Air Quality in the Sydney Metropolitan Region during the 2013 Blue Mountains Wildfire

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ABSTRACT

Australia commonly experiences extensive wildfires, mostly during its hot dry summers. These often lead to a significant loss of life and property. The October 2013 Blue Mountains Fire burnt through more than 100,000 hectares and generated a large amount of fire dust that was transported to the downwind community residing in the Sydney metropolitan area, which is the largest city in Australia. Record-breaking temperatures in New South Wales and strong winds worsened the wildfire danger index, and the extensive fires that broke out by 17th October lasted for more than a week. Analysis of the particulate matter monitored by the New South Wales Environmental Protection Authority around the fire zone showed that the concentrations of PM10 and PM2.5 increased by more than twofold (> 200%) and remained high for a week. During the peak fire period, SOx, NOx and O3 concentrations increased by 52%, 29% and 42%, respectively, above the usual levels recorded in metropolitan Sydney. The increase in the concentrations of these air contaminants in the Sydney metropolitan region over such an extended period may have caused increased human health risks, which are also examined in this paper.

Keywords: Wildfire; Wind-transported; PM10; PM2.5; SOx; NOx; Ozone.

INTRODUCTION

Wildfires (also called bushfires) are common in Australia during the hot summer days when the temperature is high and humidity is low (Attiwill and Adams, 2013). Due to the inner areas of Australia being covered by Eucalyptus trees, in particular, there is an increased risk of severe fires in these regions. Eucalyptus leaves produce volatile highly combustible oil. Fallen Eucalyptus leaves on the ground create carpets of flammable material, and the trees’ bark peels off in long streamers that drop to the ground, providing additional fuel. The phenolic compounds present in the bark and leaves prevents breakdown of litter. During such wildfires, a substantially larger amount of smoke containing dust particles is released into the atmosphere as air contaminants. During periods of heavy winds, smoke can travel hundreds of kilometers to urban and semi-urban residential areas transporting associated air pollutants. Gaseous pollutants at certain concentrations are hazardous to human health and can contribute to global climate change. The degree of their impact depends on the type of pollutant particles released during combustion and the time of exposure (Pitman et al., 2007; Goldammer, 2015). The Blue Mountains wildfire was started by both human activity (either directly or indirectly) and lightning that occurred across multiple locations. The event caused a considerably large mass of fire dust to enter the atmosphere and was severe enough to cause traffic disruption due to reduced visibility.

Many researchers have reported the impacts of fire dust on downwind communities (Reisen and Brown, 2009; Kang et al., 2014). Urban metropolitan Sydney lies in the southeastern coastal fronts below the Blue Mountains where the wind favours an outward and eastward movement from the mountains to the plains. The 2013 Blue Mountains wildfire occurred during a period of high temperature (exceeding the previous year’s record high by 3°C), low humidity and high wind speeds (Fig. 1). The fire dust released into the atmosphere from the fires located at the lower western and lower southern sides of the Blue Mountains was transported in a south easterly direction by a north-west wind. The dust contained particulate matter less than 10 µm (PM10) and 2.5 µm (PM2.5), oxides of sulphur (SOx), oxides of nitrogen (NOx) and ozone (O3), which were dispersed around the western and south-eastern regions of metropolitan Sydney (Rea et al., 2016).

PM10 (coarse particulates) and PM2.5 (fine particulates)
Fig. 1. (a) Wildfire in Blue Mountains region (image adopted from AFP/NASA/Jeff Schmaltz) and (b) pollutants data monitoring stations. *Note: red circles in Fig. 1(b) represent monitoring stations and fire symbol shows area burned.

