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Technical Note

Real-Time Measurements of Ozone and UV Radiation during Pyrotechnic Displays

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ABSTRACT

Real-time measurements of ozone, NO_x, aerosols and radiation were performed very close to the launch area of high intensity pyrotechnic spectacles, the so-called *Mascletàs*, typical of celebrations in eastern Spain. During these events, a considerable number of spectators are potentially exposed to high concentrations of pollutants directly or indirectly produced by the ignition of thousands of firecrackers at ground-level. This work is focused on the mechanism of ozone formation throughout the *Mascletàs*. After the initial decrease in O_3 levels (minimum concentration < 10 μg m^{-3}) due to the reaction with NO emitted by fireworks explosions, peak concentrations of up to ~150 μg m^{-3} were recorded, clearly indicating that ozone was generated during these events. The results suggest that UV light produced by fireworks displays photolyzes O_2 releasing O to form O_3 as in the stratosphere.

Keywords: Ozone formation; Fireworks; UV radiation; People exposure; Correlation analysis.

INTRODUCTION

Several festivals worldwide are celebrated with pyrotechnic displays that are responsible for a significant increase in air pollutant concentrations. The burning of firecrackers and sparkles produces important amounts of particles (Moreno *et al.*, 2007; Vecchi *et al.*, 2008; Crespo *et al.*, 2012; Lin *et al.*, 2014) and gaseous pollutants, such as volatile organic compounds (Chang *et al.*, 2011; Nishanth *et al.*, 2012), sulfur dioxide (Moreno *et al.*, 2007; Croteau *et al.*, 2010; Chatterjee *et al.*, 2013), nitrogen oxides (Moreno *et al.*, 2007; Godri *et al.*, 2010) and ozone (Attri *et al.*, 2001; Nishanth *et al.*, 2012; Kavouras *et al.*, 2013; Yerramsetti *et al.*, 2013). Although the deterioration of air quality during this type of events has limited time duration (generally less than 24 h), the potential health impacts cannot be considered negligible (Godri *et al.*, 2010; Beig *et al.*, 2013), especially for ground-level displays because of the proximity of the people attending the performance (Croteau *et al.*, 2010).

Surface ozone is a secondary pollutant that can cause serious damage to human health, natural vegetation, crops and materials (Percy *et al.*, 2003; Screpanti *et al.*, 2009; Nuvolone *et al.*, 2013; Tomer *et al.*, 2015). Additionally, ozone acts as a potent greenhouse gas due to its light-absorbing properties (IPCC, 2007). Ground-level ozone is formed by chemical reactions of nitrogen oxides (NO_x) and volatile organic compounds (VOCs) in the presence of sunlight. The photolysis of NO_2 (λ < 420 nm) leads to the formation of atomic oxygen, which reacts rapidly with molecular oxygen to produce O_3 (Atkinson, 2000).

$$NO_2 + h\nu \rightarrow NO + O(^3P) \quad \text{(R1)}$$

$$O(^3P) + O_2 + M \rightarrow O_3 + M \ (M = O_2, N_2) \quad \text{(R2)}$$

In the absence of other pollutants O_3 reacts with NO, resulting in not net formation or loss of ozone.

$$NO + O_3 \rightarrow NO_2 + O_2 \quad \text{(R3)}$$

However, the chemical degradation of VOCs in the troposphere produces alkyl peroxy radicals (RO_2) and hydroperoxy radicals (HO_2) that can also convert NO to NO_2, which obviously results in net formation of O_3.

$$NO + RO_2 \rightarrow NO_2 + RO \quad \text{(R4)}$$

$$NO + HO_2 \rightarrow NO_2 + HO \quad \text{(R5)}$$

A few previous studies have reported the generation of O_3 in the absence of sun radiation attributed to fireworks displays. Typical components of fireworks include an

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oxidizer (generally potassium nitrate), a reducing agent or fuel (commonly sulfur and charcoal), a binder used to improve the cohesion of the ingredients, and coloring agents (metals or metal salts). When metals are heated at the very high temperatures reached during fireworks ignition, they emit radiation covering a wide spectral range, including visible and UV light (Steinhauser and Klapötke, 2008; Russell, 2009). Light emission during fireworks displays can account for night-time formation of ozone, even when NO_2 is not present (Attri *et al.*, 2001). However, mechanisms still remain uncertain. Attri *et al.* (2001) suggested that ozone is formed from the photolysis of molecular oxygen following a process equivalent to that occurring in the stratosphere.

