Remember, remember the 5th ofNovember

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Remember, remember the 5th of November; gunpowder, particles and smog

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Abstract

In the UK on 5 November, Guy Fawkes Night is celebrated with bonfires and fireworks. An undesirable consequence of these activities is a statistically significant reduction (~25%) in atmospheric visibility nationwide. This reduction is caused by increased loading of atmospheric particulate matter generated by bonfires and fireworks. The effect of this increased loading on visibility is investigated in greater detail for the city of Nottingham where larger visibility decreases compared to the national average are observed. Visibility reduction is more significant when the background particulate matter loading and/or the atmospheric relative humidity are high.

Introduction

Fireworks are often used to celebrate festivals and special days, for example, Bastille Day, Independence Day, New Year's Eve, Diwali, Chinese New Year and large sporting events. Within the UK, the biggest fireworks event is Guy Fawkes Night which is celebrated around the 5 November every year. It commemorates the events of that day in the year 1605 when the Gunpowder Plot, involving the eponymous Mr Fawkes, failed to blow up the Houses of Parliament. Typically the celebrations involve both bonfires and fireworks (ground and air detonating). For public safety, the UK government has legislation surrounding the purchase and use of fireworks during the celebration period which limits the dates on which fireworks displays can occur.

While fireworks and bonfires have tremendous and enduring appeal, some of their effects are not always beneficial. Incorrect handling and use of fireworks can lead to injury (Vernon, 1988) and allergy (Becker *et al.,* 2000). They can be distracting through various human senses (sight, sound and smell). They can generate dense clouds of smoke in the lower atmosphere (Drewnick *et al.,* 2006) and are sources of pollution including gas phase species (e.g. sulphur dioxide, ozone, etc.) and particulate phase species including black carbon and metals (Ravindra *et al.,* 2003; Seidel and Birnbaum, 2015), some of which have negative associated health effects (Ravindra *et al.,* 2001). Within the UK, several studies have linked the use of fireworks with changes in air quality (Knox *et al.,* 2008; Godri *et al.,* 2010). Of particular interest to this study is the effect of the smoke on visibility. Reductions in visibility can deleteriously affect public safety, transportation, and tourism (Singh and Day, 2012). Over the past few years several studies have connected fireworks to visibility issues (for example, Wang *et al.,* 2007; Vecchi *et al.,* 2008; Saha *et al.,* 2014; Kong *et al.,* 2015). Local scale and short term pollution episodes can cause large decreases in visibility potentially with devastating consequences. For example, in 2011 a tragic incident occurred on the M5 motorway near Taunton, Somerset, where seven people died and 57 were injured due to a car crash. The resulting investigation found that a local fireworks display near the road might have contributed to the poor visibility on an already foggy night albeit no blame was assigned to the organizer of the fireworks event (Rose, 2014).

Particulate matter (PM) can scatter and absorb light, to an extent dependent upon its size and composition, and hence its introduction into the atmosphere (via fireworks, bonfires or any other source) can lead to reductions in visibility (Appel *et al.,* 1985). The ability of PM to scatter and absorb light is dependent upon the size and composition (refractive index) of the PM. Absorption increases with increasing PM mass. The amount of scattering for a given PM ensemble is much more finely tuned to the given particle size and composition distribution. In general, the closer the PM size matches with the wavelength of the light, the greater the scattering (Mie, 1908).

Nearly all atmospheric PM are hygroscopic to some degree, that is to say, their water content is dependent upon the local relative humidity. As relative humidity increases, so does the water content of the PM. This effect changes both the particle size and the average composition. For a given PM starting composition, its size will increase with increasing relative humidity, and its refractive index will be lowered because the refractive index of water is typically lower than the other common PM components (e.g. minerals, organics, sulphates, nitrates) (Harrison *et at.,* 2004).