are considered as effective air quality indices and are primary by-products of fire dust (Bravo et al., 2002; Delfino et al., 2009; Konovalov et al., 2011). The effects of wildfires in Sydney on daily mortality and hospital admissions have been reported as being a 1.24% increase in respiratory hospital admissions and a 5.20% increase in associated adult asthma hospital admissions for every 10 µg m$^{-3}$ increase in PM$_{10}$ (Morgan et al., 2010). In a similar study, it was found that PM$_{10}$ concentrations greater than the 99 percentile value were associated with a 5% increase in non-accidental mortality (Johnston et al., 2011). PM$_{2.5}$ particles have an even more detrimental impact on public health than PM$_{10}$ particles due to their ability to reach to the lungs, liver and blood stream. It has been reported that if PM$_{2.5}$ were reduced by 10 µg m$^{-3}$ in denser European cities, the number of cardiopulmonary hospital admissions could be reduced thereby increasing the life expectancy from one month to 2 years by age 30 (Boldo et al., 2006). In a similar study in the US (Pope III et al., 2009), it was found that life expectancy could be increased if fine particulates could be reduced by 10 µg m$^{-3}$.

Along with PM$_{10}$ and PM$_{2.5}$, other contaminants that are released during a wildfire of sulphur, nitrogen, and ozone. Sulphur occurs freely in nature and readily forms sulphur oxides under combustible conditions, and these readily dissolve in water producing sulphuric acid (H$_2$SO$_4$). The oxides of sulphur, when released in abundance into the atmosphere during wildfires, may result in acid rain under certain conditions. In humans, the oxides of sulphur can cause respiratory and cardio-vascular illness (Crabbe, 2012). In Western Europe it has been found that an increase of 50 µg m$^{-3}$ in sulphur dioxide concentration was associated with a 3% increase in daily mortality rate (Katsouyanni et al., 1997). The most common types of impacts reported are respiratory, bronchial and thoracic illnesses (Walters et al., 1994; Katsouyanni et al., 1997).

While most of the oxides of nitrogen occur in the atmosphere due to oxidation processes, estimates have shown that wildfires and other biomass combustion contributes to about 10–12% of the global mass (Khoder, 2002; Reid et al., 2005). Oxides of nitrogen cause acute and chronic respiratory and vascular illnesses in children and adults (Stamler et al., 1993). The nitrogen dioxide produced during wildfire combustion combines with water in the atmosphere to form toxic nitric acid, which contributes to impacts on natural ecosystems and to warming at the global scale (Nordhaus, 2001; Pearson, 2011; Liu et al., 2016).

Ozone is a major secondary air pollutant and is formed by the complex photochemical reaction of primary pollutants such as NO$_x$. It has been observed that ground-level ozone causes deleterious impacts to human health including cardiovascular and respiratory illnesses, melanomas and cataracts (Knowlton et al., 2004; Ashmore, 2005; Bell et al., 2007; Fang et al., 2013). Due to ozone being easily transportable over thousands of kilometers, its impacts are prominent even far from the origination (Anenberg et al., 2009) and it peaks only downwind of a fire location. Several other researchers have also demonstrated comparable ozone transport behavior and impact (Morris et al., 2006).

In this study, in-situ observations were used to assess the change in air quality including PM$_{10}$, PM$_{2.5}$, SO$_x$, NO$_x$, and ozone in the Sydney region before and after the October 2013 fire in the Blue Mountains. Pearson correlation and multivariate cluster analysis were applied to estimate the relationship among the observed variables.

**Topography and Geography**

Geographical location and meteorology affect the origin, suspension, composition and transportation of dust across a region (Aryal et al., 2008; Kang et al., 2014). Much of the Blue Mountains lies on sedimentary rocks consisting of shales, coals and sandstones. These make up the two types of distinct land mass, namely the upper Blue Mountains and plateau range and the lower Cumberland plains (Cunningham, 1984). Except for narrow gorges and gullies formed by the
escarpments, most of the range is exposed to external dryness, which makes it susceptible to seasonal wildfires.

Wildfires in NSW and the Role of Vegetation and Weather

Historically, the majority of extensive wildfires in New South Wales (NSW) have occurred during the hot and dry summer season. High temperatures, decreased humidity and high-speed winds create an environment that is conducive for wildfires. The majority of tree species in this area are *Eucalyptus* which shed their flammable oily leaves and barks making them particularly fire-promoting (Waters et al., 2010; Matthews et al., 2012; Jenkins et al., 2016; Prior et al., 2016). *Eucalyptus* fires are the primary source of harmful dust in the Sydney region (Cunningham, 1984; Bradstock et al., 2002).

