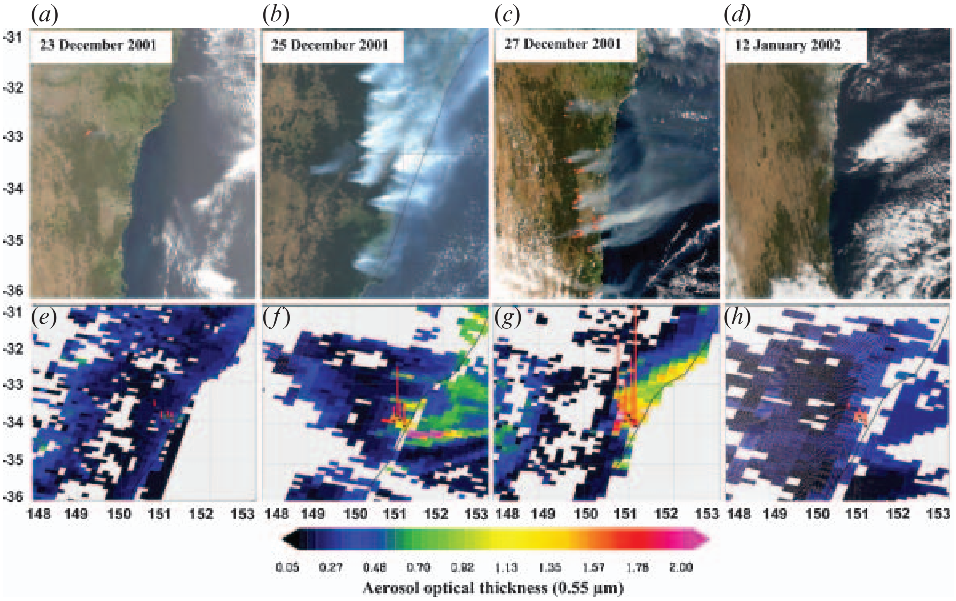

Figure 2. Bush fires in Sydney and surrounding area as observed from space. The top panels show the Terra-MODIS three-band true-colour images before, during, and after major bush fires. Bottom panels are the aerosol optical thickness retrievals that are an indicator of particulate-matter air quality. The bars in the bottom panel indicate $PM_{2.5}$ [$PM_{2.5}\,\mu g\,m^{-3}$=length of bar (degree) × 50] data reported from ground measurements. The air-quality categories are colour-coded based on the regression relationship between MODIS AOT and $PM_{2.5}$ mass.

increased AOT and $PM_{2.5}$ mass values. The fires increased in intensity on 27 December (figure 2(*c*)) and continued for more than 15 days. The post-fire image taken on 12 January 2002 (figure 2(*d*)) does not show any large-scale fire activity in the area, and AOT and $PM_{2.5}$ mass values dropped to normal levels.

Figure 3 shows the $PM_{2.5}$ mass concentration and MODIS AOT at Earlwood and Lidcombe over a period of a month, which covers before, during, and after the December 2001–January 2002 fire episode. Figure 3 clearly demonstrates the effect of bushfire as seen in the increases in aerosol loading between December 25 2001 and 6 January 2002. Both $PM_{2.5}$ mass and AOT values are low from 15 December to 25 December, and air quality is in the good category. As fires started in the area, there was more than a 200% increase in $PM_{2.5}$ mass measured at the surface, and more than a 500% increase in AOT observed from space in two days from 25 December to 27 December. Both the ground measurement and the satellite-derived values follow a similar trend. As bushfires remained intense from 25 December 2001 to 1 January 2002, pollution levels in the Sydney basin remained very high, and air-quality conditions quickly reached the unhealthy category. The $PM_{2.5}$ mass began decreasing from 1 January and dropped to normal levels by 15 January. All the stations measured extremely high $PM_{2.5}$ mass concentrations on 30 December except at Woolooware, where data were not available on this day. The sudden decrease in $PM_{2.5}$ mass and AOT values on 6 January 2002 is associated with heavy rainfall experienced in the Sydney area. The Bureau of Meteorology rain gauge located in Schofield (33.4° S and 150.5° E) measured a total rainfall of around 40 mm on 6 January 2002, which washed out the aerosols from the atmosphere, and

