Sensor measurements and large-eddy simulation of point source plumes over a complex urban terrain

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1 INTRODUCTION

The deliberate or accidental release of toxic chemicals in a city can create a threat to public health [1], and therefore the understanding of the dispersion of pollutants through a city is important. A vehicle fire in Bristol, UK, has provided a real example measurement of pollutant dispersion [2,3]. Bristol City Council and University of Bristol measurement sites have seen an elevation of toxic metals, PM_{10} and CO after the vehicle fire.

2 MATERIALS AND METHODS

2.1 Incident and Measurement Site Locations

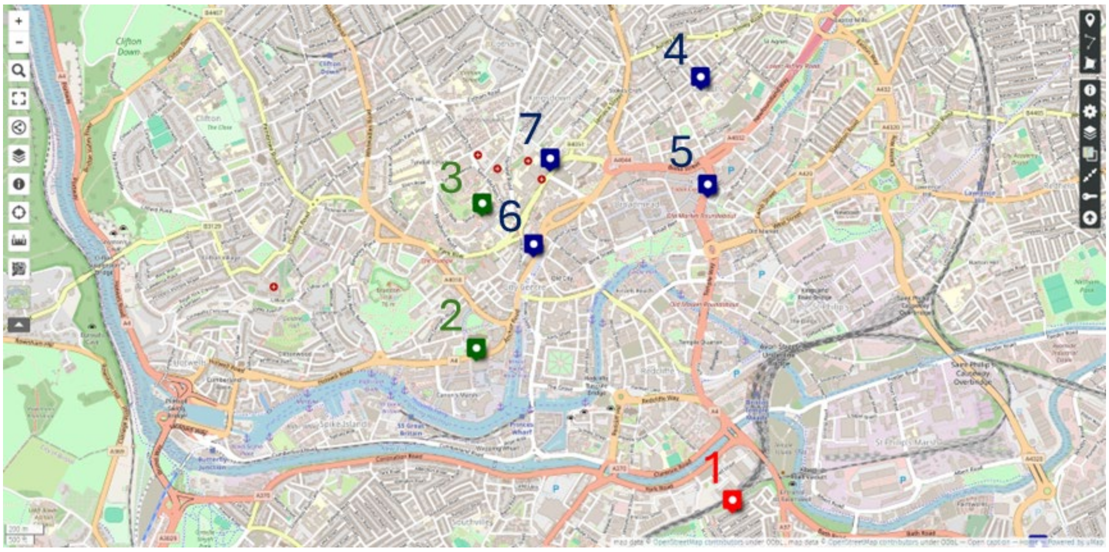

Figure 1, Map of Bristol indicating the position of (1) the car fire (2) the We The Curious measurement position (3) the Biomedical Sciences Rooftop anemometer and (4) the DEFRA AURN Air quality site at St Pauls and (5,6,7) the Bristol City Council air quality stations at Temple Way, Colston Avenue and Marlborough Street respectively. Map generated by OpenStreetmap using uMap © Openstreemap Contributors https://www.openstreetmap.org/copyright.

A vehicle was set alight in Totterdown, Bristol, on 13th January 2022 at 08:45 in the evening (all times UT) with the fire spreading to three other vehicles but extinguished by firefighters that evening [2,3]. The vehicle location was on a domestic street on top of a hill in a residential area (51.441684, -2.570497). Throughout 2021 and into January 2022, metals were sampled onto a quartz filter using a Sven Leckel LVS3 aerosol sampler in a 24-hour sample once a week at the We The Curious science museum (51.450487, -2.600856). The fire increased the level of pollutants measured in the PM_{10} sample; metals including lead, cadmium and chromium increased more than two standard deviations above the previous yearly average [4].

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2.2 Pollutant and Meteorological Measurements

Throughout 2021 and early 2022, a measurement site was set up at We The Curious, Bristol, that recorded CO using a Thermo Scientific 48i TLE , and meteorology using a Gill Maximet throughout the period, with O_3 (Thermo Scientific 49i) added later in the year. Air samples were drawn from an inlet on a first floor balcony and sampled at 1 s intervals, later averaged to 1 hour. Zero checks were made every two hours and span measurements made monthly.

