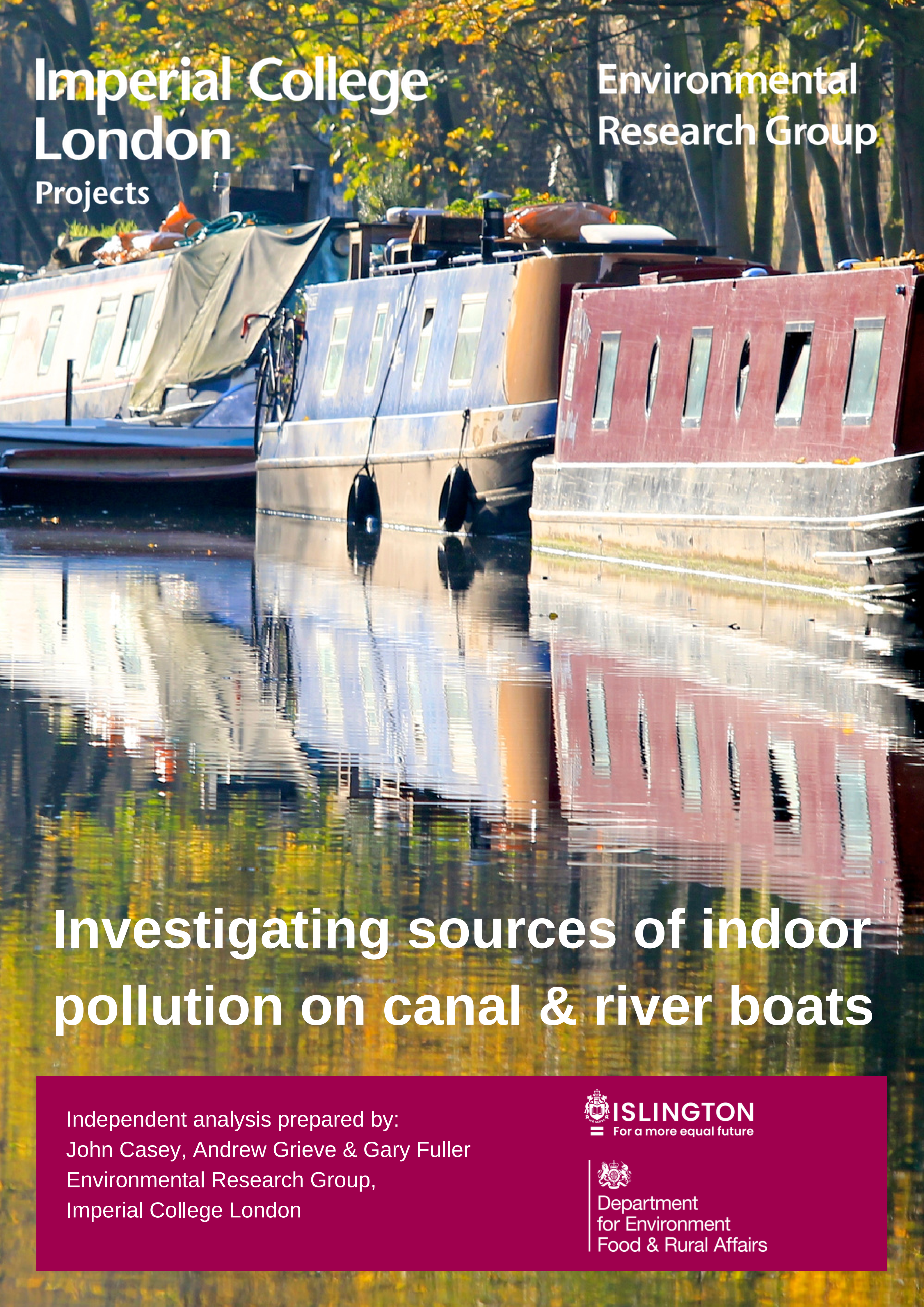

Imperial College London
Projects

Environmental Research Group

Investigating sources of indoor pollution on canal & river boats

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For a more equal future

Department
for Environment
Food & Rural Affairs

Contents

1. Main Findings

- Many of the highest Black Carbon air pollution measurements were during periods when the engine was in use for either charging batteries or moving the boat, resulting in emissions from a boat’s diesel engine entering the indoor living area.

- Generally opening the door of a stove to light a fire or add fuel resulted in emissions from the stove entering the indoor environment. All fuels and stove types contributed to indoor pollution with the highest pollution levels being observed when smokeless briquettes were added to a stove.

- Cooking, including grilling, frying, baking and use of the oven were a significant source of indoor air pollution.

2. Background

Combustion of solid and fossil fuels results in tiny particulate air pollution emissions.

Black Carbon is a measure of airborne soot-like carbon and contains known toxic constituents. Other carbon particles are also produced, some of which have a firmly established toxicity.

Islington has been creating Ecozones by installing electric charging points along a stretch of Regents Canal, allowing boaters to use electric charging and eliminate the need to run diesel engines and generators and move away from solid fuel burning.

The Ecozone

Using Defra funding, Islington has been working on a pioneering project to create an EcoZone by installing electric charging points along a stretch of the Regents Canal in the south of the Borough. These charging points were due to be installed in 2019,but did not become fully operational until 2021. The charging points allow boaters to use electric charging eliminating the need to run diesel engines and generators and to move away from solid fuel burning. The engagement with boaters and the Canal River Trust throughout the project has identified a number of additional measures that were required to encourage a move to cleaner fuels in canal boats including further communication with boater community, need to look at retrofitting technology, further support with education, training and technical assistance.

In order to improve pollution from the Regents Canal in Islington and more widely, the main objectives for charging points installation project were:

- Installation of charging points across Regent's canal.
- Engagement with boaters, the Canal River Trust and other local authorities on issue of air pollution from canals.
- Increasing awareness among boaters of the impact of diesel engines and solid fuel burning on air pollution.
- Increasing awareness among boaters of the impacts of air pollution on health
- increasing use and easing transition to electricity.
- Encouraging wider uptake of electricity chargers along the canal network and adaptations to canal boats.
- Producing legacy beyond project completion.
- Encouraging best practice uptake by sharing findings.