Photodisociation of O_2 in the 176–242 nm range is the major source of stratospheric ozone (Parker, 2000):

$$O_2 + h\nu \rightarrow O(^3P) + O(^3P) \quad \text{(R6)}$$

$$O(^3P) + O_2 + M \rightarrow O_3 + M \ (M = O_2, N_2) \quad \text{(R2)}$$

According to Attri *et al.* (2001) a fraction of the light emitted by the bursts of sparkles has a wavelength below 240 nm and thus is sufficiently energetic to dissociate the oxygen molecule and produce the atomic oxygen required for ozone formation. Alternatively, Nishanth *et al.* (2012) ascribed the formation of O_3 to reactions R1 to R5 since (1) there was no UV light in the emission spectra of different sparkles and powders they examined and (2) a positive correlation between O_3 and NO_2 was found.

In the present work, O_3, NO, NO_2, aerosols and radiation were continuously monitored during high intensity pyrotechnic events, the so called *Mascletàs*, which take place every year during the *Hogueras de San Juan* Festival in the city of Alicante (southeastern Spain). The main objective of this work is to improve the understanding of the mechanism of ground-level ozone formation during such episodes.

METHODS

Monitoring Site

The Mascletàs are sonorous and visual pyrotechnic performances produced by the burst of thousands of firecrackers, principally at ground-level. These events take place every day at 2 pm from 19 to 24 June next to a downtown square of the city of Alicante (Fig. 1). A high number of spectators (around 20,000 people) gathers in the streets adjacent to the pyrotechnic venue and therefore are directly exposed to the pollutants produced throughout these events.

Measurements were made from a balcony (~15 m above ground level) of a building situated within the area where pyrotechnic devices were set off during the 2013 Alicante Festival (Fig. 1). It is important to indicate that the burst of firecrackers does not occur simultaneously in the entire area marked in Fig. 1. Moreover, the launch sequence of firecrackers varies from day to day, although the duration of each *Mascletà* is very similar (~9 minutes). For example, the event on 24 June can be divided in three stages of approximately three minute duration each one. The pyrotechnic spectacle began in the nearby square (zone A), in which aerial fireworks predominated. Then, firecrackers started being detonated, principally at ground-level, following the trajectory along the line from B to C. In the last stage, pyrotechnic explosions concentrated in zone C. Therefore, fireworks explosions are mobile sources relative to a fixed measurement location. A video of the *Mascletà* on 24 June is included in the Supplementary material. More information about the *Mascletàs* and the sampling location is given in Crespo *et al.* (2012).

Instrumentation

Ozone was monitored by UV absorption at $\lambda = 254$ nm using a 2B Technologies Inc. ozone analyzer, model 202. The instrument has 10-second measurement cycles with a dynamic range extending from a detection limit of 3.0 μg m^{-3} up to an upper limit of 1,000 μg m^{-3}. Data were registered every 10 seconds with a precision of 2%.

The measurements of NO_x were carried out using a SIR chemiluminiscence NO-NO_2-NO_x analyzer, model S-5012. This technique relies on the measurement of light (λ = 600–2400 nm) emitted by excited NO_2 produced by the gas-phase reaction of nitric oxide and ozone. The intensity of light generated in the reaction is proportional to the concentration of NO present in the sample. NO_2 is indirectly measured by reducing it to NO onto a heated catalyst. The analyzer normal measurement cycle is approximately of 24 seconds with a 0.8μg m^{-3} detection limit and a precision of 0.5%.

Particle number size distributions in 31 size channels from 0.25 μm to 32 μm were measured using a Grimm 1109 optical particle counter, and data were recorded every 10 seconds. The uncertainty in the measurements of particle number concentration with a Grimm optical counter is lower than 10% taking a Mobility Particle Size Spectrometer containing a Differential Mobility Analyzer (MPS-DMA) as a reference for the same particle range (Burkart *et al.*, 2010).

Radiation was measured every second with an AvaSpec-3648 fiber optic spectrometer with a scan range of 176–1100 nm and a bandwidth of 0.34 nm. The uncertainty in UV irradiance (200–240 nm) measurements is 10%.

The instruments were mounted on a platform and the monitor inlets were positioned facing the fireworks plume. Monitors started recording approximately 10 minutes before the beginning of the event, and recording continued for a further 5 minutes after it was finished.

RESULTS AND DISCUSSION

The amount of ozone detected at the monitoring site was dependent on the *Mascletà* design. Within the study period, ozone formation was recorded at the measurement point during the *Mascletàs* on 20 and 24 June. This work is mainly focused on the event on 24 June.

O_3 and Particles

Particles in the accumulation mode (0.1–1 μm) can be used as tracers of pyrotechnic activity (Wehner *et al.*, 2000;

Fig. 1. Location of the measurement site (indicated by a star) and the *Mascletà* area. A, B and C are related to the sequence of the Mascletà.