Sydney is located on coastal lowlands and is sandwiched between the Pacific Ocean and the Blue Mountains. High-speed coastal winds and interiorly built pressure winds from the higher altitudes can transport smoke from upwind wildfires. Fire dust is a common occurrence in the Sydney urban region (Johnston et al., 2014). In Sydney, air pollution from wildfires (Johnston et al., 2014) occurs for an average of 4–5 days a year.

The statewide average maximum temperature during October 2013 was 2.5°C above average and was the tenth warmest on record for NSW. Temperatures were more than 10°C above normal across most of the NSW area on the 10th and 21st of October. The humidity during the period was 51% while it was less than 8% in the previous year. The fire started in the lower Blue Mountains through human error on 19th October 2013. It quickly spread to multiple locations due to gusty winds (> 70 km h⁻¹). This led to the generation of a very large volume of fire dust particles containing ambient air contaminants including PM₁₀ and PM₂.₅. The south westerly wind helped the fire dust to move to the downwind communities located in the Sydney metropolitan area. This type of dust transport to downwind communities is similar to the findings reported from fire events in the Northern Europe (Makkonen et al., 2010) (2008), Quebec (Kang et al., 2014), California (Phuleria et al., 2005; Wu et al., 2006; Cisneros et al., 2012), and Greece (Lazaridis et al., 2008).

METHOD

**Study Area**

The study area is the greater Blue Mountains and the surrounding region in the state of NSW, Australia. Located 45 to 100 km west of Sydney and forming a part of the Great Dividing Range, the Blue Mountains consist of formidable escarpments, table lands, narrow gorges and gullies. The Mountains are seated on one of the oldest sandstone beds that was formed more than 200 million years ago when Australia was still a part of the super mass Pangea in the Triassic period (180–300 million years ago). Extending more than 90 km and elevated at heights of 50m to 1190m, it is geographically situated at 33°43′55″S 150°18′38″E. This study included PM₁₀, PM₂.₅, SO₄, NOₓ, and ozone data. There was a total of 42 stations and not all stations monitored all mentioned parameters. The pollutants concentration data for these locations for the month of October 2013 were provided by the NSW Environmental Protection Authority (EPA).

**Data Analysis**

The measured concentrations of each contaminant type were compared before and after the fire. Days 1–16 before the ignition were categorized as being the period before the fire while days 17–30 were defined as being in the post-fire period. Temporal and spatial distributions of measured concentrations were compared for 1st, 10th (before the fire period), 19th (during the peak fire period) and 30th (after the fire period) days of the month by plotting contour diagram in MATLAB (version 9.1). The relationships among the observed air quality parameters were investigated by Pearson correlation analysis and a multivariate cluster study was performed using SPSS (version 21) for each contaminant type.

A statistical analysis of the linear dependence of the variables PM₁₀, PM₂.₅, SO₄, NOₓ and O₃ was carried out using Pearson’s Correlation Matrix where the coefficient ‘r’ (–1 < r < 1) of the variables represents the degree of dependence or association between the variables. The correlation was computed for the average values of the concentrations both before the severe fire period (days 1–16) and after the fire period (days 17–28). The degree of dependence or relation between any two variables in this analysis is given by a 5 × 5 correlation square matrix.