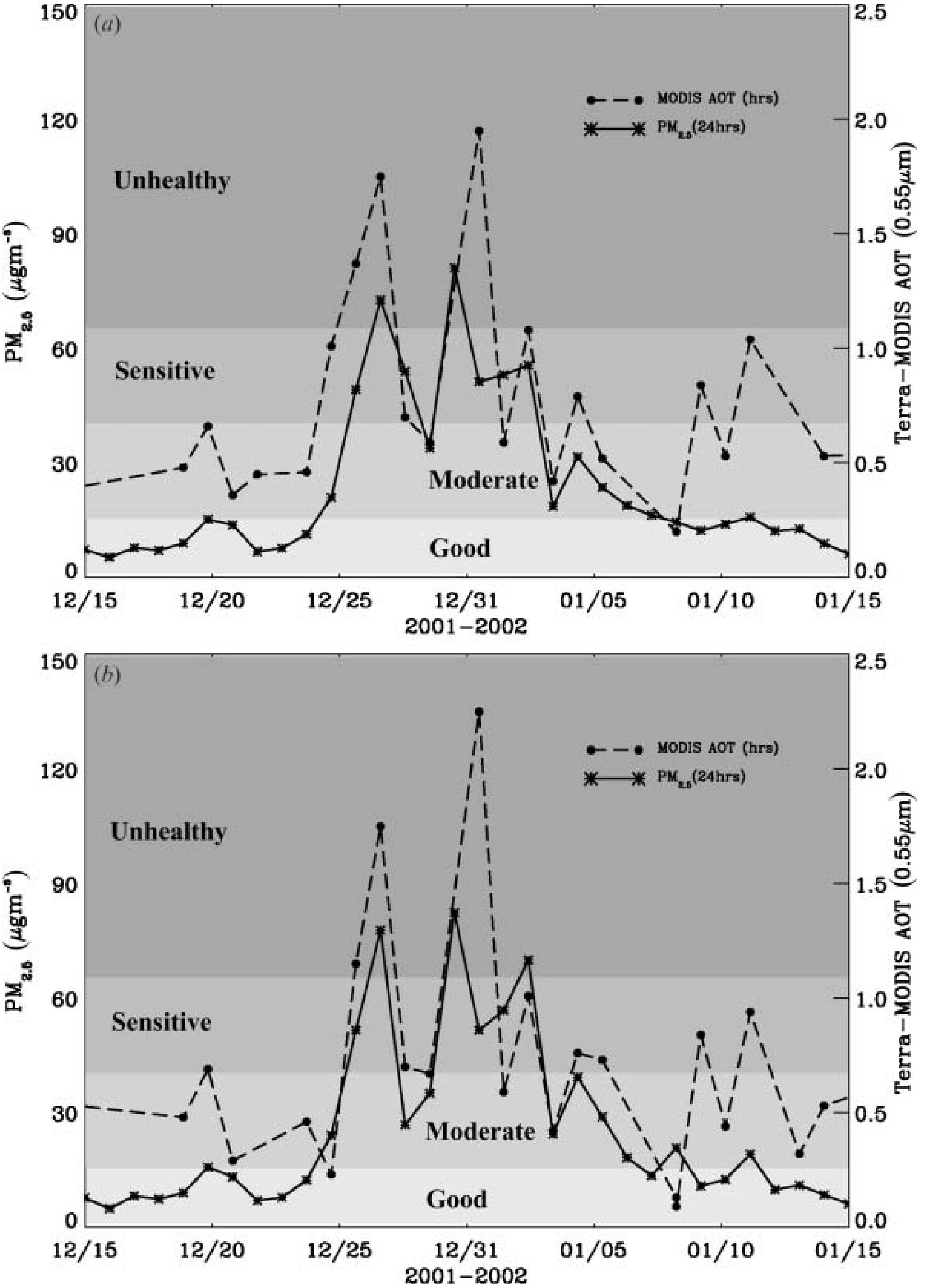

Figure 3. Effect of bushfires on hourly mean $PM_{2.5}$ mass and MODIS AOT over two selected stations (*a*) Earlwood and (*b*) Lidcombe in Sydney during December 2001–January 2002.