Nicolás *et al.*, 2009; Richard *et al.*, 2011; Crespo *et al.*, 2014). In the present work, we have selected the particle number concentration (PNC) in the 0.25–0.28 μm size channel as an indirect indicator of the arrival of the plume to the sampling site. Fig. 2 shows the variation in the concentrations of O_3 and particles between 0.25 and 0.28 μm during the *Mascletà* on 24 June 2013.

A sudden increase in aerosol concentration occurred just after the *Mascletà* started, accompanied by a rapid drop in ozone concentration from approximately 74 μg m^{-3} to less than 10 μg m^{-3}. During the whole event, which lasted approximately 9 minutes, an opposite variation in ozone and particle concentrations was found ($r = -0.69$, p-value < 0.05). This is likely due to the reaction between O_3 and NO, released along with particles from the combustion of fireworks, during the transport of the pyrotechnic plume to the measurement site. Additionally, calcium-rich particles resuspended during the displays (Crespo *et al.*, 2012) could catalyze the heterogeneous destruction of ozone in a similar way to that reported during Saharan dust intrusions (Bonasoni *et al.*, 2004; Nicolás *et al.*, 2014). So, although it is obvious from Fig. 2 that ozone was generated during the *Mascletà*, the net effect of this event was a reduction in O_3 concentrations, as can be deduced from the data presented in Table 1. Average, maximum and minimum values correspond to concentrations measured for the period of the *Mascletà*. Background levels were calculated as the average of concentrations measured during 10 minutes before the start of the *Mascletà*. It is important to highlight that these are not the usual concentrations registered at the sampling site since the streets nearby the pyrotechnic site are closed to vehicular traffic 6 hours before the beginning of the displays. Data presented in Table 1 also show a spectacular increase in the concentrations of submicron aerosols and NO. Nitrogen oxides produced during fireworks activity arise from transformation of nitrate components of black powder (Drewnick *et al.*, 2006). The increase in average NO concentration during the *Mascletà* is consistent with the observed reduction in mean O_3 concentration since a parallel increase in the levels of both pollutants is unfeasible.

O_3 and NO_x

Fig. 3 shows the variation in the concentrations of O_3, NO and NO_2 before, during and after the *Mascletà*. Abrupt changes in the concentrations of the measured species were observed throughout the event with a sharp decrease after the event was finished due to the quick dispersion of the pyrotechnic plume.

As mentioned before, at the beginning of the *Mascletà* O_3 was rapidly consumed by reaction with NO emitted by fireworks, resulting in the formation of NO_2 (reaction R3). However, the variation in ozone concentrations registered afterwards clearly indicates that ozone was generated throughout the event.

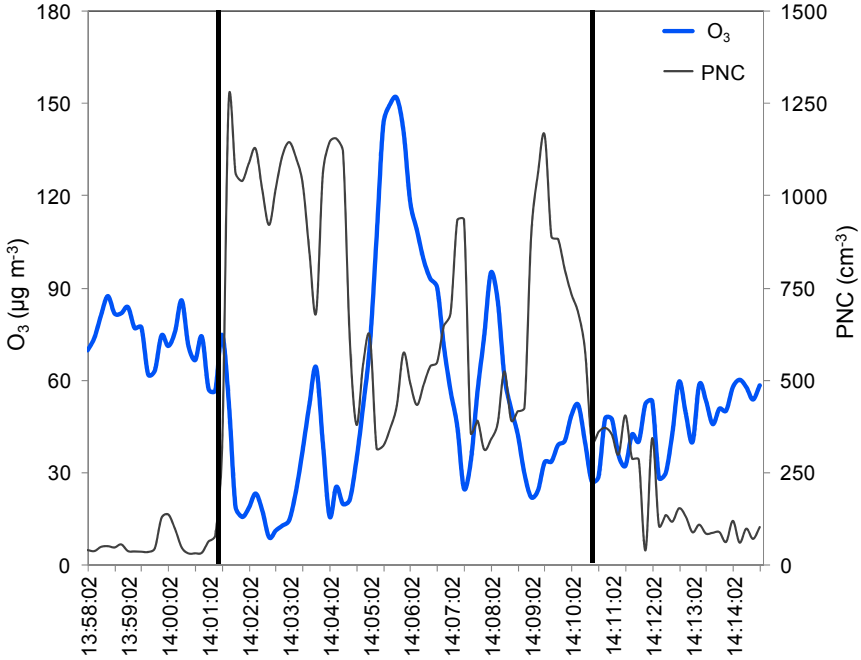

Fig. 2. Temporal variation of ozone and particle number concentrations (PNC) in the 0.25–0.28 µm size range during the *Mascletà* on 24 June 2013. Lines indicate the start and end of the pyrotechnic event.

Table 1. Concentrations of gaseous pollutants and particles (PNC) in the 0.25–0.28 µm size range before (background) and during the *Mascletà* on 24 June (average, maximum and minimum).