**RESULTS AND DISCUSSION**

**Change in Concentration of PM₁₀ and PM₂.₅**

Increases in the concentration of airborne coarse and fine particles to levels exceeding national guidelines (50 µg m⁻³) were observed during the Blue Mountains wildfire (Figs. 2(a) and 2(b)). Six monitoring stations are highlighted in Figs. 2(a) and 2(b) for clear view on pollutants’ concentration change before and after the fire. The average PM₁₀ value before the fire event was 24 µg m⁻³. After the fires were out the concentration remained at an average of 52.1 µg m⁻³ for over a week, which is higher than the national exceedance guideline value. The concentration in the metropolitan area increased more than two fold during the peak fire period and remained above the national guideline level for more than four days. In the metropolitan region shown in Fig. 2(a), average concentrations of 86.5 µg m⁻³ and 67 µg m⁻³ were recorded at Wollongong (south of Sydney) and Richmond (west of the Sydney), respectively. During the peak fire period, the downstream area of Wollongong experienced PM₁₀ concentrations of around 209 µg m⁻³. The PM₁₀ particles in the 2013 Blue Mountains wildfire consisted of less organic carbon (45%), more sea salt (9.5%) and slightly more other primary organic matter (33%) and secondary organic aerosols (6.2%) than usual urban PM₁₀ particles (Rea et al., 2016).

The increase in PM₂.₅ was even greater after the fires. Some areas experienced PM₂.₅ by more than three times over the 24 h national exceedance guideline value of
Fig. 2. Change in concentration (µg m⁻³) of (a) PM₁₀ and (b) PM₂.₅ before, and after the 2013 Blue Mountains fires (Rigid horizontal line show national guideline value in Australia).

25 µg m⁻³. The PM₂.₅ concentration peaked between the 17th and 19th October across most locations and slowly declined after the 22nd, from which time the severe fires were contained. The average concentration of PM₂.₅ for the six monitoring locations before the fire was 8.3 µg m⁻³ but this increased during the fire period to 28 µg m⁻³. In few areas like Wollongong and Richmond, the average PM₂.₅ concentrations were 69 µg m⁻³ and 43 µg m⁻³, respectively.

The PM₂.₅/PM₁₀ ratio usually provides information regarding the particulate sources. Sydney region had this ratio 0.33 (in average) before the fire. This ratio jumped to 0.53 during and after the fire (till the end of October). The value dropped down to 0.34 in the first week of November and this value remained similar (0.36) throughout November. This indicated that there was a significant change in the air quality during the fire and for a week after the fire.

The contour diagrams for PM₁₀ in Figs. 3(a), 3(b), 3(c) and 3(d) correspond to the 1st, 10th, 17th, 19th, 21st and 31st days of the month, respectively. The red band (red being maximum on the scale of 0–300) in Fig. 3(c) shows that the maximum concentration was recorded on the 19th. The concentration decreased to normal levels towards the end of the month on the 31st (Fig. 3(f)). Also for PM₂.₅, the concentration reached a maximum value on the 19th, as shown in Fig. 4(d), but the concentrations settled back to normal conditions towards the end of the month (Fig. 4(f)).

Change in Concentration of SOₓ, NOₓ and O₃ (O₃)

The average SOₓ, NOₓ and O₃ concentrations before the fire (days 1–16) were 0.08, 1.1 and 2.37 ppbm, respectively. The corresponding values for SOₓ, NOₓ and O₃, during the fire, had increased to 0.12, 1.21 and 2.89 ppbm, respectively. In some downwind areas, the increase was up to 195% for SOₓ, 330% for NOₓ and 3,626% for O₃, during the fire compared to before the fire. Relative increases in SOₓ, NOₓ and O₃ concentrations after wildfires have been reported in
Fig. 3. Contours of PM$_{10}$ on day (a) 1, (b) 10, (c) 17, (d) 19, (e) 21, and (f) 31 of October (scale 0–300 µg m$^{-3}$).
Fig. 4. Contours of PM$_{2.5}$ on day (a) 1, (b) 10, (c) 17, (d) 19, (e) 21, and (f) 31 of October (scale 0–100 µg m$^{-3}$).
various parts of the world (McKeen et al., 2002; Phuleria et al., 2005; Pfister et al., 2006; Viswanathan et al., 2006; Pfister et al., 2008; Tanimoto et al., 2008; Bencardino et al., 2011; Jaffe and Wigder, 2012; Singh et al., 2012; Chalbot et al., 2013; Jaffe et al., 2013; Kang et al., 2014). Although there was no published report of public health risks associated with these pollutants for this wildfire, in the past there have been increases in hospital admissions for respiratory problems (Johnston et al., 2011; Martin et al., 2013). Both SO\(_2\) and NO\(_x\) are chemically reactive and unstable which explains the decreasing concentrations after the fire. Ozone concentrations were higher towards the second week of the month. However, even the ozone concentrations decreased towards the end of the month when the volumes of dust in the atmosphere decreased to normal levels. Figs. 5, 6 and 7 provides spatial changes in chemical concentration in SO\(_x\), NO\(_x\) and O\(_3\) on 1\(^{st}\), 10\(^{th}\), 17\(^{th}\), 19\(^{th}\), 21\(^{st}\) and 30\(^{th}\) of October 2013 surrounding of Blue Mountains, respectively.