Mathematically, visibility (V) can be represented as a function of the extinction coefficient (β_{ext}) via equation 1, where the constant k is equal to 3.912 which assumes a visibility contrast threshold of 2 % (Koschmeider, 1924).

$$V = \mathrm{k}/\beta_{ext} \tag{1}$$

The extinction coefficient is dependent upon both the scattering (sca) and absorption (abs) due to PM and gases ($\beta_{ext} = \beta_{gas,sca} + \beta_{gas,abs} + \beta_{PM,sca} + \beta_{PM,abs}$). Typically the contribution of PM to the extinction coefficient far outweighs the contribution of gases with the one possible exception being nitrogen dioxide (NO_2) which has a significant visible absorption coefficient (Groblicki *et al.,* 1981) and may be present with appreciable abundance. For PM with a given size distribution and composition the extinction coefficient is linearly dependent upon the PM number concentration, hence, visibility can be used as a metric of atmospheric pollutant levels.

In this paper we provide evidence for a significant reduction in visibility in the UK on the 5 November which is largely caused by the PM generated from the combination of fireworks and bonfires.

Data Collection and Methodology

Two distinct data series were generated for this paper: 1. UK average visibility maps for the dates of the 2 - 8 November inclusive, and 2. Average visibility time series for

Nottingham in the months of October and November. Due to limited availability of visibility stations which co-located with pollution sensors and limited data-sets, Nottingham has been selected. The visibility maps allow for the detection of regional changes in visibility associated with Guy Fawkes Night, while the longer time series of the Nottingham data allows for the attribution of the change in visibility on Guy Fawkes Night to the change in atmospheric composition.

The hourly values of horizontal visibility (maximum visible distance along a horizontal line at the earth's surface) and relative humidity data were obtained from the British Atmospheric Data Centre (BADC), (www.badc.nerc.ac.uk), for 34 stations situated throughout the United Kingdom. For the locations of the stations see Figure 1.

Daily mean pollutant data were obtained for a city centre location in Nottingham. In particular, data for the gas phase species nitrogen dioxide (NO_2) and sulphur dioxide (SO_2) were obtained in addition to three PM metrics: PM with diameter less than 10 µm (PM_{10}), PM with diameter less than 2.5 µm ($PM_{2.5}$), and black carbon (BC) PM. These data were obtained from the DEFRA Automatic Urban and Rural Monitoring Network (AURN) (http://uk-air.defra.gov.uk/).

Both the meteorological and pollutant data sets were obtained for a 13 year period encompassing the years 2000-2012. The length of the time period investigated was constrained by the availability of the AURN data. The $PM_{2.5}$ data are only available for the period 2009-2012. As official fireworks displays typically start after 1900 h, we selected visibility and humidity data-set for 2100 h for study. Whilst many fireworks displays occur on the 5 November not all do; often official displays will be performed on the weekend preceding or subsequent to the 5. Within our 13 year data set, the number of days that November the 5 fell on a given day of the week was: Monday (3), Tuesday (1), Wednesday (2), Thursday (1), Friday (2), Saturday (2) and Sunday (2).

The available visibility data network is not sufficiently dense to allow for the visibility mapping of the whole of the UK. The maps were produced by assuming that the measurement at each station was reliable until the distance exceeded 32 km, which represents a typical upper limit to visibility for the UK measured in November (albeit not for Guy Fawkes Night). Where two measurements overlap, the visibility is approximated by inverse distance weighting interpolation of the multiple measurements. This approach necessarily assumes that visibility is homogenous within the area defined by the visibility measurement; in reality, visibility is affected by local orography and other effects and can be highly heterogeneous. Data manipulation was carried out using R software, where ggplot tool has been used for spatial mapping. The meteorology and pollution data were analysed using Matlab (2014a) software.