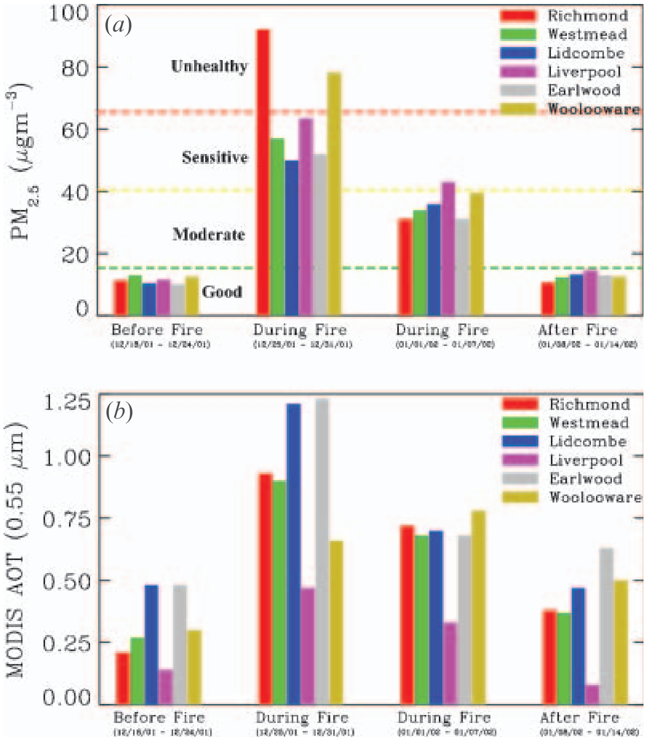

Figure 4. Effect of a major bushfire on air quality in Sydney during December 2001 and January 2002. Weekly mean values from six locations before, during, and after bushfire events. (*a*) $PM_{2.5}$ mass concentration measured at ground. (*b*) Columnar AOT measured from MODIS. The horizontal lines in (*a*) show the boundaries of the air-quality categories.

the AOT dropped to almost 0.1. However, since the fire was not completely extinguished, there were still some smoke plumes causing high AOT values on the following days. To quantify the effects of bushfires on local air quality over a slightly longer period, patterns in weekly mean values of $PM_{2.5}$ mass concentration and MODIS AOT before (1 week), during (2 weeks) and after (1 week) the fire are shown in figure 4. The weekly averaged values shown in figure 4 indicate that all stations experienced very poor air quality during the first fire week, with increases in weekly mean $PM_{2.5}$ mass concentration nearly five to 10 times greater than pre- and post-fire weeks. The corresponding increase in MODIS AOT values was also three to four times larger when compared with normal conditions (figure 4(*b*)). During the second week, the $PM_{2.5}$ mass decreased and reached 30–40 $\mu g\, m^{-3}$ over different stations. The week after the fire, the $PM_{2.5}$ mass values dropped down to their normal range of values of about 10–15 $\mu g\, m^{-3}$.

Our previous study (Gupta *et al.* 2006) shows that the air-quality conditions in Sydney during bushfire events is comparable to conditions in highly polluted cities such as Hong Kong and New Delhi. Due to a limited number of ground stations, it is very difficult for the local agencies to provide air-quality alerts over large spatial scales during major bushfire events. In such cases, the monitoring of atmospheric aerosol loading, with high spatial and temporal resolution using different satellite platforms, could be a valuable tool.

Table 3. Statistics of $PM_{2.5}$ mass concentration and MODIS AOT for 2002 on six stations around Sydney area.

