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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 PM_{10} and $PM_{2.5}$ increased by more than twofold (> 200%) and remained high for a week. During the peak fire period, SO_x, NO_x and O_3 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; PM_{10}; $PM_{2.5}$; SO_x; NO_x; 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 south-eastern 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 (PM_{10}) and 2.5 μm ($PM_{2.5}$), oxides of sulphur (SO_x), oxides of nitrogen (NO_x) and ozone (O_3), which were dispersed around the western and south-eastern regions of metropolitan Sydney (Rea *et al.*, 2016).

PM_{10} (coarse particulates) and $PM_{2.5}$ (fine particulates)

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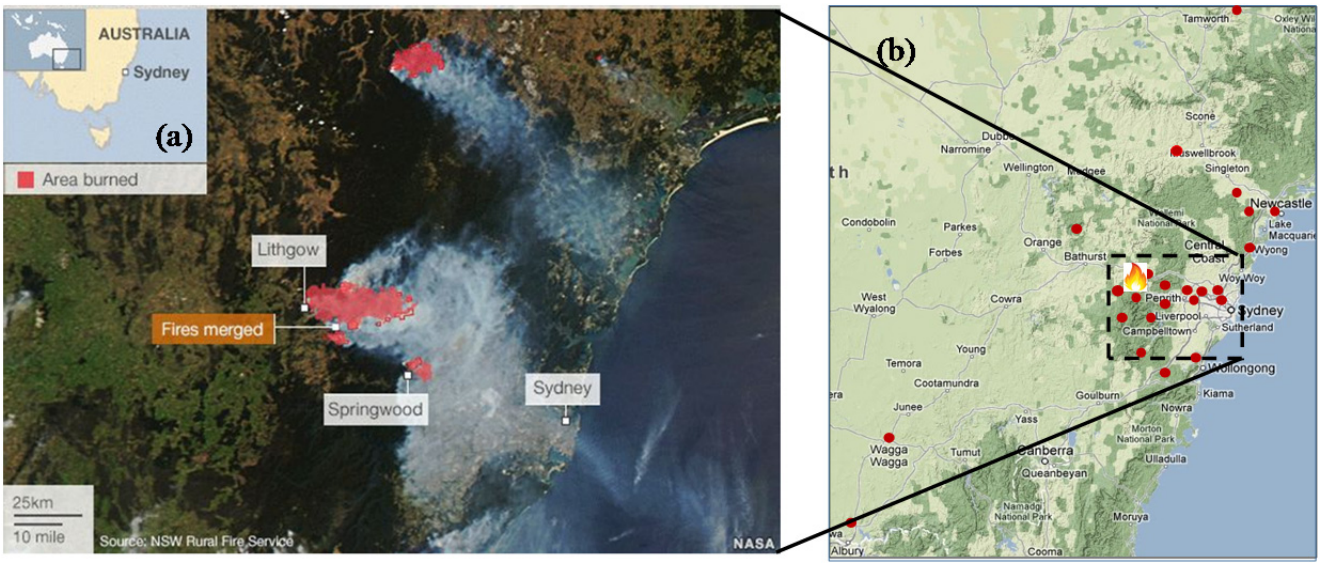

Fig. 1. (a) Wildfire in Blue Mountains region (image adopted from AFP/NASA/Jeff Schmaltz) and (b) pollutants data monitoring stations. *Note: red circles in Fig. 1(b) represent monitoring stations and fire symbol shows area burned.

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.*, 2013), 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_2SO_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 PM_{10} and $PM_{2.5}$. 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 is 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′05″S 150°18′38″E. This study included PM_{10}, $PM_{2.5}$, SO_x, NO_x 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 PM_{10}, $PM_{2.5}$, SO_x, NO_x and O_3 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 PM_{10} and $PM_{2.5}$

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 PM_{10} 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 PM_{10} concentrations of around 209 μg m^{-3}. The PM_{10} 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 PM_{10} particles (Rea *et al.*, 2016).