Bristol City Council have several air quality sites that measure NO_x and selected other pollutants. Within our study area, there is one Automatic Urban Monitoring Network site controlled by the UK government Department of Food and Rural Affairs (DEFRA) at St Pauls (51.462839, -2.5844834) [5] which measured O_3, NO_x, PM_{10} and $PM_{2.5}$. Three other sites are run directly by Bristol City Council at Temple Way (51.457968, -2.583975), Colston Avenue (51.455269, -2.5966489) and Marlborough Street (51.459142, -2.5954328) [6].

Wind measurements were made by a Gill GMX501 on the roof of the We The Curious science museum at 1 s sampling intervals, and on the roof of the Biomedical Sciences Building within the University of Bristol using a Gill Windmaster 3d sonic anemometer, measuring at 20 Hz and averaged to 5 s.

2.3 WRF-Chem chemistry simulations

The WRF-Chem-CRI model having a domain covering South and South West England with a 2 km x 2 km resolution and a size of 134 (E-W) by 146 (N-S) grid cells and 41 vertical levels was run from 11 January 2022 00:00 to 21 January 2022 18:00 LT. The meteorology, chemical boundary, biogenic emissions and anthropogenic emissions were adopted in the model from ECMWF ERA5 reanalysis data, WACCM forecast data, MEGAN model data, EDGAR v5.0 emission inventory, respectively.

2.4 Large-Eddy Simulations

In Bristol, field measurements are being compared with large-eddy simulations (LES) using a 15 km x 15 km domain to better interpret the results. Point source releases using inert tracers can be used to measure pollutant dispersion [7] and a tracer point source release in Clifton was compared to an LES point source release. A 5 km x 5 km area was chosen to incorporate the relevant local topography. The model was run in Palm4U, with hour initialisation, a release for 15 minutes and sample for 30 minutes, to align with experimental data. 3D Terrain elevation data was gathered from Ordnance Survey and a 4 km x 4 km area using LIDAR data at 1 m resolution is surrounded by digital terrain model data at a spatial resolution of 5 m, the 2 datasets were then merged.

3 RESULTS

Figure 2(a, b) shows the time series of CO and O_3 measured at We The Curious, PM_{10} measured at two Bristol AQ sites and a selection of metals sampled within 24 hour samples of PM_{10}. Figure 2(c) shows the pollutant metals between Thursday 6th January and Thursday 20th January, including the vehicle fire on 13th January. The CO measured at the We The Curious site was consistently between 100 and 200 ppm before the vehicle fire, and increased after the fire for the following week by several hundred ppm.

The PM10 measurements at the St Pauls and Temple Way air quality measurement sites also increased after the fire. Figure 2(d) shows the observed and WRF-Chem modelled CO and figure 2(e) shows the observed and modelled O_3 for a shorter time. The WRF-Chem model reproduces the variation of CO and O_3 at We The Curious with a reasonable agreement between mixing ratios in the modelled and measured data (biases -114 ppb and -0.25 ppb for CO and O_3, respectively). There is a large discrepancy between model-measurement data of CO during 13-14 January 2022, which could be possibly due to not including the car fire emissions in the model. The CO and Volatile Organic Compounds emitted from the car fire can have a significant impact on ozone levels, but the absence of these emissions in the model increases the discrepancy (bias: -10.7 ppb) between the model and measurement O_3 data during 14-15 January 2022. CO is mainly produced at the surface during incomplete combustion from anthropogenic activity and biomass burning. The car fire on 13 Jan 2022 9 pm can produce a significant amount of CO. Because of its long tropospheric lifetime (about 2 months), it can transport from the fire source to the monitoring station leading to a higher level than the background CO concentration. The

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model underpredicts CO relative to measurement during 13 Jan to 15 Jan 2022 which is to be expected because the model did not include this point source in its emission inventory.