Station name	No. of points	Corr. coeff. (R)	$PM_{2.5}$ ($\mu g\,m^{-3}$) Min	Max	Mean	SD	MODIS AOT (0.55 μm) Min	Max	Mean	SD
Richmond	233	0.11	5.1	59.3	16.2	7.5	0.01	0.60	0.10	0.08
Westmead	247	0.31	1.8	76.8	11.0	7.0	0.01	0.78	0.12	0.10
Lidcombe	106	0.48	6.2	50.3	15.0	5.8	0.05	0.60	0.30	0.12
Liverpool	245	0.40	5.3	51.2	13.6	5.2	0.06	0.70	0.28	0.13
Earlwood	308	0.32	4.2	53.1	12.8	6.1	0.02	0.78	0.25	0.15
Woolooware	168	0.32	4.4	64.1	13.8	6.2	0.02	0.76	0.20	0.13

4.3 *Relation between MODIS AOT and $PM_{2.5}$ mass*

Table 3 presents statistics of MODIS AOT and $PM_{2.5}$ mass for six stations in Sydney. The Linear Correlation Coefficient (LCC) between MODIS AOT and hourly $PM_{2.5}$ mass is calculated for each station. The LCC varies from 0.11 at Richmond where mean AOT is also lowest (0.10) to high values of 0.48 at Lidcombe where mean AOT is also highest (0.30). The LCC values at other stations are around 0.3, with small changes from one to another station. Research studies (Wang and Christopher 2003, Engel-Cox *et al.* 2004) in the United States show similar variations in LCC values. The observed LCC behaviour in Sydney (low LCC for low mean AOT and vice versa) is indicative of uncertainties in MODIS AOT from low to high aerosol loadings. As discussed earlier, the error in MODIS AOT could be high for small values of AOT (<0.10), and as AOT values become large, the errors are reduced significantly. Hence, the smaller value of LCC over Richmond could be due to large uncertainties in MODIS AOT, as the mean AOT (0.10) is very low. Similarly, the higher value of LCC at Lidcombe could be due to smaller uncertainties in MODIS AOT. High correlations between MODIS AOT and PM2.5 mass are to be expected when aerosols are primarily in the lower boundary layer so that the columnar AOT are representative of PM measurements and when aerosol loading is high so that the surface effects are minimized. Further correlation analysis on the data shown in figure 3 was also performed to examine the usefulness of satellite observations during high aerosol loading conditions. The highest LCC value (0.61) was found when air quality was in the 'sensitive category' and was lowest (0.19) when air-quality conditions were 'good', indicating that the satellite data were valuable for characterizing poor air-quality conditions.

The value of LCC not only depends on the accuracies in retrieval of MODIS AOT, but is a function of percentage cloud cover in MODIS pixel, ambient relative humidity, vertical distribution of aerosol in the atmosphere (e.g. atmospheric mixing height) and local meteorological conditions (Wang and Christopher 2003, Gupta *et al.* 2006). Nevertheless, our analysis indicates that for a high aerosol loading that is indicative of poor air quality, satellite data are useful for providing air-quality information over large scales. Sensitivity studies show that the LCC values are larger when mixing heights are low and are smaller when mixing heights are high. When mixing heights are low, aerosols are primarily in the lower atmosphere, and so surface measurements will observe concentrations of aerosols similar to those seen by satellites. However, as mixing height increases, aerosols are redistributed in the troposphere, and there could be large differences between surface measurements and satellite-derived values. In order to quantify these effects and to remove the upper-atmospheric contribution of aerosols in total AOT, information on vertical distribution of aerosol is very important. One of the most efficient methods obtaining the vertical distribution of aerosols is from lidar measurements. There are currently no lidars in the area of study, although several lidar networks such as the Micro-Pulse Lidar Network (MPLNET in USA) and European Aerosol Research Lidar Network (EARLINET in Europe) are beginning to provide vertical distribution data that will be important for both research and operational purposes. The successful launch of space-based lidars such as CALIPSO (Winker *et al.* 2003) on 28 April 2006 will provide vertical information of aerosols over global regions with sufficient resolution, which will be a tremendous asset to both the research and forecasting communities.