To help Islington Council achieve this, several actions were taken while some of the initially planned activities had to be amended in the process. The points below summarise the actions over the years:

- Conducting engagement work with boaters –
    - Surveys and informal discussions to assess understanding and any sticking points preventing uptake of cleaner fuels.
    - Engaging with boaters on the issue of air quality and its impacts on health.
    - Working with Imperial College on monitoring several boats and the impacts of pollution.
    - Explaining local Eco Zone changes to ensure smooth transition.

- Installation of charging points – co-operation with CRT and other stakeholders, technical teams, etc. to ensure installation is successful and provides electricity supply to visitor moorings along the canal.
- Hiring boating ranger in June 2021 to engage with boaters and work with the borough and Canal River Trust.
- Building legacy including improvements in relationships between all involved parties, producing information about air quality, sharing our findings with other local authorities and more widely.
- Monitoring and evaluating project – ongoing as continuing to monitor air quality along the canal, conduct surveys through booking site, monitor usage of electric mooring and share findings and best practice.

Charging points were installed at 3 sections. All installations are now complete.

Zone 1: Colbrooke Row to Danbury Street
Zone 2: Treaty Street to York Way
Zone 3: Caledonian Road to Muriel Street

Micro-Aethalometer measurements

For this investigation a micro-Aethalometer was used to sample and obtain a snapshot of indoor pollution levels on canal & river boats. The focus was on emissions which result from fuel burning activities, such as heating, cooking and power. Activities which could potentially be eliminated or reduced with the use of electrical appliances and electrical charging points. It is an investigation into how emissions change for different activities and how different fuels and appliances affect emissions

The micro Aethalometer samples air at a set rate onto filter paper. It measures the concentration of black carbon (BC) (soot) by measuring light absorbed by the particles - at near infra-red (880 nm) - in the sample collected on the filter paper. The aethalometer also measures the light absorbed when ultra-violet (UV) light is shone onto the sample. This can provide information about the composition or type of particles.

Most of the particles produced from wood burning are not sooty (Fuller et al, 2014). Other particles are produced too, mostly organic carbon (Andreae and Gelenscer 2006). Some of these organic carbon particles have no toxicity, like the sugar levoglucosan, but others have a firmly established toxicity including many types of poly-aromatic hydrocarbons (PAHs). These organic particles tend to be good absorbers of UV light and result in an enhanced UV absorption at 370 nm relative to IR absorption at 880 nm. (Wang et al 2011). An enhancement in UV response relative to BC indicates the presence of these UV absorbing compounds. This enhanced UV response should not be treated as a quantification in the same way as the black carbon measurement (Magee, 2005). For instance, a study in Northern Ireland (Brown et al 2016) showed that the UV absorption measured by aethalometers could be a good indicator of PAH from coal and wood burning. BC and UV traces are identical in the absence of specific UV absorbing material. (Magee 2005).

A calculated value, 'Delta-C', obtained by subtracting the 880 nm-based BC concentration from the 370 nm-based concentration has been used as an indication of residential wood combustion in the outdoor environment. From a study in the US, a PM2.5 to Delta-C ratio of

7.5 was observed (Wang et al 2011), although not specifically in in an indoor environment, it does give an indication of the levels of PM2.5 that can be associated with the UV measurement.

Black carbon (BC) is a measure of airborne soot-like carbon (WHO 2021). It is a primary pollutant, indicating it's emitted directly into the atmosphere. It exists as fine particles in the atmosphere and is formed by the incomplete combustion of fossil fuels, wood and other biomass. (UNEP, 2011). In urban areas, although BC emissions arise mainly from diesel vehicles (AQEG, 2012), these are declining rapidly with improved exhaust control on new vehicles (Butterfield et al., 2016). Residential heating (e.g. small coal or wood burning stoves) are considered a major source of BC. (EEA, 2013) It is present in smoke from wood and coal fires (Andreae and Gelenscer 2006). BC particles are very small, typically less than 50 nm in diameter (Wang et al 2015) and are an individual component of PM2.5. In urban areas BC is considered a better indicator of harmful particulate substances from combustion sources than either PM10 or PM2.5 (particulate matter less than 10 µm or 2.5 µm in aerodynamic diameter). It can include known carcinogens and other toxic species (WHO, 2012).

As a fine particle, BC can be inhaled and consequently deposited in the lungs, becoming more harmful to people than other contaminants such as PM10, PM2.5 (Kumar et al 2018). There is concern over the potential impacts on health of black carbon, and a review of the literature by WHO (WHO Regional Office for Europe, 2013a) concluded that evidence links black carbon particles with cardiovascular health effects and premature mortality, for both short- (24-hour) and long-term (annual) exposures. (WHO 2021)

To illustrate typical ambient levels of BC, the results from the United Kingdom Black Carbon Network can be used (Butterfield et al., 2016). Annual mean concentrations of BC measured in 2015 were 0.2–0.4 μgm^{-3} in rural sites, 1.0–2.0 μgm^{-3} in urban background stations and 1.4–5.1 μgm^{-3} in roadside locations. Illustrative annual mean concentrations where statistically significant associations with health outcomes have been found were 1.08–1.15 μgm^{-3} for black carbon. Although the evidence base is insufficient to set a certain Air Quality Guideline level to provide a basis for legally binding limit values. (WHO 2021)

BC particles contain known toxic constituents such as carcinogens and are co-emitted with other toxic pollutants that are also products of incomplete combustion, including carbon monoxide, polycyclic aromatic hydrocarbons, and VOCs. (WHO 2021)

Polycyclic aromatic hydrocarbons (PAHs) are ubiquitous environmental pollutants generated primarily during the incomplete combustion of organic materials (e.g., coal, oil, petrol, and wood). Many PAHs have toxic, mutagenic and/or carcinogenic properties. (Abdel-Shafy and Mansour 2016)

3. Method

Black carbon and other carbon particulate levels were monitored in the main living area of four boats to provide a snapshot of indoor pollution onboard.

Pollution measurements were linked to activities onboard by the owner maintaining a diary.