The increase in $PM_{2.5}$ was even greater after the fires. Some areas experienced $PM_{2.5}$ by more than three times over the 24 h national exceedance guideline value of

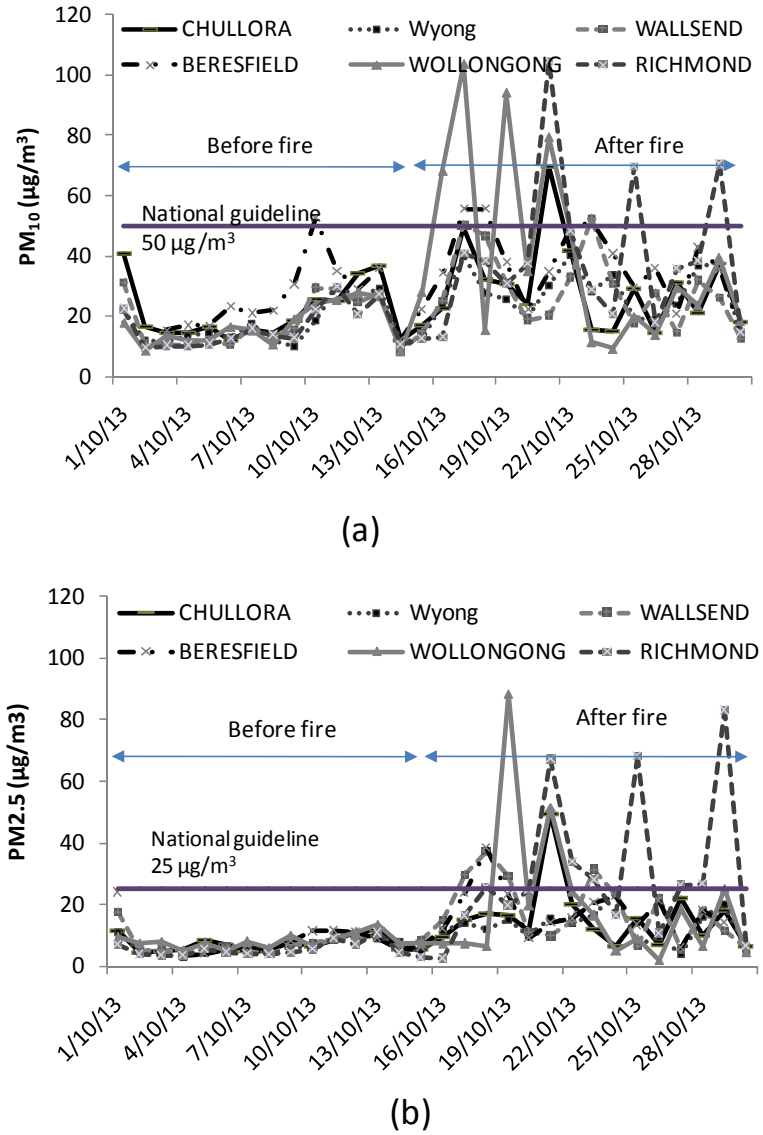

Fig. 2. Change in concentration (µg m^{-3}) of (a) PM_{10} and (b) $PM_{2.5}$ before, and after the 2013 Blue Mountains fires (Rigid horizontal line show national guideline value in Australia).

25 µg m^{-3}. The $PM_{2.5}$ 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 $PM_{2.5}$ 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 $PM_{2.5}$ concentrations were 69 µg m^{-3} and 43 µg m^{-3}, respectively.

The $PM_{2.5}/PM_{10}$ 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 PM_{10} 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 $PM_{2.5}$, 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 SO_x, NO_x and Ozone (O_3)

The average SO_x, NO_x and O_3 concentrations before the fire (days 1–16) were 0.08, 1.1 and 2.37 pphm, respectively. The corresponding values for SO_x, NO_x and O_3, during the fire, had increased to 0.12, 1.21 and 2.89 pphm, respectively. In some downwind areas, the increase was up to 195% for SO_x, 330% for NO_x and 3,626% for O_3during the fire compared to before the fire. Relative increases in SO_x, NO_x and O_3 concentrations after wildfires have been reported in