	O_3 (µg m^{-3})	PNC (cm^{-3})	NO (µg m^{-3})	NO_2 (µg m^{-3})
Background	74	39	1	7
Average	51	629	559	20
Max.	152	1261	1448	178
Min.	9	41	0	0

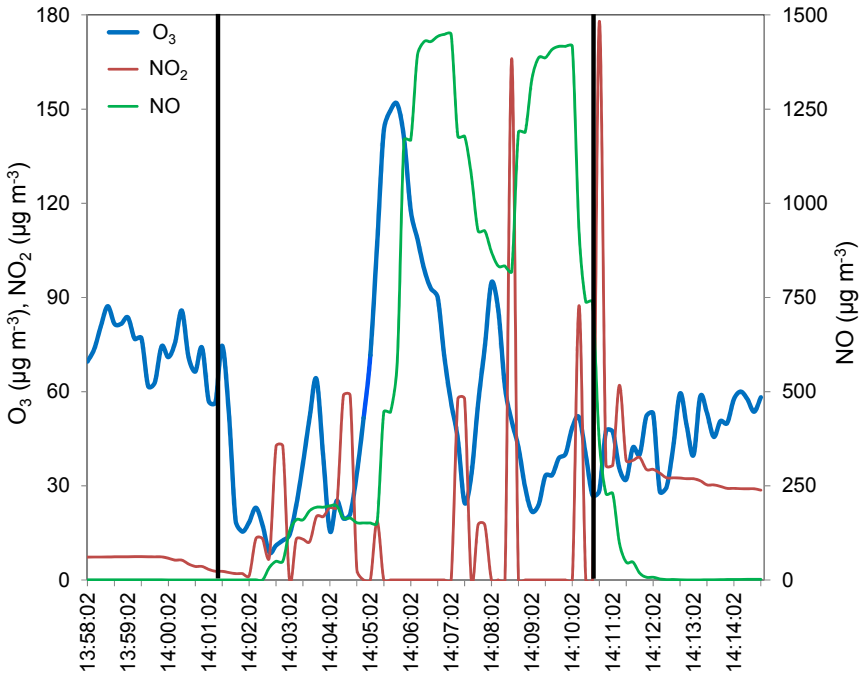

Fig. 3. Temporal evolution of ozone and nitrogen oxides concentrations during the pyrotechnic performance on 24 June 2013. Lines indicate the start and end of the pyrotechnic event.

The absolute maximum (152 μg m^{-3}) occurred approximately 4 minutes after the *Mascletà* started, and a secondary maximum (95 μg m^{-3}) appeared around 2.5 minutes later. Both maximums were followed by a significant reduction in O_3 concentrations concurrently with a remarkable increase in NO levels (up to ~1500 μg m^{-3}). Peak NO_2 concentrations occurred a little after maximums in NO. The most likely explanation for such a variation is that ozone was not formed from the reactions of NO_x and VOCs, and that once O_3 was generated, it reacted with NO emitted by the successive bursts of firecrackers to produce NO_2. In fact, the observed profile does not match with the typical diurnal pattern for ozone and NO_x in polluted urban areas (Xu *et al.*, 2011; Melkonyan and Kuttler, 2012; Hassan *et al.*, 2013).

Fig. 4 shows the diurnal variation in the concentrations of ozone and nitrogen oxides in Alicante during the days leading up to the Festival.

The morning peaks in concentrations of NO and NO_2 are related to NO emissions during the rush hour traffic and the immediate conversion of NO to NO_2 as a result of the reaction with VOCs. As solar radiation increases ozone begins to accumulate, reaching a maximum during the central hours of the day due to higher photochemical activity. NO emissions during the evening rush hour cause ozone removal and therefore concentration decreases. It can be observed that the maximum concentrations of O_3 and NO_x do not occur in the same order as in the *Mascletà* (see Fig. 3).

O_3 and UV Radiation

The obvious question that arises from the considerations above is: how is O_3 produced during these high intensity pyrotechnic displays? The most likely explanation is that atmospheric O_2 dissociates into atomic oxygen by absorption of UV light ($\lambda < 242$ nm) emitted during fireworks ignition. The subsequent combination of atomic and molecular oxygen enables ozone formation, as proposed by Attri *et al.* (2001).

In order to check that ozone was formed at ground level by reactions R6 and R2, it is required to confirm the emission of UV radiation during fireworks displays. The measurements made with the spectrophotometer corroborate that radiation containing the range of wavelengths capable of producing O_2 photodisociation was released throughout the *Mascletà*, as shown in Fig. 5. UV radiation intensity was integrated between 199.99 and 242.96 nm, then 4-second moving averages were calculated and normalized by the maximum value obtained.