All boats used solid fuel stoves as a heating source, one of which was DEFRA approved. A variety of fuels were used in stoves across each boat. All boats except one, used a diesel engine.

Boat Monitoring

Continuous measurements of black carbon were carried out on each of four boats, identified for the purpose of this study as Boat A, Boat B, Boat C & Boat D. Boat owners were asked to keep a diary of events and their times, relating to any activity or interaction with the stove, cooker or the engine on each boat. Each diary enabled observed measurements from the monitor to be linked to events on the boat.

Boat A

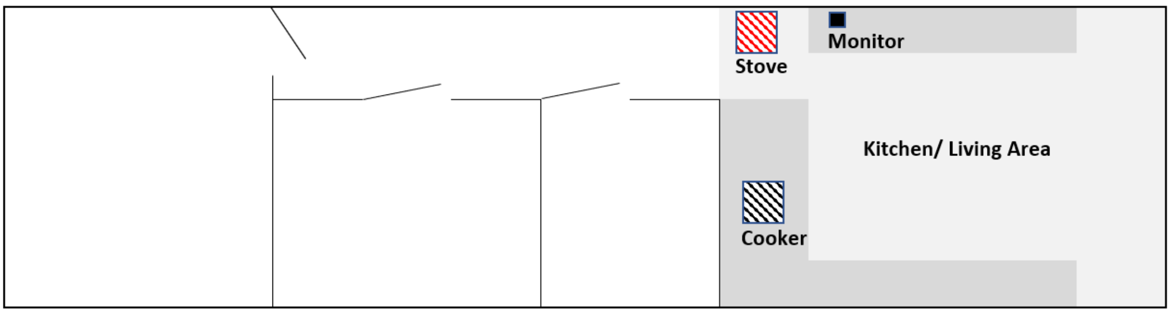
Boat A is a 15m x 4m steel wide beam solar electric barge. The barge was located at Hambleden Marina, Henley-on-Thames for the duration of the monitoring. A photo of the boat can be seen in figure 3-1.

The boat had a Chili Penguin 'Hungry Penguin' stove with a back boiler, located in the kitchen/main living area. The stove was DEFRA approved. It had a 1.3 m internal flue and 0.5m external flue. Recycled hardwood briquettes were used as the only fuel in the stove. These briquettes were produced from kiln dried wood and had a very low moisture content of 8-10 %. When the stove was in use it was remade each day. The stove was lit using an eco-biomass firelighter and 1 or 2 briquettes broken into 3 or 4 pieces. Vents were opened for approximately 15 minutes. Once a flame was established across the entire surface of fuel, vents were closed to the DEFRA approved position.

Figure 3-1. Boat A on River Thames

The back boiler was in passive thermosiphon mode until water was up to temperature. A pump and valve operated to switch from space heating to water tank heating once the boiler was up to temperature. The boat has Thermolam electric underfloor heating. It had a Viscount electric cooker in the kitchen/living area. In addition to mains supply the boat also had solar panels 5.4kW PV in 2 arrays and electrical generators, a 5kVA LPG generator and a 2.3kV LPG generator to provide backup/winter power when needed. The boat was insulated to a high standard, so did not need to run the stove all day unless well below freezing outside. In addition to window and door ventilation there was also a low-level vent of 37,500 mm^2 adjacent to the stove. The boat did not use an engine, it was all electric for propulsion as well as the domestic side. A simple layout of Boat A is presented in figure 3-2. showing the location of the kitchen/main living area and the position of the stove, cooker and monitor within this area. For the duration of the monitoring period, the monitor was on a desk approximately 0.5m from the stove and 0.5m off the floor.

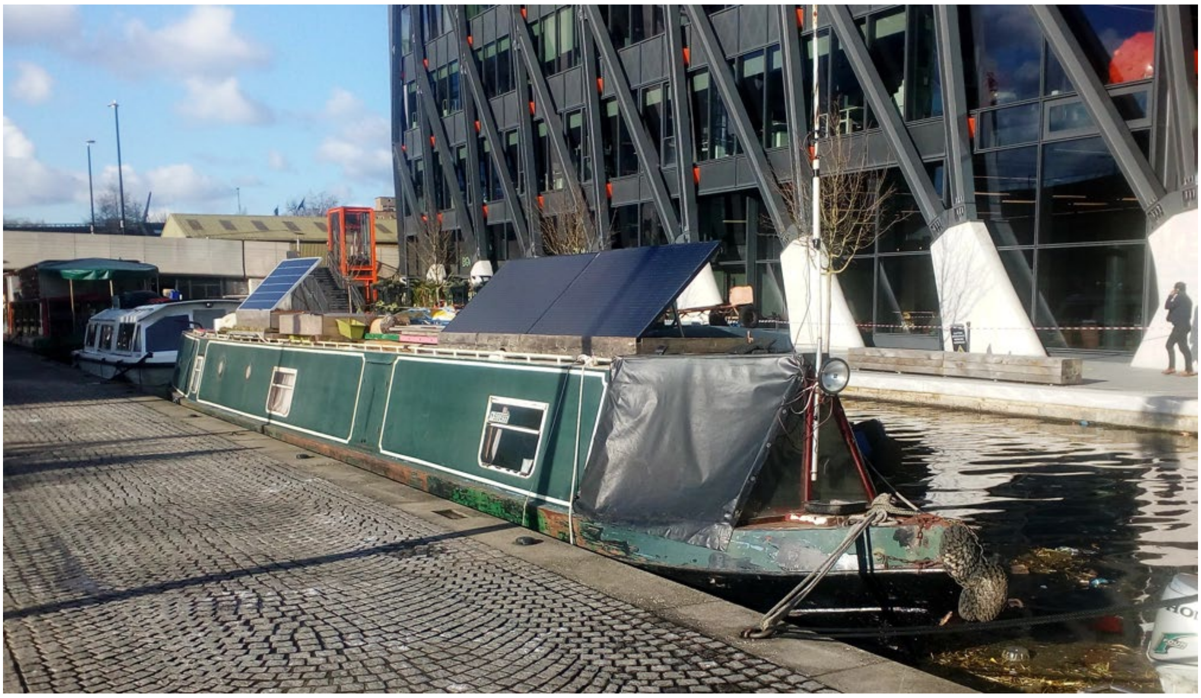
Figure 3-2. Boat A simple internal layout showing position of stove, cooker & monitor in the kitchen/main living area.