Results and Discussion

The change in the UK visibility over Guy Fawkes Night and the surrounding days is shown in Figure 1. The spatial trend analysis is presented using 34 stations with 0.29^{o} x 0.29^{o} distance resolution. This is a latitude equivalent to 32 km and a longitude equivalent to 20.3 km. 32 km represents a typical upper limit value for visibility in the UK in November. In Figure 1, a dramatic dip in visibility can clearly be seen for November 5 compared with preceding and subsequent days. The average visibilities observed at the 34 stations on the 2, 3, 4, 5, 6, 7, and 8 November are 20.0±4.6, 17.8±4.0, 17.6±5.1, 14.8±5.2, 16.9±4.4, 18.3±3.8 and 20.5±4.1 km respectively, with a mean reduction of ~25% on 5 November compared with other days (2, 3, 4, 6, 7, and 8 November). It can be seen that the 6 November has the next lowest visibility after the 5 which may be due to higher atmospheric PM loading persisting following Guy Fawkes on the preceding night. The effect of the fireworks on visibility is observed at all sites. Typically, urban locations show the greatest visibility loss. 82% of the UK population lives within urban locations (http://data.worldbank.org) and hence poor visibility in these regions has greater potential for disruption.

To better understand the change in visibility caused by Guy Fawkes Night, we investigate the 13 year average 2100 h visibility values for a single site (Nottingham-Watnall, SYNOP code number = 3354, station source ID = 556) for the months of October and November. Again there is a clear dip in visibility occurring on the 5 November showing the effect of Guy Fawkes Night (a reduction of more than 55% compares to the 2, 3, 4, 6, 7, and 8 November). Investigation of the 24 hourly data over Nottingham also indicates that visibility starts decreasing from 1900 h on the 5

November and is stable after 0100 h on the 6 November, due to changes in the loading of firework-derived PM.

This Guy Fawkes driven dip in visibility becomes even more pronounced when the effect of relative humidity is taken into account. The daily relative humidity (measured at 2100 h) shows the expected seasonal increase as the date progresses from the start of October to the end of November, see Figure 2 panel (a). The relative humidity increases from ~85 to 90 % over the course of the two months, with significant variability. Whilst this represents only a modest increase in relative humidity, such a change of 5 % in this region of a PM hygroscopicity growth curve can be significant (e.g. Pope *et al.,* 2010). As discussed in the introduction, as relative humidity increases so does particle water content with the corresponding changes in size, composition, refractive index and hence extinction coefficient. Since the composition and size distribution of the PM is unknown, the effect of relative humidity cannot be explicitly calculated but a simple correlation curve between visibility and relative humidity can be generated. The relationship between visibility and relative humidity (RH) can be reasonably approximated using a linear relationship, $V = m \times RH + c$, where the constants m and c are best described by -1.19 % and 119.42 km, respectively, with a R^2 value of 0.60. This approach assumes that the non-water component of the PM loading, composition and size stays constant over the time period analysed, clearly this necessitates the exclusion of the data from Guy Fawkes Night.

Using the relationship between visibility and relative humidity, the visibility anticipated for the 5 November in the absence of Guy Fawkes Night can be predicted, see Figure 2 panel (b). It is discernible that the predicted visibility shows reasonable agreement with the observed visibility except on the 5 Nov. Panel (c) in Figure 2 shows the difference between observed visibility and predicted visibility and the effect of Guy Fawkes Night on visibility is even more apparent. This analysis suggests that Guy Fawkes Night in Nottingham reduces visibility by approximately 10 km which corresponds to a 64% reduction in visibility. This reduction in visibility is highly significant as it lies below four standard deviations (± 8.88 km) of the average visibility, see figure 2 panel (c).