The emission of UV radiation by the burst of pyrotechnic devices was observed during the whole event, although ozone formation was not always detected. The most important variables that influenced the detection of O_3 at the monitoring site were (1) the distance between the zone where fireworks explosions took place and the measurement point; and (2) the number of bursts per unit area, which could be called surface density of explosions.

At the beginning of the *Mascletà* (zone A, see section 2.1) a relatively low number of pyrotechnic explosions occurred far from the monitoring site. The observed reduction in the concentration of ozone could have been the result of the reaction between O_3 and NO emitted by fireworks during the transport of the plume to the monitoring site.

The principal maximum (zone B-C) was detected when a high number of fireworks explosions occurred very close to the sampling site (on the way from B to C). This outcome is consistent with the experiments by Attri *et al.* (2000) that showed a very good correlation between the quantity

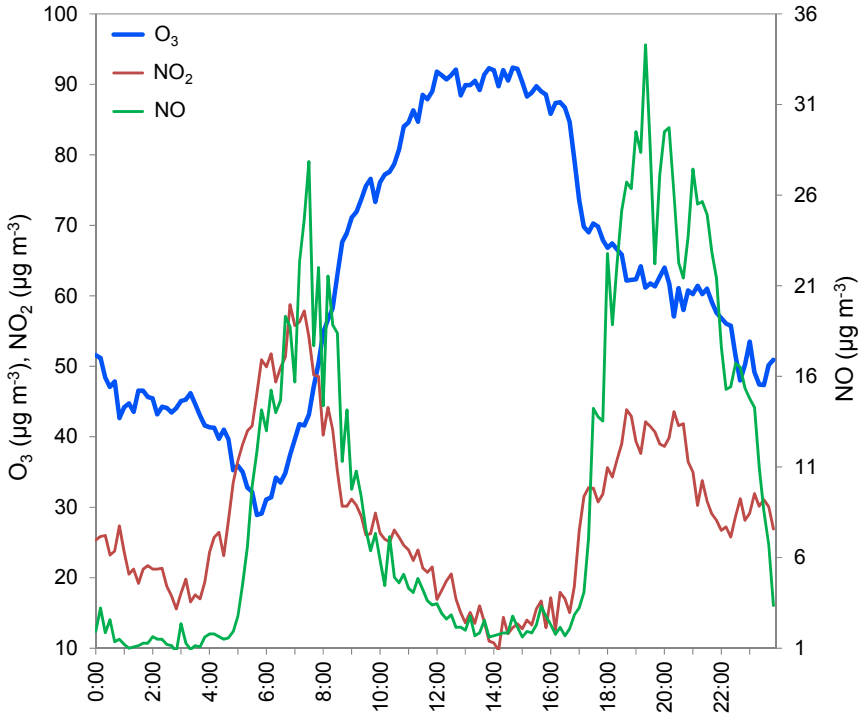

Fig. 4. Typical daily cycles of ozone and nitrogen oxides in Alicante during summer.

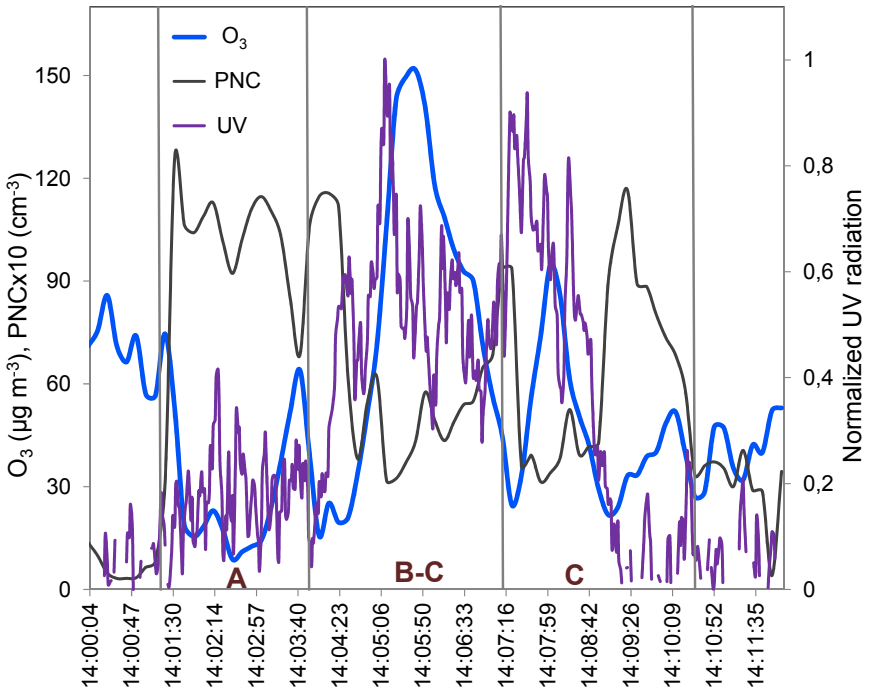

Fig. 5. Temporal variation of ozone, particle number concentrations (0.25–0.28 µm) and UV radiation during the pyrotechnic displays on 24 June 2013. The different areas marked in the figure correspond to the zones where fireworks are successively ignited (see section 2.1 and video in the Supplementary material).