Boat B

Boat B is a 59 ft traditional stern steel narrowboat, continuous cruiser. It was located alongside Paddington Station on the Paddington arm of the Grand Union Canal for the duration of the monitoring. A photo of the boat can be seen in figure 3-3.

Figure 3-3. Boat B located alongside Paddington Station on the Paddington arm of the Grand Union Canal



It had a Villager Heron solid fuel stove located in the kitchen/main living area, with approximately 1.5 m flue inside and only a few centimeters of flue protruding outside. Newheat Briquettes were used as the fuel in the stove. This is a smokeless fuel which comprises petroleum coke - as to approximately 60 to 65% of the total weight - and anthracite - as to approximately 30 to 35% of the total weight - together with a cold setting resin binder, hardener, and low temperature stabiliser - as to the remaining weight. To light the stove, paper was placed under sliced wood kindling with a spray of oil, and briquettes on top. The bottom door of the stove was kept open until the briquettes are alight and then closed. Generally, the stove was topped up with briquettes each day and continually kept alight. Every one to two weeks, the fire needs to be remade and relit. At certain times of the year (October and March to April) scavenged wood is sometimes used solely for a couple of hours in the evening or morning. Lighting then doesn't involve briquettes.

The boat used a Morco propane gas water heater located in the kitchen. The cooker was also fuelled by propane gas. Solar panels, the engine alternator and a petrol generator were used to charge batteries for power on the boat, depending on the season. The boat had a diesel engine. Ventilation was provided by mushroom vents in the roof and vents in the front door, opening windows and side hatch. In addition, a small computer fan acting as an extractor fan was used at times during cooking.

The monitor was situated approximately 1-2m from the stove, 1m above the floor in the kitchen/living area. The location of the kitchen/main living area and the position of the monitor on the boat is indicated in figure 3-4. A photo of the monitor in situ and a photo showing its position within the kitchen and main living area during the monitoring period can be seen in figure 3-5.

Figure 3-4. Boat B simple internal layout plan (drawing from the boat owner).

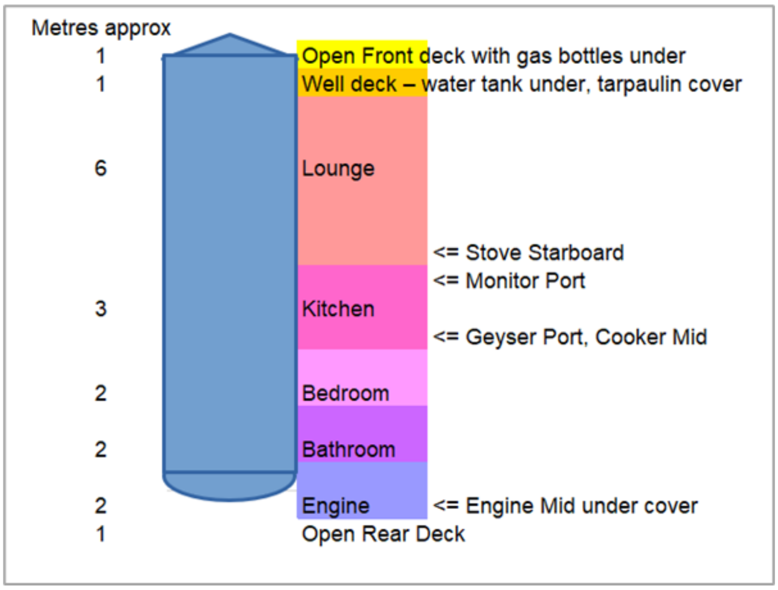
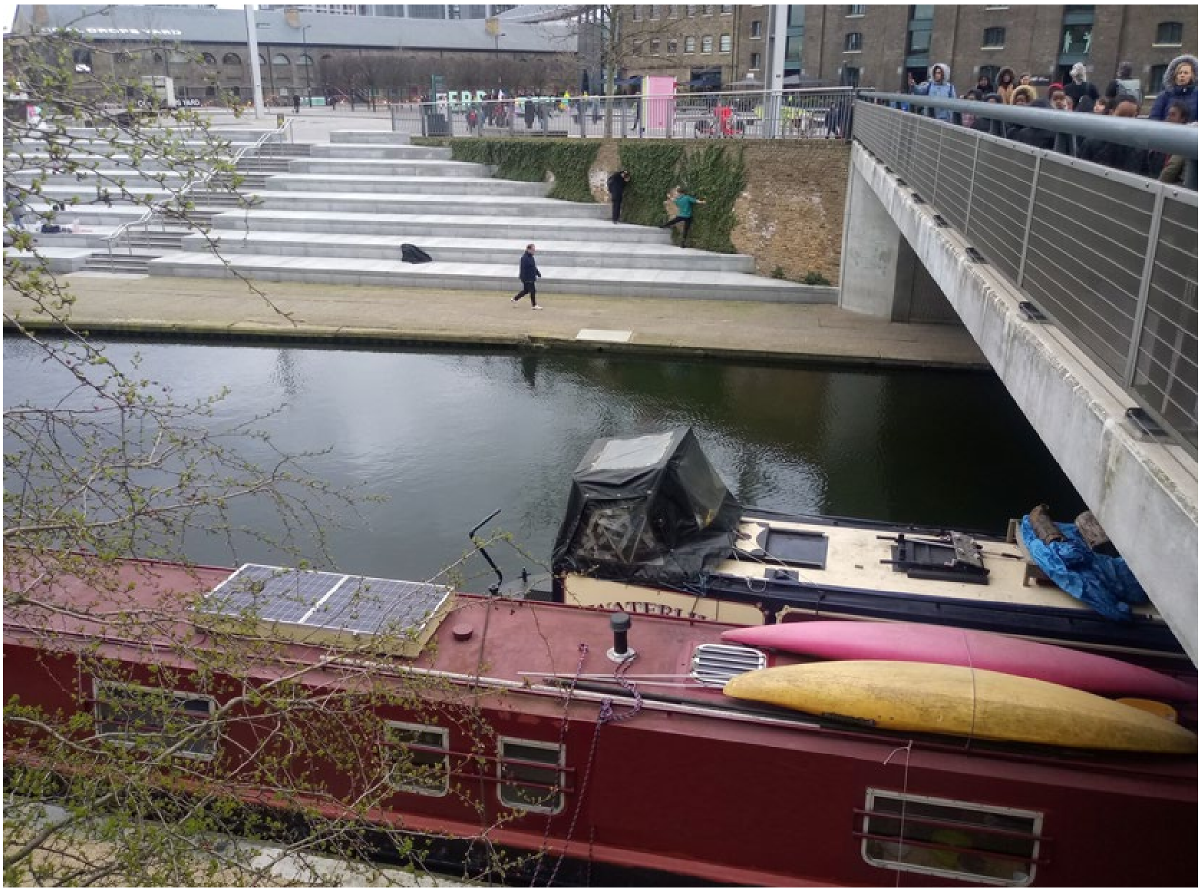