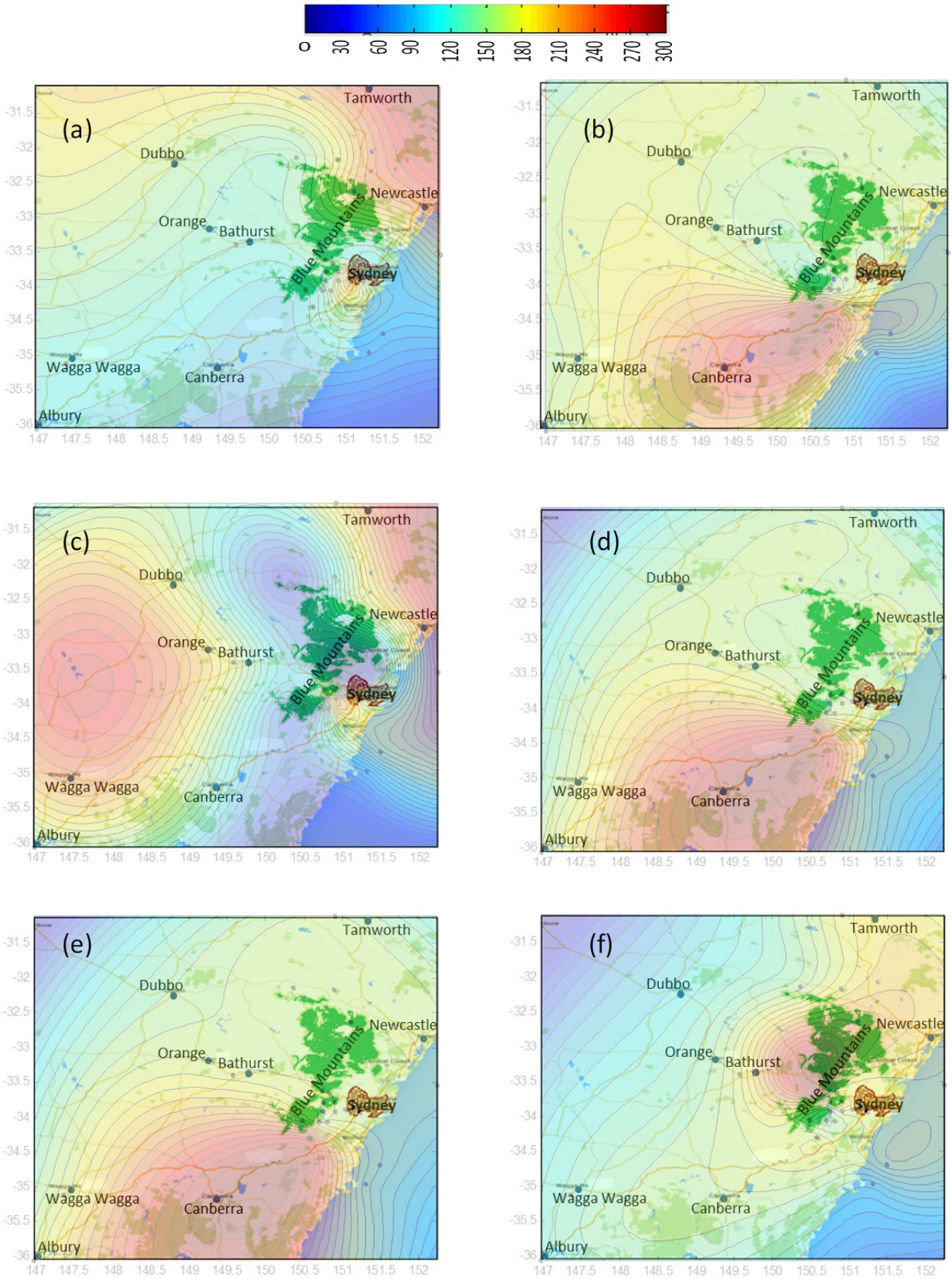

Fig. 3. Contours of PM_{10} on day (a) 1, (b) 10, (c) 17, (d) 19, (e) 21, and (f) 31 of October (scale 0–300 μg m^{-3}).