The change in visibility due to Guy Fawkes Night is compared with atmospheric pollutant concentrations in Figure 3. There are clear spikes in the $PM_{2.5}$, PM_{10} and black carbon PM matter on Guy Fawkes Night which suggest that these pollutants are, at least in part, responsible for the reduction in visibility for this night. $PM_{2.5}$, PM_{10} and black carbon PM concentrations were ~253%, ~62% and ~201% greater, respectively. It is emphasized again that the $PM_{2.5}$, data set only contains 4 years of data whereas the PM_{10}, black carbon and visibility data sets encompass 13 years. The corresponding reduction in visibility for the time period of the $PM_{2.5}$ measurements is 63%. The $PM_{2.5}$, data are noisier compared with the other data streams. This is due to shorter measurement period which introduces more statistical noise in addition to a greater 'day of the week' effect on the average data. Over longer averaging periods, the likelihood of the 5 November falling preferentially on specific days of the week becomes less likely. The data suggest that the average concentration of $PM_{2.5}$ was higher on both 5 (31.25 μg m^{-3}) and 6 November (38.75 μg m^{-3}) compared with rest of the investigated dates, see Figure 3, panel d. In 2010 there was an exceptionally large signal on the 6 November (Saturday) which explains the Guy Fawkes Night $PM_{2.5}$ peak occurring on both the 5 and 6 November.

The influence of NO_2 on visibility was also investigated. The NO_2 concentration did not show any significant change over the Guy Fawkes Night period. Hence none of the visibility loss can be ascribed to gas phase absorption of light. Likewise gas phase scattering will not be affected by Guy Fawkes Night. Therefore the change in the extinction coefficient over the celebration period must be due to changes in PM absorption and scattering. This is expected because the contribution of gases to the extinction coefficient is typically negligible except in pristine conditions or conditions with exceptionally high NO_2.

The most significant component of PM that absorbs light is black carbon. The incremental loading of black carbon on Guy Fawkes night can be directly converted into an PM absorption coefficient ($\beta_{PM,abs}$) through use of the recommended value of the mass normalized absorption coefficient (σ), 7.5 m^2 g^{-1} (Bond and Bergstrom, 2006) and equation 2, where BC is the black carbon mass concentration (g m^{-3}).

$$\beta_{PM,abs} = \sigma \times BC \quad (2)$$

The average observed visibility for Guy Fawkes Night (2000-2012) is 5.1 km and the predicted visibility in the absence of celebrations is 14.8 km which correspond to extinction coefficients of 0.77 and 0.26 km^{-1}, respectively. The average black carbon concentration on Guy Fawkes Night was 6.04μgm^{-3}. The average non Guy Fawkes Night background black carbon concentration was 2.00μgm^{-3}. The corresponding average PM absorption coefficients for Guy Fawkes Night and non-Guy Fawkes Night period are 0.045 and 0.015 km^{-1}, respectively. Hence the PM absorption coefficient only accounts for 5.9 and 5.8 % of the total extinction coefficient for the two different time periods. Even though the absolute loadings are very different on Guy Fawkes Night compared with the normal background conditions, the percentage contribution of black carbon to total visibility reduction is largely independent of Guy Fawkes Night which is surprising.

In contrast to the PM absorption coefficient, it is more difficult to estimate the enhancement in the PM scattering coefficient ($\beta_{PM,sca}$) due to Guy Fawkes Night, because key parameters are unknown, including the distribution in the particle size and composition and how these differ from the background PM. Nevertheless the increment in $PM_{2.5}$ loading over the Guy Fawkes Night period can be used to estimate the effect if several assumptions are made: 1) the distributions of aerosol size and composition are the same as the background PM; 2) the only difference between the PM distributions is the number concentration of PM, i.e. Guy Fawkes Night introduces an additional source of PM which has identical properties to the background aerosol; 3) $PM_{2.5}$ is a good proxy for light scattering PM which are largely sub-micron in size; 4) the component of the extinction coefficient due to gas phase species is negligible. With these assumptions the scattering coefficient can be calculated through knowledge of the extinction and absorption coefficients using equation 3.

$$\beta_{PM,sca} = \beta_{ext} - \beta_{PM,abs} \quad (3)$$

The validity of these assumptions can be tested by comparing the scaling constant (k) required to convert the $PM_{2.5}$ concentration into a scattering coefficient, i.e. $\beta_{PM,sca} = \delta \times PM_{2.5}$. The calculated scattering coefficients for Guy Fawkes Night and non-Guy Fawkes Night period are 0.67 and 0.25 km^{-1}. The corresponding values for δ are 0.021 and 0.020 m^3 μg^{-1} km^{-1}. Given the assumptions used in deriving the scattering coefficients, the two derived values of δ are in remarkably good agreement. The contribution of the scattering coefficient to the total extinction coefficient for Guy Fawkes Night and non-Guy Fawkes Night is 94.4 and 96.1 %.