4.4 *Satellite and ground-based assessment of air quality in Sydney*

Particulate-matter air quality in Sydney was examined from both space and ground-based instruments during a period of 4 (from ground) to 5 (from satellite) years (2000–2005). The $PM_{2.5}$ stations cover residential, commercial, roadside, and park areas. Figure 1(*a*) shows the spatial distributions of a 5-year (January 2001–December 2005) mean AOT over Australia as observed from MODIS onboard Terra. The AOT averaged over all of Australia is less than 0.2 during all 5 years, although high AOT ($\sim$0.3–0.5) regions were found in the central and Northern parts of Australia. The MODIS currently does not report AOT over bright targets such as deserts. Figure 1(*c*)–(*h*) shows the diurnal variation (in local standard time) of $PM_{2.5}$ mass concentration averaged for different seasons. The largest change in $PM_{2.5}$ mass occurred in the morning hours from 0700 h to 0900 h with peak value at around 0800 h, then decreases from 0900 h to 1300 h, and remains steady with very small changes during the next 2–3 h. It starts increasing again in early evening hours from 1600 h to 2100 h and then shows small decreases until the early morning hours. These diurnal changes are similar during all four seasons except in the winter season, when there is a sharp increase around 2000 h. On average, the Southern Hemisphere summer and spring months show larger values compared with winter and autumn months. The diurnal patterns in $PM_{2.5}$ mass in Sydney are similar to those reported by Wang and Christopher (2003) over the south-eastern United States. The diurnal patterns in $PM_{2.5}$ mass are mainly due to changes in the height of the planetary boundary layer (PBL) because of changes in solar heating and local traffic flow. As solar heating increases during the day, the height of the PBL increases, thereby redistributing the aerosols in the atmospheric columns resulting in low values of $PM_{2.5}$ mass during the afternoon hours. During the morning hours, the coupling of traffic flow with possible buildup of residual precursors during the night results in a higher $PM_{2.5}$ mass concentration, which shows as peak values around 0800 h.

Collocated MODIS AOT and $PM_{2.5}$ mass observations in 2002 were used to calculate detailed statistics over each station (table 3). Table 3 also represents a summary of average air-quality conditions as observed in the Sydney area. The mean $PM_{2.5}$ mass value is less than 15 $\mu g\,m^{-3}$ (good air quality; table 2) over all the stations except over Richmond where it is slightly higher (16.2, moderate air quality). The columnar mean AOT values are as low as 0.10 in Richmond and as high as 0.30 at Lidcombe. Westmead has a large range of $PM_{2.5}$ mass value from 1.8 $\mu g\,m^{-3}$ to 76.8 $\mu g\,m^{-3}$ with mean values of 11.0 $\mu g\,m^{-3}$. Lidcombe experiences a mixture of aerosols from industries, motor vehicles, and other human activities. This station has a highest annual mean AOT value of 0.30, and the mean $PM_{2.5}$ mass concentration is $15.0\,\mu g\,m^{-3}$.

Figure 5 represents a time series of the 24-hour average $PM_{2.5}$ mass concentration and MODIS instantaneous AOT during 2002 averaged over all six stations in the Sydney area. The inset in the figure presents the seasonal mean $PM_{2.5}$ mass concentration and MODIS AOT with their standard deviation. A colour-coded bar on the left-hand side of the figure represents the air-quality standards as defined by the US EPA. The seasonal plot shows that air quality is poor during the summer months when compared with other seasons, which is due to the effect of bushfire smoke reported in January and December (§4.2). Also, the large standard deviation in both AOT and $PM_{2.5}$ mass is due to the large-scale bushfire event in the area during the months of December 2001 and January 2002. High AOT values in the summer and spring season could also be due to the hygroscopic nature of particles, which grow in humid environments and scatter more light. On the other hand, during the dry winter months, the hygroscopic effect is less, and AOT shows very low values for similar amounts of aerosol loading. However, large errors could result in MODIS retrievals for low AOT values (§2). If the effect of bushfires is removed from the $PM_{2.5}$ mass for the summer and spring months, then the $PM_{2.5}$ mass does not show the high seasonal changes as seen in the AOT values. This flat seasonal pattern in $PM_{2.5}$ mass could be related to pollution sources, which are mainly local in nature. Also, a 10-day back trajectory analysis using Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) shows that air masses reaching Sydney, Australia originate over the Indian Ocean during summer months, but originate inland of Australia during winter months. Pollution carried by this air mass is trapped in the Sydney basin due to its low elevation relative to the