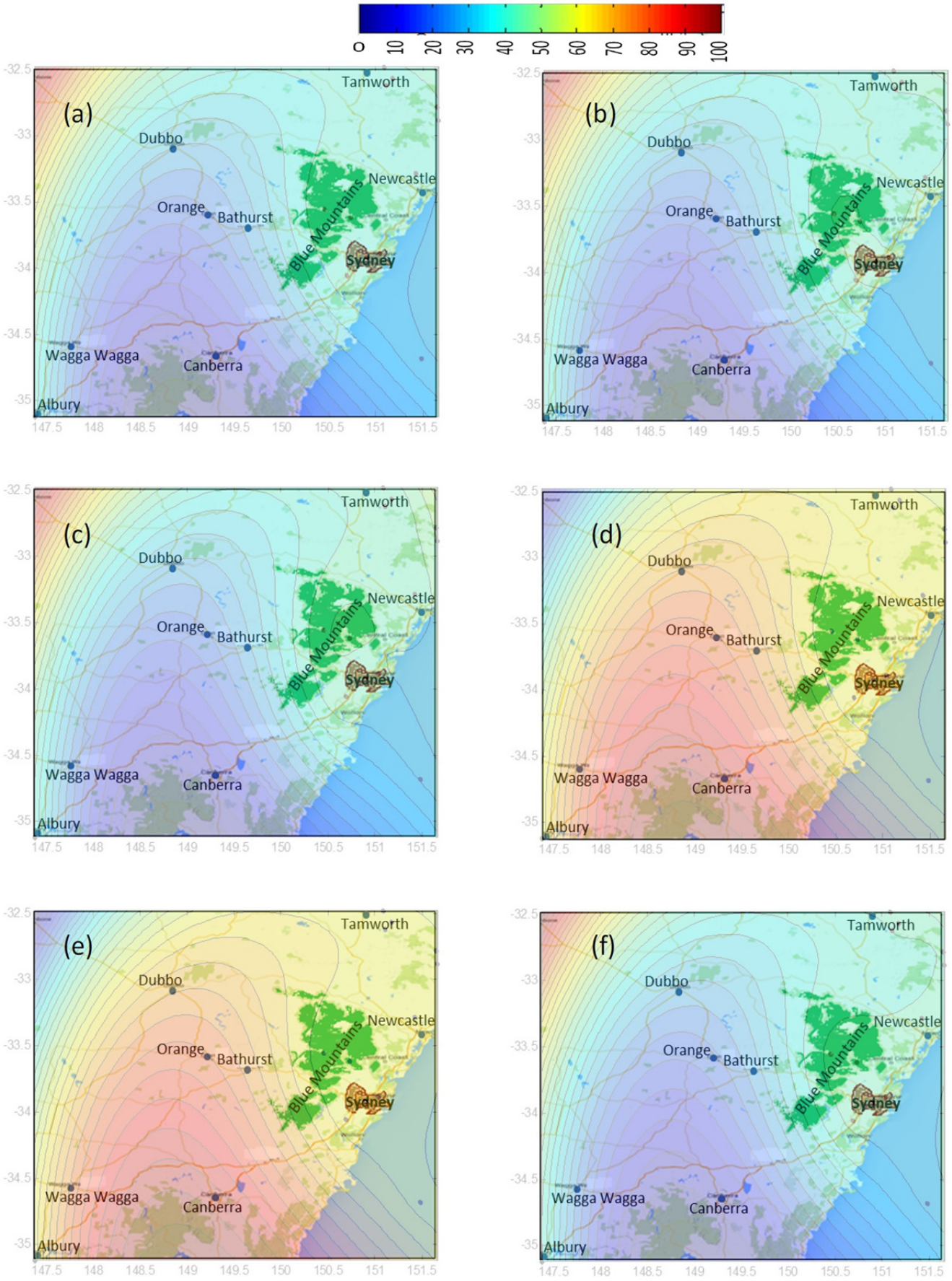

Fig. 4. Contours of $PM_{2.5}$ on day (a) 1, (b) 10, (c) 17, (d) 19, (e) 21, and (f) 31 of October (scale 0–100 μg m^{-3}).