In addition to visibility altering pollutants, the gas phase concentration of SO_2 was also investigated. No significant changes in SO_2 were observed over the celebration period. Therefore for the site investigated, SO_2 is not a good chemical marker for Guy Fawkes Night. This is surprising since enhanced SO_2 has previously been associated with fireworks (Ravindra *et al.,* 2003).

Conclusions

In the present study, the role and influence of firework and bonfire emissions on visibility and short term air quality has been quantified. Although Guy Fawkes Night only occurs once a year, the associated celebrations occur over a wider time range (on the order of a week). Using data from 34 meteorological stations, sharp reductions in nationwide visibility were clearly observed on Guy Fawkes Night. However, the effect is short-lived, with average visibility returning to normal within two days due to the dispersal of the additional PM loading. More detailed analysis on the data from a single urban area (Nottingham) showed that the effect of Guy Fawkes Night is even more pronounced when the effect of relative humidity, through its influence on the extinction coefficient of PM, is taken into account.

The reduction in visibility on Guy Fawkes Night is caused by increases in atmospheric PM loading which is generated through bonfires and fireworks. In particular there is clear anti-correlation between the $PM_{2.5}$, PM_{10} and black carbon PM with the observed visibility. It is interesting to note that as the UK becomes ever more multicultural, we might expect the frequency and magnitude of festivals/celebrations that use fireworks to increase with corresponding visibility reduction hotspots.

The data and analysis shown above, indicates that the public should be made aware of the possibility of low visibility on Guy Fawkes Night which can be very localized. In particular, care should be taken when relative humidity is predicted to be high and the atmosphere already has a high PM loadings. Since fireworks displays are planned months in advance, weather and pollution forecasts of sufficient skill are unavailable to help in their planning. However, if forecasts subsequently suggest that the planned display will coincide with conditions likely to exacerbate poor visibility then the organizers and local authorities should be prepared to issue poor visibility warnings in advance. This precautionary step can help to increase enjoyment, or at least prevent unnecessary accidents, during Guy Fawkes Night which is a much loved and highly anticipated celebration.