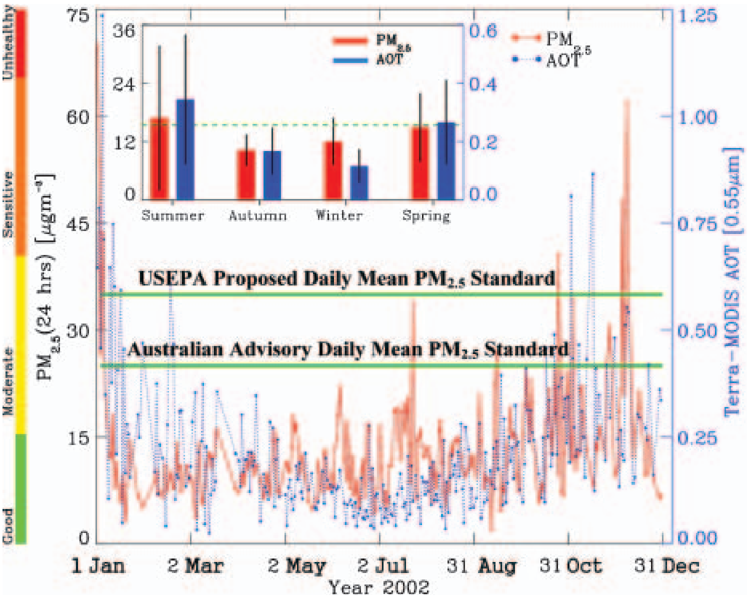

Figure 5. Time series (2002) of daily mean $PM_{2.5}$ mass concentration and MODIS AOT averaged over all six stations in the Sydney area with a colour-coded air-quality bar, which shows the daily changes in air-quality conditions. The inset shows the seasonal variations with standard deviation in $PM_{2.5}$ and AOT.

surrounding areas. Most of the particle emission sources are from anthropogenic sources such as motor vehicles, industries, airport, seaport, and petroleum refineries. Emission from these sources does not vary appreciably from one season to another. The small variations seen in seasonal $PM_{2.5}$ mass values are largely driven by their interaction with other atmospheric constituents and local meteorology. The National Centers for Environmental Prediction (NCEP)-derived monthly mean wind speed values range from 2–5 ms^{-1} during October–January to 5–8 ms^{-1} during June–August. High wind speeds during dry conditions can lift particles from the surface and transport them from source to different regions and altitudes. Similar flat patterns in $PM_{2.5}$ mass and large seasonal variations in AOT are also seen in the long-term (4 years) monthly mean values of $PM_{2.5}$ mass, as shown in figure 6.

The time series of $PM_{2.5}$ mass and MODIS AOT shown in figure 5 clearly demonstrate the high value of both parameters during bushfire events in January 2002 and again in November–December 2002. Except for bushfire-affected days, when air quality reached the unhealthy category, air quality in the Sydney basin remained in the good category throughout the year with small day-to-day changes. Note that these air-quality categories were derived based on the United States EPA standards. Long-term analysis (figure 6) also shows good air-quality conditions in the Sydney area except during bushfire events. The horizontal green line in figure 5 sets an upper limit for good air quality. All the days below the green line represent good air quality in the area. Out of 276 total collocated $PM_{2.5}$-AOT days, air quality is found to be ‘good’ on 207 days (75%), and it is moderate for 62 days (22%). The air-quality category is poor on seven (<3%) occasions. The 24-h mean $PM_{2.5}$ mass concentration values show small-scale (1–5 $\mu g\,m^{-3}$) to large-scale (10–40 $\mu g\,m^{-3}$) day-to-day variations. Mostly, small-scale variations are observed on the normal days (no fire) and could be associated with local meteorological conditions. These normal $PM_{2.5}$ mass values represent the regular source strength as described by Corbyn (2004). Only 7 days with sensitive to unhealthy air quality were found as a result of bushfire events in the months of October, January, and December.