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_x 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 1st, 10th, 17th, 19th, 21st and 30th 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_{10} 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_x 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_x. 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 (Grutzen and Andreae, 1990; Kirchhoff and Rasmussen, 1990; Tsutsumi *et al.*, 1999). SO_x had a negligible positive correlation with NO_x both before and after the fires. There was no correlation between ozone and SO_x. 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; Rodríguez *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

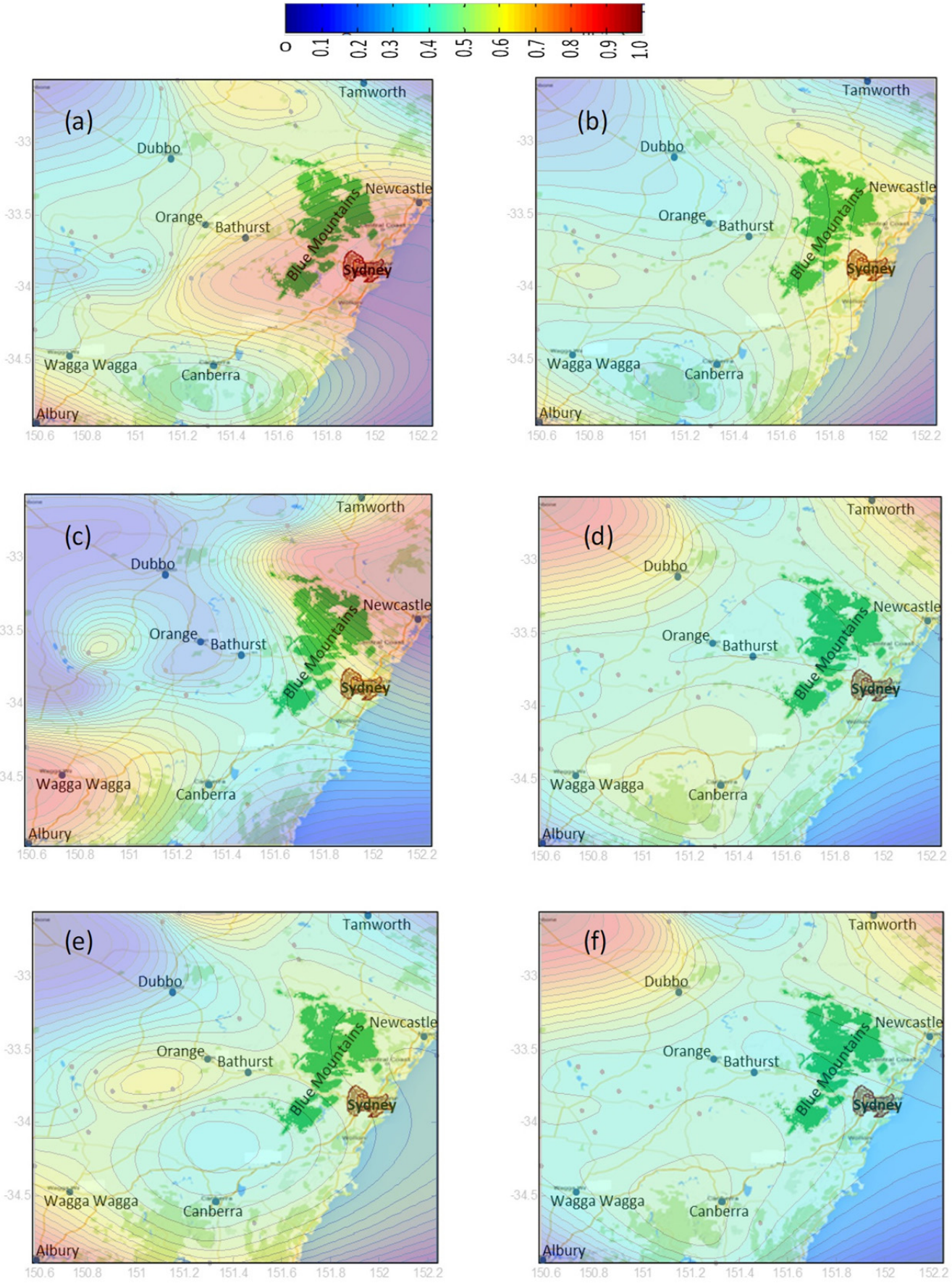

Fig. 5. Contours of SO_x on day (a) 1, (b) 10, (c) 17, (d) 19, (e) 21, and (f) 31 of October (scale 0–1 pphm).