**Statistical Analysis**

**Pearson Correlation Analysis**

With five different variables for the fire dust in the ambient air, a total of 15 correlations were obtained in each case for comparison of their linear association (Table 1). Six out of the 15 correlations showed positive association between the variables before fire, and four correlations were inversely associated. The linear dependence changed after the fire.

A significant positive correlation was observed between NO\(_x\) and both PM\(_{10}\) and PM\(_{2.5}\) before the fire but the correlation value decreased after the fire. This indicates that the amount of NO\(_x\) in the ambient air atmosphere had changed with the change in particulate concentration. NO\(_x\) is a precursor to O\(_3\) in the wildfire zones and rapidly undergoes photochemical reaction in the presence of light. Compared to the more stable particulate matter, the concentrations of NO\(_x\) diminish with time. A similar decreasing trend in the correlation analysis of particulates and NO\(_x\) has been shown in previous studies (Ovadnevaite et al., 2006; Wu et al., 2006).

Ozone concentrations were negatively correlated with both PM\(_{10}\) (\(r = -0.656\)) and PM\(_{2.5}\) (\(r = -0.456\)) before the fire. The relationship changed with PM\(_{10}\) after the fire (\(r = 0.116\)) but showed a positive correlation with PM\(_{2.5}\) (\(r = 0.613\)). The change in correlation is possibly due to an increase in the concentration of ozone with increasing PM\(_{10}\) and PM\(_{2.5}\) after the wildfire, indicating that both of these elevated concentrations originated from the fire. Other researchers have found a comparably positive correlation between PM\(_{0}\) and ozone and PM\(_{2.5}\) and ozone after a wildfire (Miranda et al., 2007; Morgan et al., 2010). During the wildfires, the primary ozone precursors (NO\(_x\) and non-methane organic carbon) contribute to O\(_3\) formation by photochemical reactions in favorable meteorological conditions. During long-range fire dust transport, finer particles carrying ozone precursors are dominant over coarse particles and this contributes to elevated ozone concentrations in downwind urban destinations.

SO\(_2\) and PM\(_{10}\) concentrations were positively correlated before the fire but not afterwards. Researchers in Lithuania (Ovadnevaite et al., 2006) reported a similar decreasing trend of linear correlation between PM\(_{10}\) and SO\(_2\). There was a strong inverse correlation between ozone and NO\(_x\) concentrations, both before and after the fires. In general, solar radiation photochemically produces O\(_3\) under high concentrations of NO\(_x\), and non-methane hydrocarbons. The eucalyptus tree produces hydrocarbons and during wildfire and may act synergistically in O\(_3\) production. There are many reports showing evidence that O\(_3\) is photochemically produced in the lower atmosphere from biomass burning (Gutzen and Andreae, 1990; Kirchhoff and Rasmussen, 1990; Tsutsu, 1999). SO\(_2\) had a negligible positive correlation with NO\(_x\) both before and after the fires. There was no correlation between ozone and SO\(_2\). There was a weak positive correlation between PM\(_{2.5}\) and PM\(_{10}\) and this increased, but only slightly, after the fire period.