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Figures

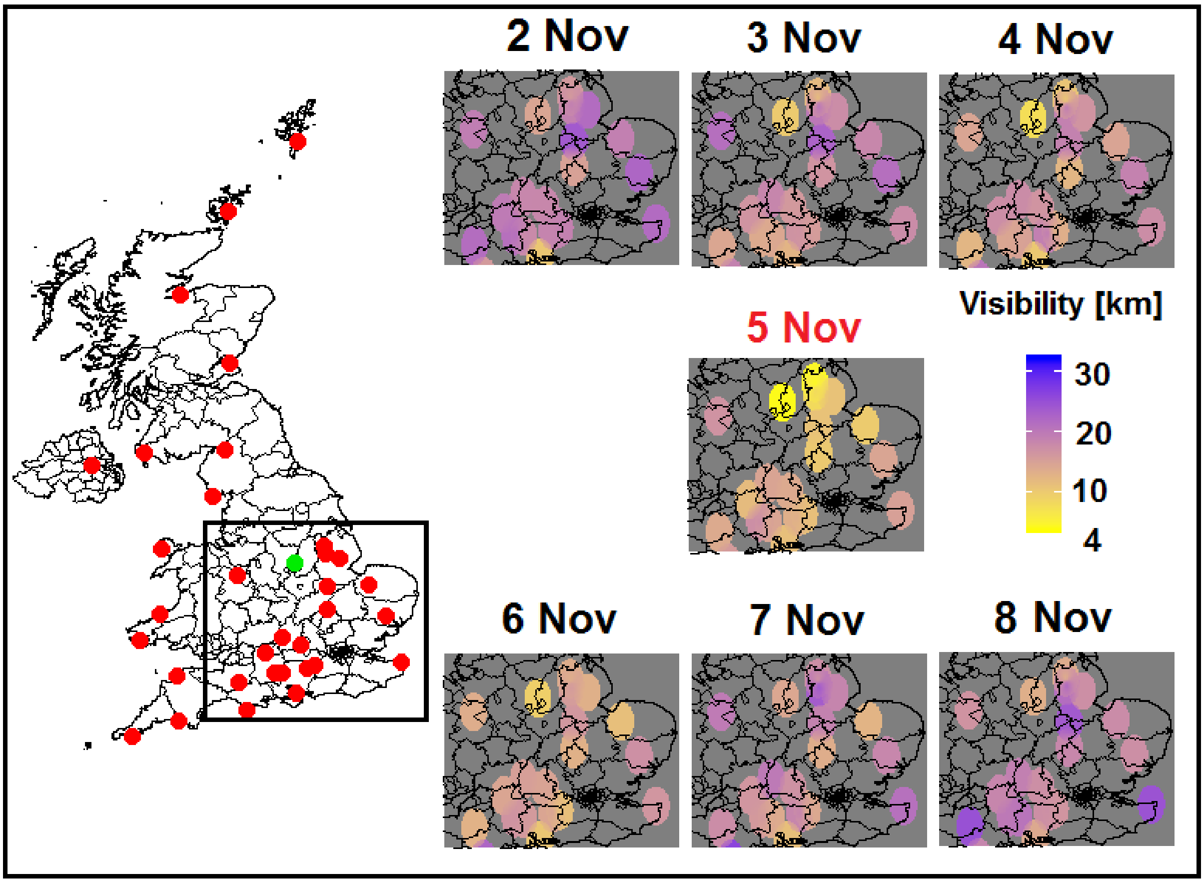

Figure 1 Visibility mapping of the UK before (2, 3, and 4 Nov), during (5 Nov), and after (6, 7 and 8 Nov) the Guy Fawkes Night using 13 years (2000-2012) data. The filled circles in the UK map represent the available meteorological stations (=34) measuring visibility. The green coloured circle represents the Watnall station (Nottingham). The meteorological stations (=20) used for the spatial mapping are indicated within the black box. The scale bar provides the visibility range.