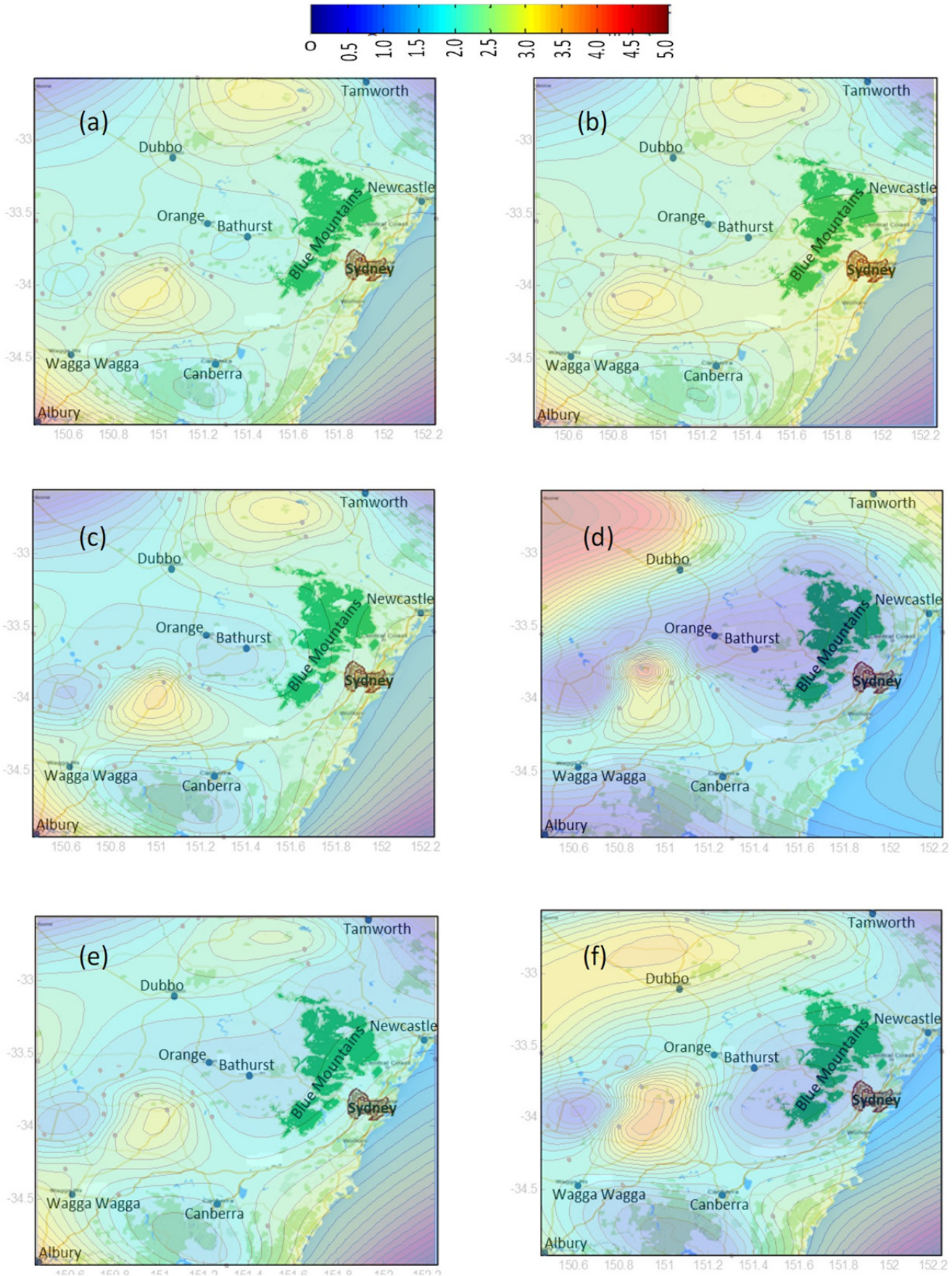

Fig. 6. Contours of NO_x on day (a) 1, (b) 10, (c) 17, (d) 19, (e) 21, and (f) 31 of October (scale 0–5.0 pphm).