Figure 3-5. Photos indicating the monitor's sampling location within the kitchen/ main living area during sampling period on Boat B

Boat C

Boat C is a liveaboard 65ft steel narrowboat. During monitoring the boat moved between Broadway Market on Reagent's Canal to a location adjacent to Hackney Marshes on the River Lea. The move took place in two stages over day 2 and day 3 of the monitoring period. A photo of the boat can be seen in figure 3-6.

Figure 3-6. Photo of Boat C (closest to camera)



There were two stoves aboard boat C. Stove 1, the main stove, was in the main open space; the living room and kitchen area. It was a Morsø Swift 1000 multi fuel & woodburning stove. It had 1.5m flue inside and 0.5m outside the boat. Stove 2 which was used less often was located in the hallway by the back entrance of the boat. It was a Morsø Hamlet Hardy. Excel briquettes were the only fuel used in both stoves. This fuel comprises 65% to 70% petroleum coke and 25% anthracite (both by weight) together with a cold setting resin binder, hardener and low temperature stabiliser as to the remaining weight. Kindling and briquettes are used to start the fire. To light the stove, paper and kindling were used. The paper was lit with matches and the stove door left open until the kindling had caught, both vents were left fully open for 5/10 minutes. When fuel was added the top vent was closed and the bottom vent was left completely open until the coal caught fire. Generally, the stove was topped up with briquettes each day and continually kept alight. Both stoves were in operation throughout the monitoring period.

The boat used a Valor Vanette 4 ring gas cooker, grill, and oven. A gas fuelled water heater was used for hot water. The engine alternator supplemented by two solar panels were used to charge batteries for power on the boat, depending on the season. During winter months the engine may need to be run for approximately one hour ever week if the boat is occupied during each day. The boat had a diesel engine. Ventilation was provided by three ceiling vents, hopper windows and a skylight that could be opened as required.

During the monitoring period the monitor was situated approximately 1-2m opposite the stove, on shelves. A photo showing its position within the main open space living room and kitchen area during monitoring can be seen in figure 3-7.

Figure 3-7. Photo indicating the monitor's sampling location within the kitchen/main living area during sampling period on Boat C

Boat D

Boat D is a 75ft steel narrow boat. It was located at Broadway Market on Reagent's Canal for the monitoring period. A photo of the boat can be seen in figure 3-8. The stove was a Morsø Squirrel. It was in the kitchen/main living area of the boat. The stove had 1.3m flue inside and 0.6m outside the boat.

Figure 3-8. Photo of Boat D

Homefire Ovals, Homefire Ecoal and seasoned logs were used as fuel for the stove. Homefire ovals comprise anthracite fines (as to approximately 50 to 75% of the total weight), petroleum coke (as to approximately 20 to 45% of the total weight), bituminous coal (as to approximately 5 to 17% of the total weight) and an organic binder (as to the remaining weight). Homefire Ecoal briquettes comprise anthracite fines (as to approximately 40 to 65% of the total weight), petroleum coke (as to approximately 20 to 40% of the total weight), bituminous coal (as to approximately 0 to 20% of the total weight), biomass (as to approximately 5 to 20% of the total weight), biomass char (as to approximately 0 to 10% of the total weight) and an organic binder or, molasses and acid binder (as to a maximum of 20% of the total weight). The procedure to light the stove involved placing a fire lighter below softwood kindling below coal. The vent door was left open for around 10 minutes until the fuel was fully alight. The stove was usually topped up with fuel each day and continually kept alight.

The boat used a Belling gas cooker. The engine alternator supplemented by three solar panels were used to charge batteries for power on the boat, depending on the season. The boat had a diesel engine. Ventilation was provided by mushroom vents in the roof and opening windows.

Throughout the monitoring period the monitor was situated approximately 1-2m across from the stove, in the kitchen/living area. The location of the kitchen/main living area and the position of the monitor on the boat is indicated in figure 3-9. A photo showing its position within the kitchen and main living area during the monitoring period can be seen in figure 3-10.

Figure 3-9. Simple Plan of Boat D (from the boat owner).