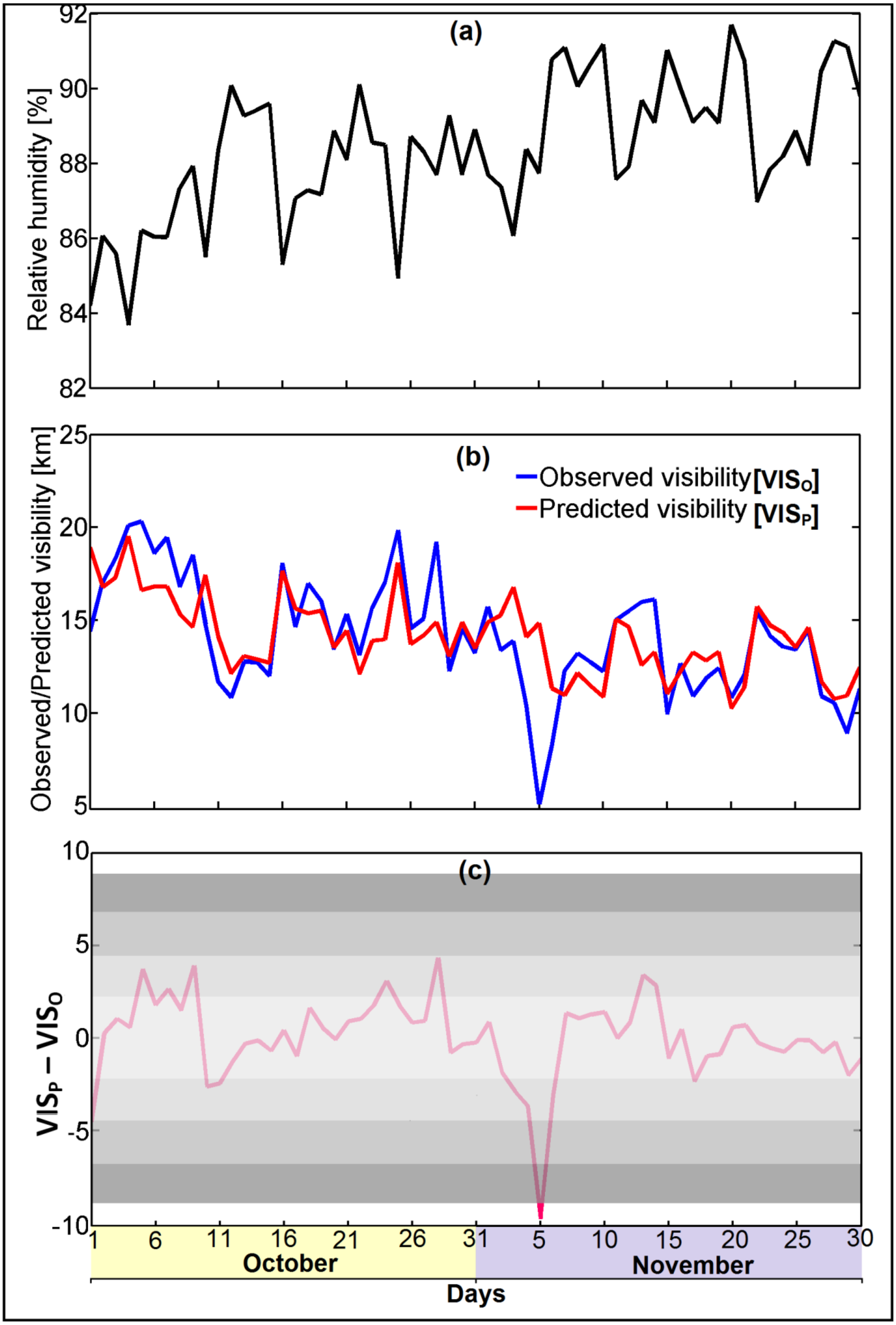
(a)
Relative humidity [%]
92
90
88
86
84
82
(b)
Observed/Predicted visibility [km]
Observed visibility [VISO]
Predicted visibility [VISP]
25
20
15
10
5
(c)
VISP – VISO
10
5
0
-5
-10
1 6 11 16 21 26 31 5 10 15 20 25 30
October
November
Days

Figure 2 Dependency of relative humidity on visibility with 13 years (2000-1012) data-set, where panel **a)** Average relative humidity **b)** Comparison of observed (VIS_O) and predicted visibility (VIS_P) **and c)** Difference between observed and predicted visibility, where grey shading strata represent standard deviations (σ) from the mean. Lightest grey = 1σ and darkest grey = 4σ.