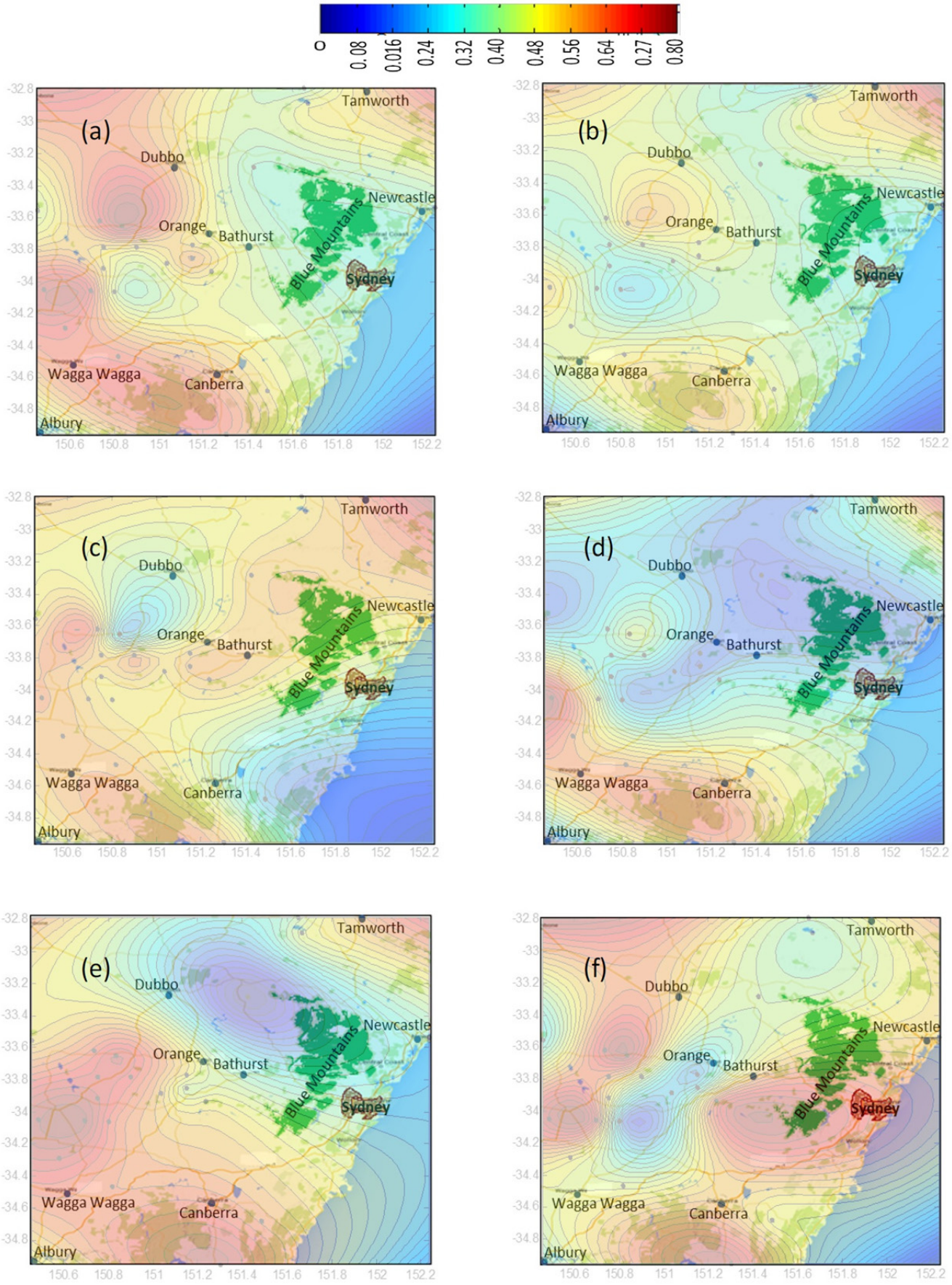

Fig. 7. Contours of O_3 on day (a) 1, (b) 10, (c) 17, (d) 19, (e) 21, and (f) 31 of October (scale 0–0.80 pphm).

Table 1. Pearson Correlation Coefficients (r) between pollutants (a) before (1–16 October) and (b) after (17–31 October) the fire.