**Multivariate Cluster Analysis**

Dendrograms were plotted to graphically observe the relationships between the pollutants (PM\(_{10}\), PM\(_{2.5}\), SO\(_x\), NO\(_x\), and ozone) before and after the October 2013 wildfire (Fig. 8). Before the fire commenced, vehicular and industrial combustion sources contributed to elevated SO\(_x\), NO\(_x\), O\(_3\) and PM\(_{2.5}\) concentrations in the Sydney metropolitan area, whereas PM\(_{10}\) was believed to have originated mainly from mineral dust, marine aerosols, petrochemical emissions, crude biomass burnings and crustal earth sources (Viana et al., 2003; Querol et al., 2004; Rodriguez et al., 2004). Due to similar sources of origin, SO\(_x\), NO\(_x\), O\(_3\) and PM\(_{2.5}\) were clustered together, separate from PM\(_{10}\) in Figs. 8(a) and 8(b) before the fire occurred. During and after the fire periods, PM\(_{10}\) and PM\(_{2.5}\) were clustered together (Figs. 8(c) and (d)). We interpret this as evidence that the wildfire was the main source of these particles in the atmosphere. A similar relationship was observed among pollutants the week after the fire was contained (Fig. 8(e)). This indicates that it took almost a week for atmospheric conditions to return to normal after the fire was contained.

**CONCLUSION**

The October 2013 wildfire in the Blue Mountains upwind of the Sydney metropolitan area more than doubled the atmospheric concentrations of PM\(_{10}\) and PM\(_{2.5}\), to levels that exceeded national guidelines. The ratio of PM\(_{2.5}\) to PM\(_{10}\) increased from less than 0.31 to > 0.5 after the fire commenced and remained high for a week, indicating that the wildfire contributed strongly to elevated levels of finer particles in downwind areas. Other pollutants recorded in the Sydney metropolitan area, including SO\(_x\), NO\(_x\), and O\(_3\) were also higher after the fire by 30%, 29% and 17%, respectively. Strong relationships were observed between NO\(_x\) and both PM\(_{10}\) and PM\(_{2.5}\) in Sydney’s atmosphere when it was affected by fire dust. There was a strong positive correlation between PM\(_{2.5}\) and O\(_3\), again indicating that fire dust contributed to elevated pollutant concentrations in the atmosphere. This was reinforced by a cluster analysis that
Fig. 5. Contours of SO$_x$ on day (a) 1, (b) 10, (c) 17, (d) 19, (e) 21, and (f) 31 of October (scale 0–1 pphm).
Fig. 6. Contours of NOx on day (a) 1, (b) 10, (c) 17, (d) 19, (e) 21, and (f) 31 of October (scale 0–5.0 ppb).
Fig. 7. Contours of O$_3$ on day (a) 1, (b) 10, (c) 17, (d) 19, (e) 21, and (f) 31 of October (scale 0–0.80 pphm).
Table 1. Pearson Correlation Coefficients (r) between pollutants (a) before (1–16 October) and (b) after (17–31 October) the fire.

|          | NOx  | O3   | PM10 | PM2.5 | SOx  |
|----------|------|------|------|-------|------|
| Before fire |      |      |      |       |      |
| NOx      | 1.000|      |      |       |      |
| Ozone    | -0.790| 1.000|      |       |      |
| PM10     | 0.658| -0.656| 1.000|       |      |
| PM2.5    | 0.566| -0.456| 0.222| 1.000 |      |
| SOx      | 0.305| -0.050| 0.612| 0.491| 1.000|

|          | NOx  | O3   | PM10 | PM2.5 | SOx  |
|----------|------|------|------|-------|------|
| After fire |      |      |      |       |      |
| NOx      |      |      |      |       | 1.000|
| Ozone    |      |      |      |       | -0.744|
| PM10     |      |      |      |       | 0.004|
| PM2.5    |      |      |      |       | 0.116|
| SOx      |      |      |      |       | 1.000|

Fig. 8. Dendrogram diagrams for day (a) 1, (b) 10, (c) 19, (d) 21, and (e) 31 of October 2013.

showed that fire dust affected the pollutant relationships for a while but that these relationships were restored a week after the fire was contained.

SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at http://www.aaqr.org.

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