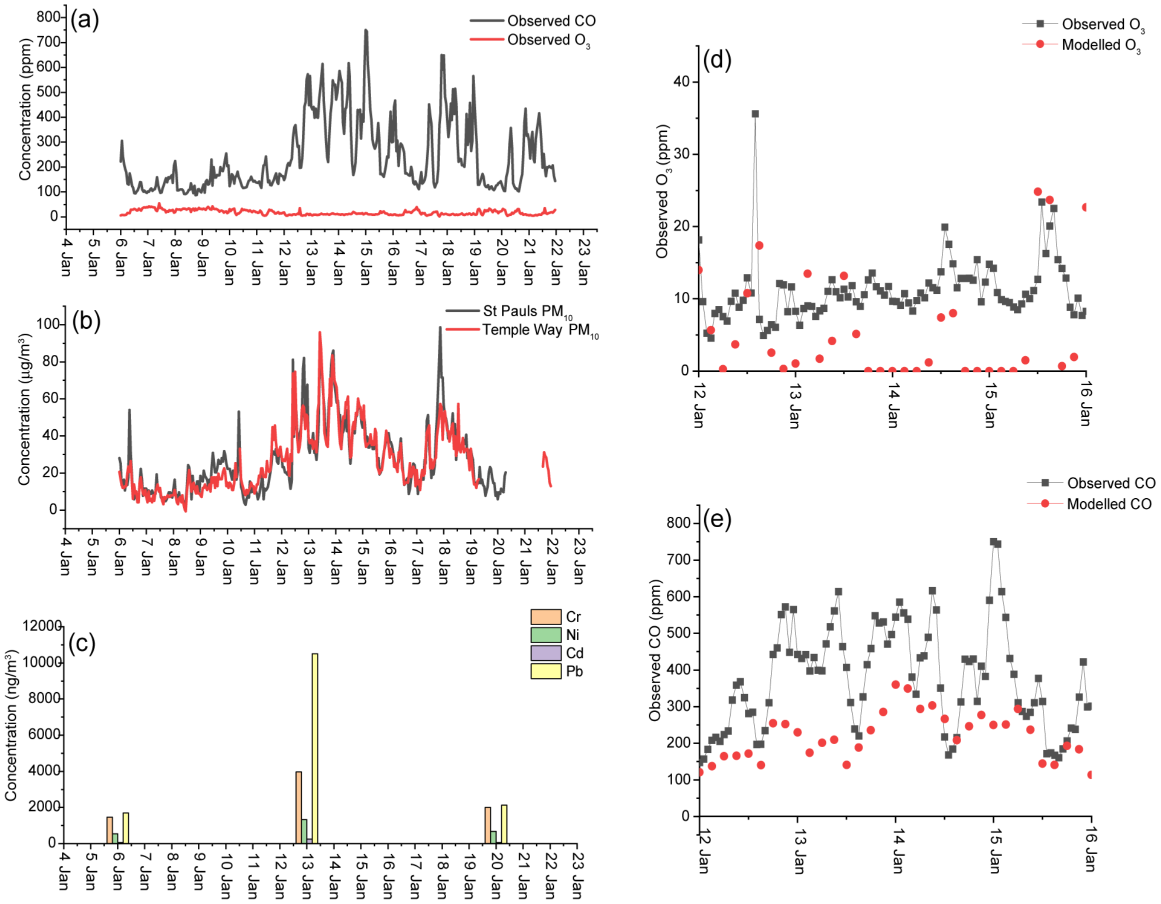

Figure 2, Time series of (a) CO and O_3 measured at We The Curious, (b) PM_{10} measured at two air quality stations and (c) metals bound to PM_{10} measured in 3 24 hour periods, and measurement and WRF-Chem model results of (d) CO and (e)O_3.

Wind speeds and direction on 13th January from the We The Curious weather station show a decrease to low wind speeds into the evening < 1 m/s with wind directions becoming more variable (figure 3). While the wind direction was consistent around SW for most of the day, by the time of the fires at 21:00 it has increased in variability and includes more northern winds. Low windspeeds can cause tracers of pollutant to spread in different directions to the predominant wind [7], and therefore CO as a long-lived pollutant produced by combustion could be seen throughout the city.