1

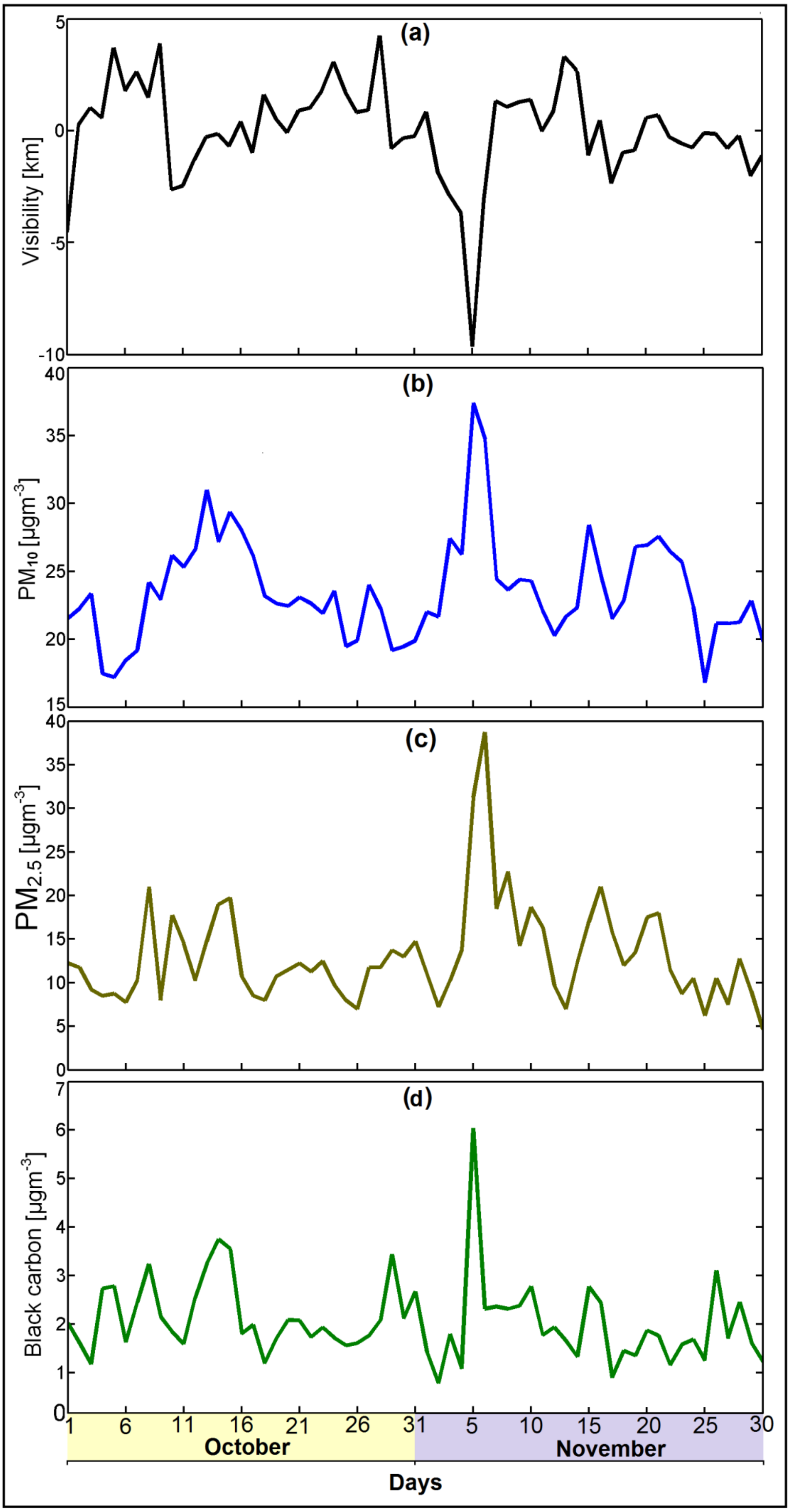
(a)
Visibility [km]
(b)
PM10 [µgm-3]
(c)
PM2.5 [µgm-3]
(d)
Black carbon [µgm-3]
1
6
11
16
21
26
31
5
10
15
20
25
30
October
November
Days

Figure 3 Comparison of pollutant concentrations with visibility measurement (predicted – observed). The visibility, PM_{10} and black carbon data sets represent 13 year averages (2000-2012), whereas the $PM_{2.5}$ data set represents a 4 year average (2009-2012).

Definitions of technical terms

Absorption coefficient – Parameter expressing the ability of PM to absorb radiation.

Contrast threshold- Smallest difference that the eye can discern between two different stimuli.

Extinction coefficient – Sum of the light scattering and absorption coefficient.

Inverse distance weighting interpolation - A mathematical technique used to estimate the visibility at locations laying between two different measurement locations.

Mass normalized absorption coefficient – Ratio of absorption coefficient to mass concentration of the absorbing material.

Scattering coefficient – Parameter expressing the ability of PM to scatter radiation.