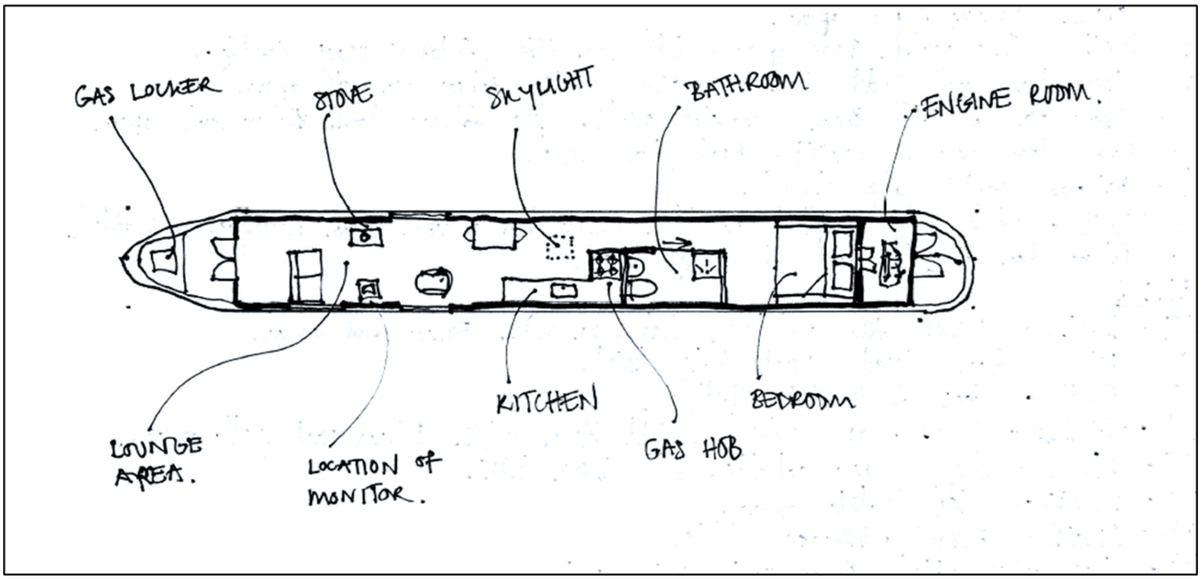


Figure 3-10. Photo indicating the monitor's sampling location within the kitchen/main living area during sampling period on Boat D

A summary of appliances and fuel used on each boat is presented in Table 1.

Table 1. Information for each boat

	Boat A	Boat B	Boat C	Boat D
Stove	Chili Penguin	Villager Heron mk1	Morsø Swift 1000 & Morsø Hamlet Hardy	Morsø Squirrel
Back Boiler (Y/N)	Y	N	N	N
DEFRA Approved (Y/N)	Y	N	N	Y
Fuel	Kiln Dried Hardwood Briquettes Kiln Dried Hardwood kindling Eco firelighters	Newheat Briquettes Sliced wood offcuts kindling	Excel Briquettes	Homefire Ovals Homefire Eco Seasoned Logs Softwood kindling Firelighters
Cooker	Viscount Hob & Cooker Electric	Hotpoint LPG Conversion - Propane	Valor Vanette 4-ring grill & oven Gas	Belling Gas
Central Heating	Thermolam underfloor Electric	None	None	None
Water Heating	Imersion Electric	Morco D61E Propane	Water Heater Gas	None
Power	Mains Solar 5.4kW PV LPG generator 5kVA & 2.3kVA	Solar 1100w or 500w Engine alternator Petrol generator	Solar Engine alternator	Solar Engine alternator
Engine	None AGNI 143 6.4kW Electric Motor	BMC1500 Diesel	Thorneycroft T105 Diesel	Beta Marine 38 Diesel

Micro-aethalometer measurements

For the study a micro-Aethalmoeter MA300 was used to continuously measure black carbon (BC) concentrations. The MA300, Figure 3-11, is a miniature, portable, highly sensitive five-wavelength Aethalometer designed for measuring light absorbing carbon ('LAC') particles. Measurement at 880nm is interpreted as the concentration of black carbon ('BC'). Measurement at 375nm is interpreted as Ultraviolet Particulate Matter ('UVPM') indicative of wood smoke, tobacco and or biomass burning.

Figure 3-11 MA300 micro Aethalometer

The MA300 includes hardware and firmware that implement the patented Dual Spot Loading Compensation method (Drinovec et al 2015) which reduces measurement post-processing.

This study used the Optimized Noise reduction Averaging (ONA) algorithm (Hagler et al 2011) to post-process data from the micro Aethalometer. The ONA method is used to resolve the noise of real-time data from the micro Aethalometer, while maintaining the highest time resolution possible.

Over a monitoring period on a boat the MA300 was placed in the main living /kitchen area and remained in the same location throughout. For this study the MA300 was set to continuously sample at a sample flow rate of 100ml/min and record an average black carbon measurement at a time base of one minute.

Monitoring details for each boat are presented in Table 2.

Table 2. Monitoring details for each boat

Boat	Location		Monitoring		
			Start	Finish	Total (hrs)
A	Hambleden Marina, Henley-on-Thames	River Thames	10-Dec-20	15-Dec-20	127
A	Hambleden Marina, Henley-on-Thames	River Thames	21-Jan-21	22-Jan-21	29
B	Paddington	Grand Union Canal	04-Feb-21	11-Feb-21	167
C	Broadway Market/Limehouse/Hackney Marshes	Reagent's Canal/River Lea	12-Feb-21	17-Feb-21	91
D	Broadway Market	Reagent's Canal	13-Mar-21	22-Mar-21	144