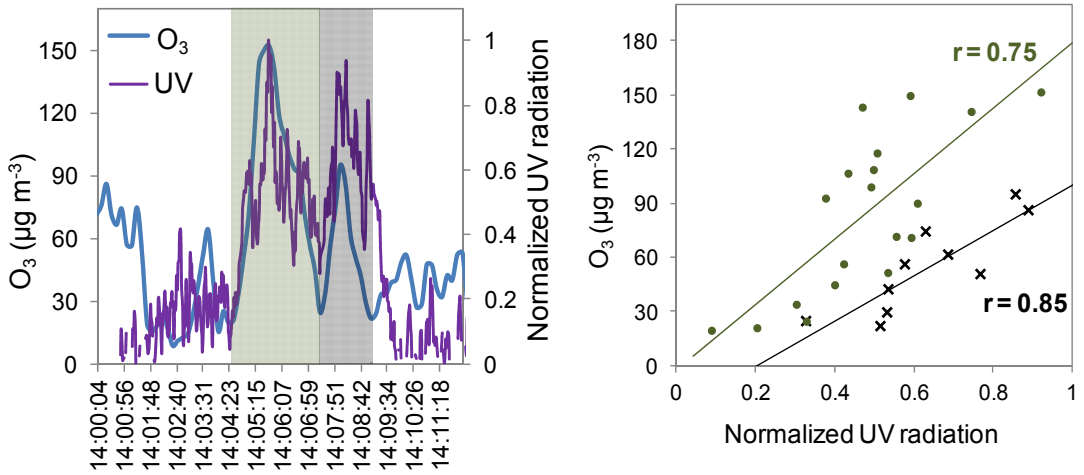

Fig. 6. (Left) Temporal variation of ozone and UV radiation during the pyrotechnic spectacle on 24 June 2013 after applying the time delay to UV radiation. (Right) Correlations of ozone with UV radiation for the intervals of the two maxima.

of O_3 formed and the amount of inflammable material present in sparkles. The ozone maximum was registered immediately after that of UV radiation, suggesting that O_3 was formed from the photodisociation of O_2. The subsequent decrease in O_3 concentrations was the result of the progressive displacement of pyrotechnic explosions away from the measurement point. A significant positive correlation between ozone concentration and UV radiation intensity (r = 0.75, p-value < 0.05, Fig. 6) was found for the interval corresponding to the principal maximum excluding the time delay (30 s). Time delay was calculated as the time difference between UV irradiance and O_3 concentration peaks. Then, O_3 concentrations were correlated with UV radiation intensity measured 30 seconds earlier.

In zone C a very high number of pyrotechnic explosions concentrated in a small surface area; however, the maximum O_3 concentration was lower than that registered at zone B-C since the distance from the measurement point was higher and a fraction of the O_3 generated by the photolysis of O_2 could have been consumed by reactions during the transport of the pyrotechnic plume. The correlation coefficient between ozone concentration and UV radiation intensity for the interval corresponding to this maximum was 0.85 (p-value < 0.05) excluding the time delay (Fig. 6).

Temporal variations in the concentrations of the measured pollutants over the *Mascletà* on 20 June were similar. Two maxima of ozone concentration and UV radiation intensity were also recorded. The correlation coefficients between both variables were 0.75 (p-value < 0.05) for the principal maximum and 0.80 (p-value < 0.05) for the secondary maximum.

CONCLUSIONS

During the summer festival held annually in Alicante (southeastern Spain), thousands of firecrackers are set off, primarily at ground level, in a short and intense pyrotechnic spectacle (*Mascletà*) launched every day at 2 pm in the city center. Ozone, nitrogen oxides, aerosols and radiation were continuously monitored throughout these events in 2013 with the purpose of elucidating the mechanism of O_3 formation associated to fireworks displays. Despite the fact that ozone average levels for the interval of the *Mascletà* (~9 min) were lower than those measured before the beginning of the event due to reaction with NO emitted by pyrotechnic explosions, peak O_3 concentrations of about 150 μg m^{-3} were observed. Our experimental data clearly suggest that ozone was unlikely formed from reactions involving nitrogen oxides. Instead, the photolysis of oxygen molecules by absorption of UV radiation emitted by firework displays, and the subsequent combination of atomic and molecular oxygen, is the most plausible mechanism to explain ozone formation. This reaction sequence corresponds to the process of ozone production in the stratosphere. The results that support the proposed mechanism are: (1) the temporal variation in the concentrations of O_3 and NO_x during pyrotechnic events was different from the usual daily cycles observed in the troposphere; (2) UV light in the range of wavelengths capable of producing the photolysis of O_2 was detected throughout the whole pyrotechnic spectacle; and (3) a significant positive correlation between ozone and UV irradiance was obtained for the intervals in which ozone concentrations were maxima.