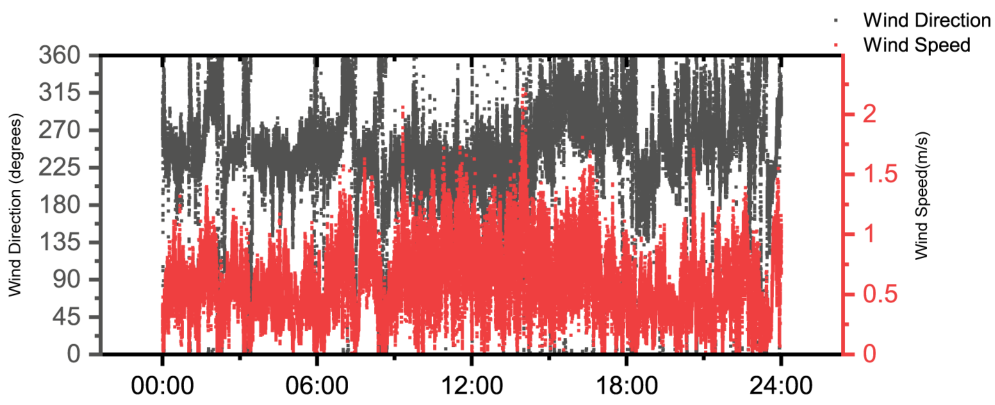

Figure 3, Wind direction (black) and wind speed (red) measured at 1 s sample interval from the roof of the We The Curious measurement site.

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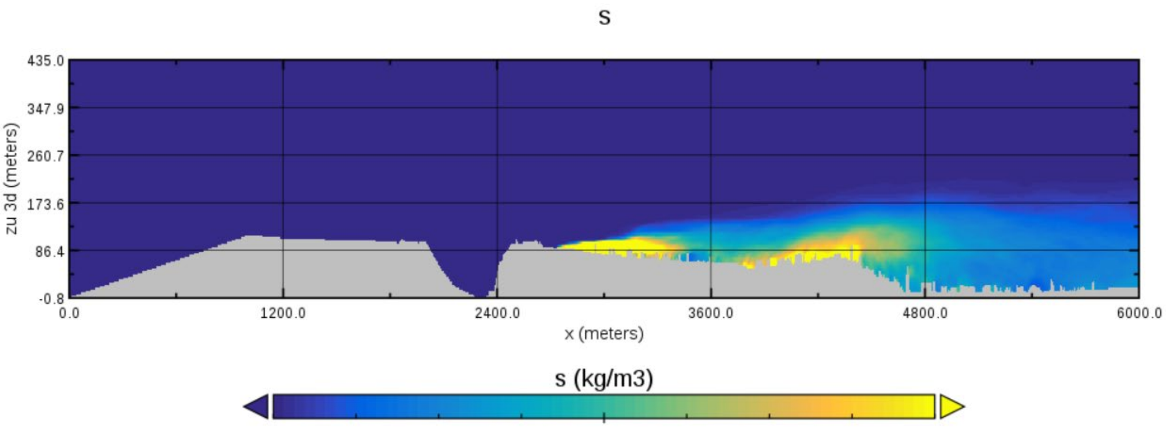

Figure 4, LES modelled source concentration along the source centre line

The LES simulation shown in figure 4 shows the mean concentration contour on the vertical plane across the source along the axial direction with a source release location at approximately 2700 m. The plume shows a second peak downstream likely due to the large buildings and the upslope from approximately 3800 m – 4400 m. The field data undercounts the model data significantly, but there is an evident correlation between the two.

4 CONCLUSIONS

A vehicle fire in South Bristol in January 2022 caused elevated levels of pollutants throughout the city, with CO remaining higher than modelled predictions after the fire had been extinguished. Wind speed and direction were such that pollutants did not clear the city and remained elevated for days after the event. LES simulations can show the importance of the city topography to pollutant dispersion.

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