4. Results

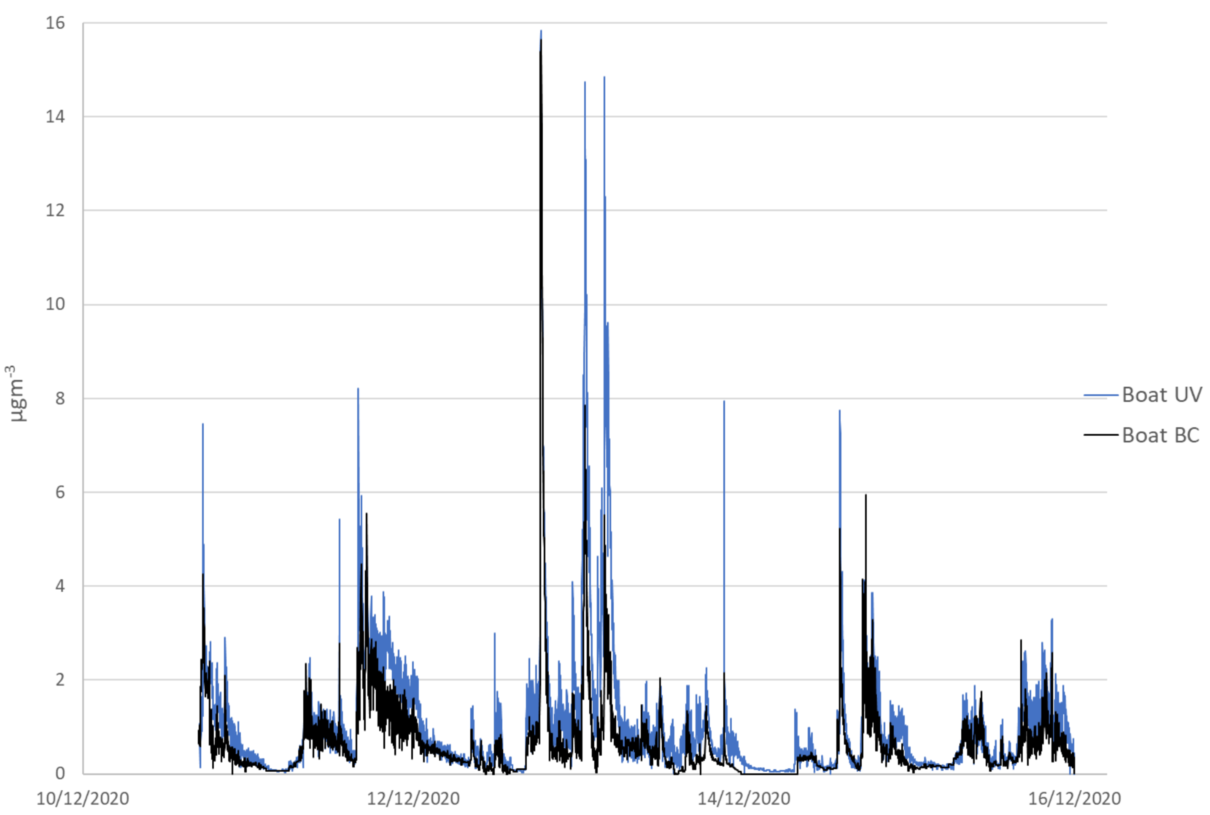
A timeline of BC measurements and UV absorption measurements were produced for each days monitoring on each boat.

Diary entries were used to identify which activities were responsible for BC and UV absorption peaks. Allowing activities to be linked to pollution emissions.

Boat A

In total 158 hours of monitoring data from Boat A was analysed with reference to a diary of activities and times, as recorded by the boat's owner. On Boat A monitoring was carried out over two separate periods, Day 1 to Day 6 in December 2020 and Day 7 & 8 in January 2021. Figures 4-1 and 4-2 show black carbon (BC) and ultra-violet (UV) measurements over both monitoring periods onboard. BC measurements ranged from 0 to ~ 16μgm^{-3} over Day 1 to 8.