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REFERENCES

Atkinson, R. (2000). Atmospheric Chemistry of VOCs and NO_x. *Atmos. Environ.* 34: 2063–2101.

Attri, A.K., Kumar, U. and Jain, V.K. (2001). Formation of Ozone by Fireworks. *Nature* 411: 1015.

Beig, G., Chate, D.M., Ghude, S.D., Ali, K., Satpute, T., Sahu, S.K., Parkhi, N. and Trimbake, H.K. (2013). Evaluating Population Exposure to Environmental Pollutants during Deepavali Fireworks Displays Using Air Quality Measurements of the SAFAR Network. *Chemosphere* 92: 116–124.

Bonasoni, P., Cristofanelli, P., Calzolari, F., Bonafè, U., Evangelisti, F., Stohl, A., Zauli Sajani, S., Van Dingenen, R., Colombo, T. and Balkanski, Y. (2004). Aerosol-ozone Correlations during Dust Transport Episodes. *Atmos. Chem. Phys.* 4: 1201–1215.

Burkart, J., Steiner, G., Reischl, G., Moshammer, H., Neuberger, M. and Hitzenberger, R. (2010). Characterizing the Performance of Two Optical Particle Counters (Grimm OPC 1.108 and OPC 1.109) under Urban Aerosol Conditions. *J. Aerosol Sci.* 41: 953–962.

Chang, S.C., Lin, T.H., Young, C.Y. and Lee, C.T. (2011). The Impact of Ground-level Fireworks (13 km Long) Display on the Air Quality during the Traditional Yanshui Lantern Festival in Taiwan. *Environ. Monit. Assess.* 172: 463–479.

Chatterjee, A., Sarkar, C., Adak, A., Mukherjee, U., Ghosh, S.K. and Raha, S. (2013). Ambient Air Quality during Diwali Festival over Kolkata – A Mega-City in India. *Aerosol Air Qual. Res.* 13: 1133–1144.

Crespo, J., Yubero, E., Nicolás, J.F., Lucarelli, F., Nava, S., Chiari, M. and Calzolai, J. (2012). High-time Resolution and Size-segregated Elemental Composition in High-intensity Pyrotechnic Exposures. *J. Hazard. Mater.* 241–242: 82–91.

Crespo, J., Yubero, E., Nicolás, J.F., Caballero, S. and Galindo, N. (2014). Time Evolution of Atmospheric Particle Number Concentration during High-intensity Pyrotechnic events. *Atmos. Environ.* 96: 20–26.

Croteau, G., Dills, R., Beaudreau, M. and Davis, M. (2010). Emission Factors and Exposures from Ground-level Pyrotechnics. *Atmos. Environ.* 44: 3295–3303.

Drewnick, F., Hings, S.S., Curtius, J., Eerdekens, G. and Williams, J. (2006). Measurement of Fine Particulate and Gas-phase Species during the New Year's Fireworks 2005 in Mainz, Germany. *Atmos. Environ.* 40: 4316–4327.

Godri, K.J., Green, D.C., Fuller, G.W., Dall'Osto, M., Beddows, D.C., Kelly, F.J., Harrison, R.M. and Mudway, I.S. (2010). Particulate Oxidative Burden Associated with Firework Activity. *Environ. Sci. Technol.* 44: 8295–8301.

Hassan, I.A., Basahi, J.M., Ismail, I.M. and Habeebullah, T.M. (2013). Spatial Distribution and Temporal Variation in Ambient Ozone and Its Associated NO_x in the Atmosphere of Jeddah City, Saudi Arabia. *Aerosol Air Qual. Res.* 13: 1712–1722.

IPCC: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (2007). Cambridge University Press, Cambridge. United Kingdom and New York, NY, USA.

Kavouras, I.G., DuBois, D.W., Etyemezian, V. and Nikolich, G. (2013). Spatiotemporal Variability of Ground-level Ozone and Influence of Smoke in Treasure Valley, Idaho. *Atmos. Res.* 124: 44–52.

Lin, C.C., Huang. K.L., Chen. H.L., Tsai. J.H., Chiu. Y.P., Lee. J.T. and Chen, S.J. (2014). Influences of Beehive Firework Displays on Ambient Fine Particles during the Lantern Festival in the YanShuei Area of Southern Taiwan. *Aerosol Air Qual. Res.* 14: 1998–2009.