Figure 6 presents the monthly mean $PM_{2.5}$ mass concentration and MODIS level 3 monthly mean AOT for 49 months during April 2000 to April 2004. The $PM_{2.5}$ mass values were averaged over all six stations, and AOT values were averaged over a 2 × 2 degree (150–152° E and 30–32° S). The MODIS AOT values show a similar seasonal pattern each year (maximum in summer and minimum in winter), whereas

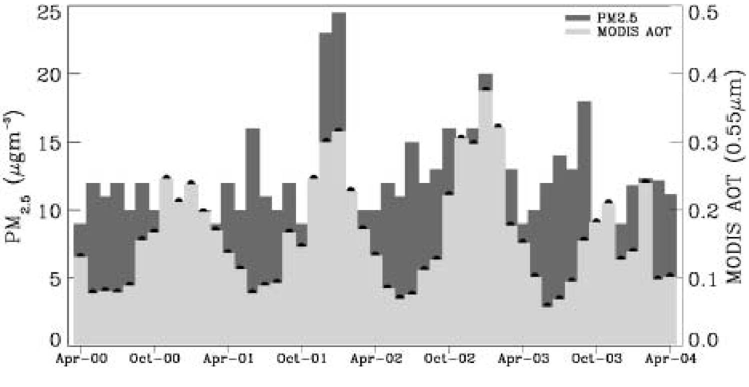

Figure 6. Multi-year analysis of monthly mean $PM_{2.5}$ mass and MODIS L3 AOT over Sydney area showing seasonal and annual patterns in both $PM_{2.5}$ and AOT.

$PM_{2.5}$ mass does not show a clear seasonal pattern. The seasonal pattern in AOT is more closely associated with change in meteorological conditions and transport of pollution from other source regions at the surface as well as in the upper troposphere. The high AOT values in the summer months could be due to the hygroscopic nature of the aerosols, which can increase their scattering efficiency. Low values of relative humidity in the winter months reduce the scattering efficiency of hygroscopic aerosols (Hess *et al.* 1998). Hence, the same amount of dry aerosol mass could produce higher AOT values in the summer months when compared with the winter months. Since production of $PM_{2.5}$ particles does not change appreciably with seasons except during specific aerosol events, their pattern is flatter when compared with columnar MODIS AOT patterns. Peak AOT values of 0.38 and 0.32 were observed in the summer months of 2001–2002 and 2002–2003. As summarized from news reports and data shown in this study, these summer months were found to be under the influence of bushfires in Sydney and surrounding areas. The monthly mean air quality (based on $PM_{2.5}$ mass) in Sydney was found to be good in 41 months, whereas moderate air quality is reported during 8 months over a period of more than 4 years. A survey of news and weather reports shows that those months with moderate air quality were found under the influence of summer and spring season bushfires. The peak $PM_{2.5}$ mass concentration of $24.8\,\mu g\,m^{-3}$ was reported in January 2002, whereas minimum values of $8\,\mu g\,m^{-3}$ were reported during the month of April in almost every year.

5. Summary and conclusions

Five years of satellite AOT and four years of ground-based $PM_{2.5}$ mass concentration data sets were used to study PM air quality over Sydney. The results were categorized according to the US EPA standards. Our results indicate that the air quality is under the good category for most of the year ($<15\,\mu g\,m^{-3}$) except during major bushfire events. Bushfires could increase the daily $PM_{2.5}$ mass loading by nearly 10 times, thereby causing extremely poor air-quality conditions. The satellite-derived AOT and $PM_{2.5}$ mass concentrations show similar trends before, during, and after bushfire events. We conclude that satellite data are a tremendous asset for studying PM air quality over large spatial scales that are not possible from ground measurements alone. Coupled with models, a network of sun photometers, size-resolved chemistry, and lidar measurements could be very beneficial for the New South Wales EPA for issuing air-quality alerts over large spatial scales.

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