	Before fire					After fire				
	NO_x	O_3	PM_{10}	$PM_{2.5}$	SO_x	NO_x	O_3	PM_{10}	$PM_{2.5}$	SO_x
NO_x	1.000					1.000				
Ozone	–0.790	1.000				–0.744	1.000			
PM_{10}	0.658	–0.656	1.000			0.004	0.116	1.000		
$PM_{2.5}$	0.566	–0.456	0.222	1.000		–0.381	0.613	0.377	1.000	
SO_x	0.305	–0.050	0.612	0.491	1.000	0.215	–0.078	0.021	–0.421	1.000

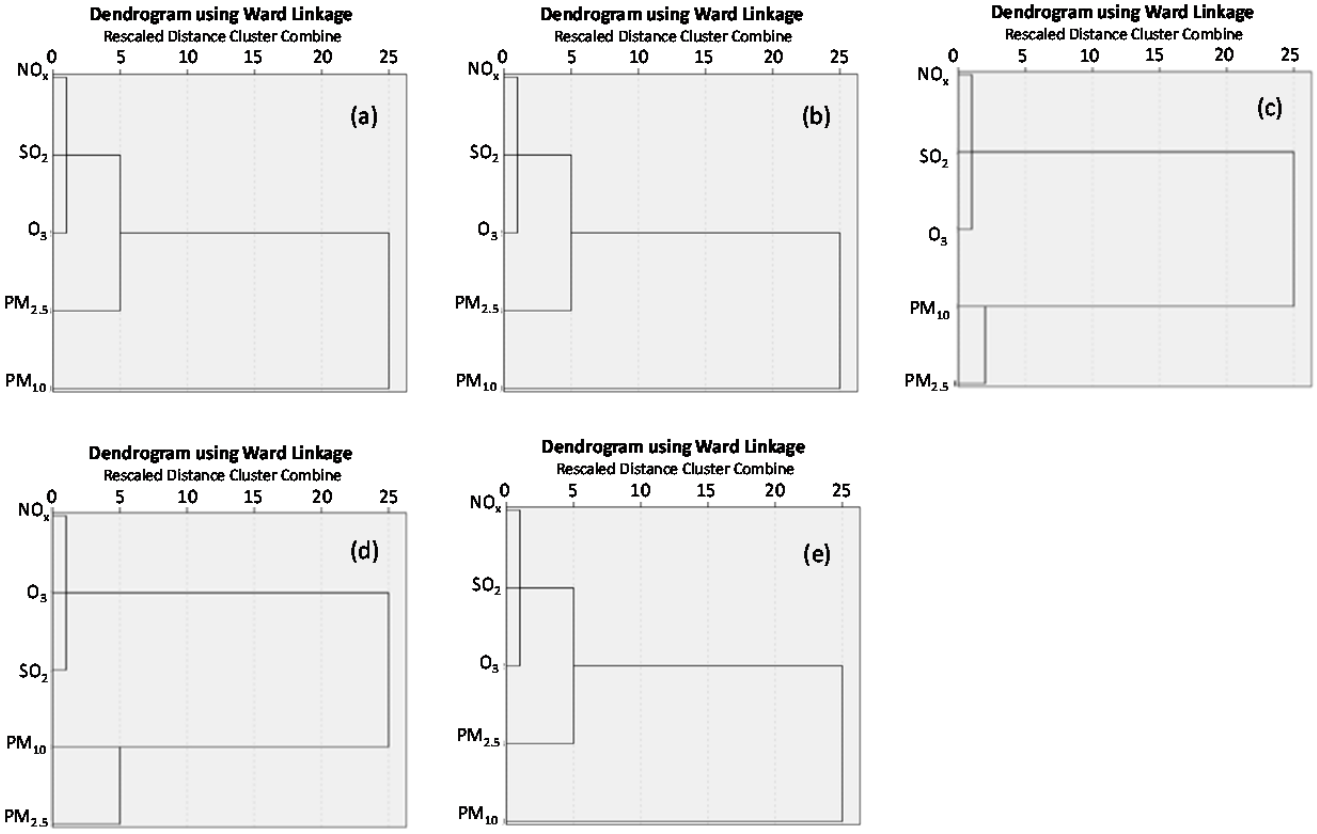

Fig. 8. Dendrogram diagrams for day (a) 1, (b) 10, (c) 19, (d) 21, and (e) 31of October 2013.

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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