Melkonyan, A. and Kuttler, W. (2012). Long-term analysis of NO, NO_2 and O_3 concentrations in North Rhine-Westphalia, Germany. *Atmos. Environ.* 60: 316–326.

Moreno, T., Querol, X., Alastuey, A., Minguillón, M.C., Pey, J., Rodríguez, S., Miró, J.V., Felis, C. and Gibbons, W. (2007). Recreational Atmospheric Pollution Episodes: Inhalable Metalliferous Particles from Firework Displays. *Atmos. Environ.* 41: 913–922.

Nicolás, J., Yubero, E., Galindo, N., Giménez, J., Castañer, R., Carratalá, A., Crespo, J. and Pastor, C. (2009). Characterization of Events by Aerosol Mass Size Distribution. *J. Environ. Monit.* 11: 394–399.

Nicolás, J.F., Crespo, J., Yubero, E., Soler, R., Carratalá, A. and Mantilla, E. (2014). Impacts on Particles and Ozone by Transport Processes Recorded at Urban and High-altitude Monitoring Stations. *Sci. Total Environ.* 446–447: 439–446.

Nishanth, T., Praseed, K.M., Rathnakaran, K., Satheesh Kumar, M.K., Ravi Krishna, R. and Valsaraj, K.T. (2012). Atmospheric Pollution in a Semi-urban, Coastal Region in India Following Festival Seasons. *Atmos. Environ.* 47: 295–306.

Nuvolone, D., Balzi, D., Pepe, P., Chini, M., Scala, D., Giovannini, F., Cipriani, F. and Barchielli, A. (2013) Ozone Short-term Exposure and Acute Coronary Events: A Multicities Study in Tuscany (Italy). *Environ. Res*. 126: 17–23.

Parker, D.H. (2000). Laser Photochemistry of Molecular Oxygen. *Acc. Chem. Res.* 33: 563–571.

Percy, K.E., Legge, A.H. and Krupa, S.V. (2003). Tropospheric Ozone: A Continuing Threat to Global Forests? *Dev. Environ. Sci.* 3: 85–118.

Richard, A., Gianini, M.F.D., Mohr, C., Furger, M., Bukowiecki, N., Minguillón, M.C., Lienemann, P., Flechsig, U., Appel, K., DeCarlo, P.F., Heringa, M.F., Chirico, R., Baltensperger, U. and Prévôt, A.S.H. (2011). Source Apportionment of Size and Time Resolved Trace Elements and Organic Aerosols from an Urban Courtyard Site in Switzerland. *Atmos. Chem. Phys.* 11: 8945–8963.

Russell, M.S. (2009). *The Chemistry of Fireworks*. The Royal Society of Chemistry. Cambridge, UK.

Screpanti, A. and De Marco, A, (2009). Corrosion on Cultural Heritage Buildings in Italy: A Role for Ozone? *Environ. Pollut.* 157: 1513–1520.

Steinhouser, G. and Klapötke, T.M. (2008). "Green" Pyrotechnics: A Chemists' Challenge. *Angew. Chem. Int. Ed.* 47: 3330–3347.

Tomer, R., Bhatia, A., Kumar, V., Kumar, A., Singh, R., Singh, B. and Singh, S.D. (2015). Impact of Elevated Ozone on Growth, Yield and Nutritional Quality of Two Wheat Species in Northern. *Aerosol Air Qual. Res.* 15: 329–340.

Vecchi, R., Bernardoni, V., Cricchio, D., D'Alessandro, A., Fermo, P., Lucarelli, F., Nava, S., Piazzalunga, A. and Valli, G. (2008). The Impact Of Fireworks On Airborne Particles. *Atmos. Environ.* 42: 1121–1132.

Wehner, B., Wiedensohler, A. and Heintzenberg, J. (2000). Submicrometer Aerosol Size Distributions and Mass Concentration of the Millennium Fireworks 2000 in Leipzig, Germany. *J. Aerosol Sci.* 31: 1489–1493.

Xu, J., Ma, J.Z., Zhang, X.L., Xu, X.B., Xu, X.F., Lin, W.L., Wang, Y., Meng, W. and Ma, Z.Q. (2011). Measurements of Ozone and Its Precursors in Beijing during Summertime: Impact of Urban plumes on Ozone Pollution in Downwind Rural Areas. *Atmos. Chem. Phys.* 11: 12241–12252.

Yerramsetti, V.S., Sharma, A.R., Navlur, N.G., Rapolu, V., Chitanya Dhulipala, N.S.K. and Sinha, P.R. (2013). The Impact Assessment of Diwali Fireworks Emissions on the Air Quality of a Tropical Urban Site, Hyderabad, India, during Three Consecutive Years. *Environ. Monit. Assess.* 185: 7309–7325.

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