Figure 4-1. BC & UV measurement data - Boat A - Monitoring Day 1- Day 6



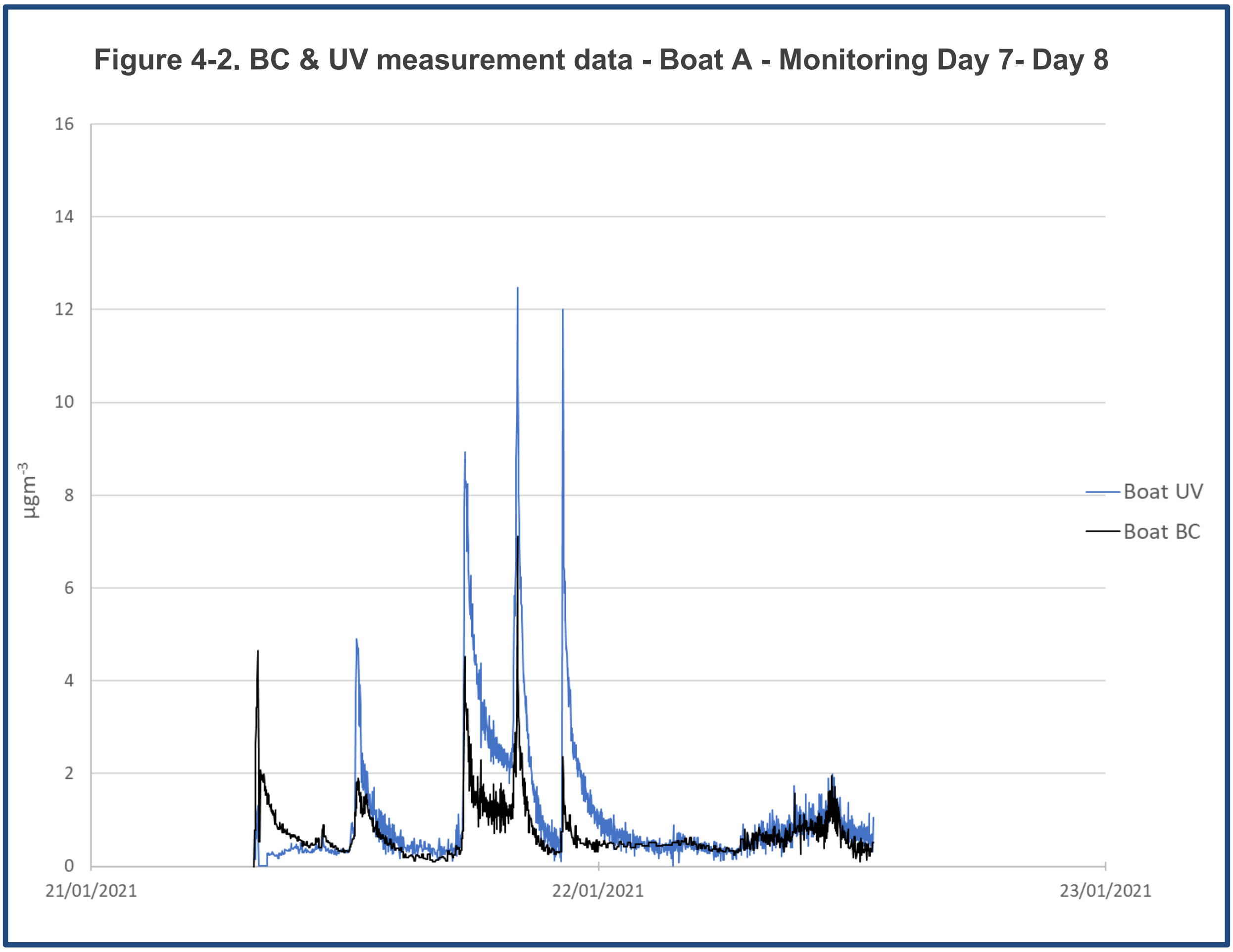
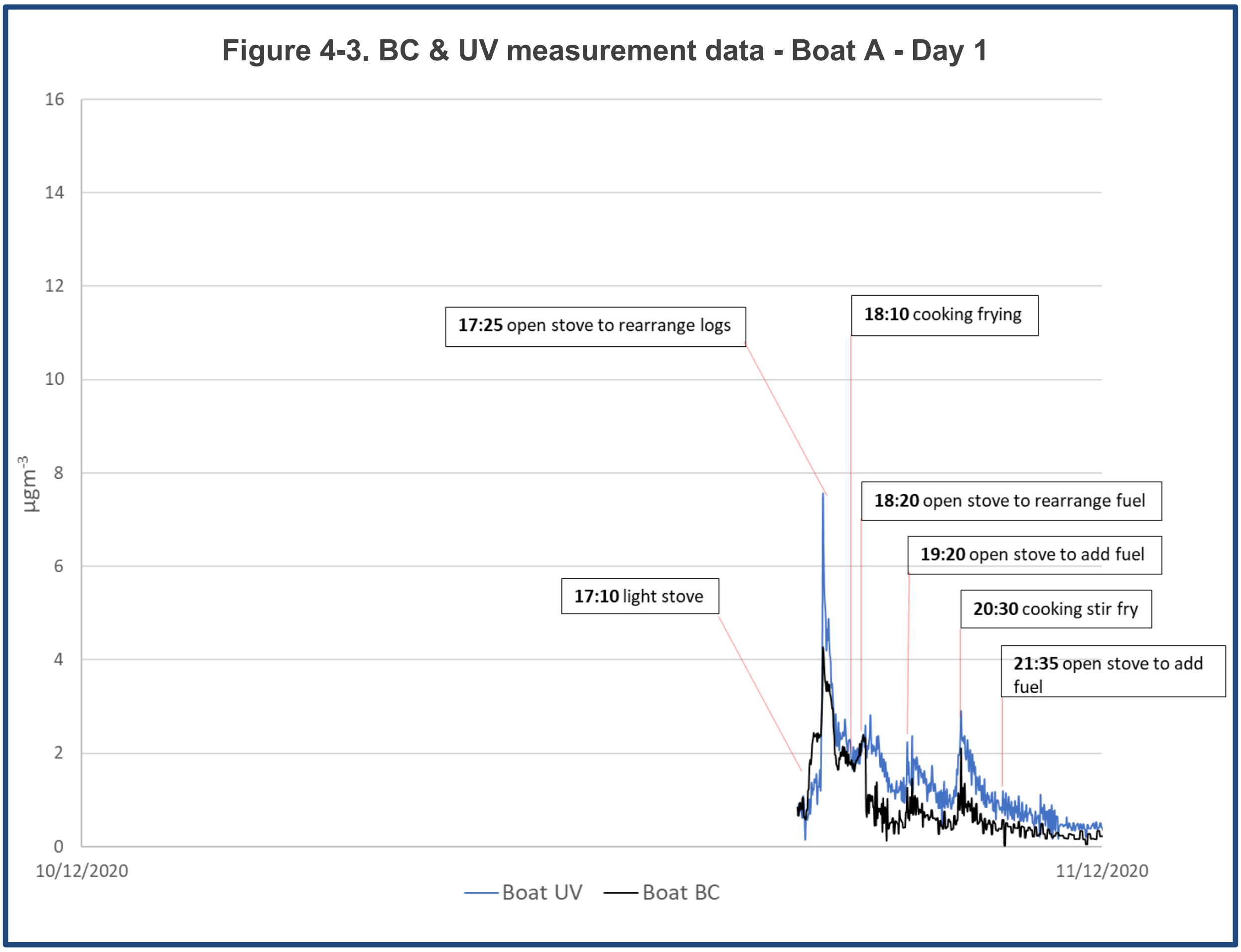


Figure 4-2. BC & UV measurement data - Boat A - Monitoring Day 7- Day 8
16
14
12
10
8
6
4
2
0
µgm-3
21/01/2021
22/01/2021
23/01/2021
Boat UV
Boat BC



BC and UV measurements on Day 1 are presented in Fig 4-3. On Day 1 at 17:10 the BC concentration increased from ~ 1 to 2.5 µgm^{-3} over the course of 15 minutes after the stove was lit. The stove door was then re-opened to arrange fuel at 17:25 and the BC concentration increased again from ~ 2.5 to 4.3µgm^{-3} over the course of two minutes before decreasing gradually. An increased UV measurement relative to BC was noted for these events. At 18:10 frying & at 18:20 opening the stove door to rearrange fuel, resulted in a slight increase in BC ~ 1 µgm^{-3} with enhanced UV measurements. With both events so close together it is difficult to attribute the increases to one or other event. Both measurements began to gradually decrease again soon after the second event. At 19:20 the stove door was opened to add fuel, BC increased from ~ 0.5 to 1.2 µgm^{-3} and there was a similar increase in the UV measurement. At 20:30 when cooking a stir fry, BC increased from ~ 0.4 to 1.2 µgm^{-3} peaking at 2.1 µgm^{-3} with a larger increase observed in the UV measurement. At 21:35 the stove door was opened to add fuel and there was a brief interruption in the decrease of the BC concentration but a slight increase in the UV measurement. Both BC and UV measurements then continued to decrease following this final activity.

Figure 4-4 shows BC and UV measurements on Boat A for Day 2. Overnight levels of BC and UV were very low with BC ~ 0.1 µgm^{-3}. At 08:05 the stove was lit, and BC levels increased from ~ 0.5 to 1.2 µgm^{-3} with peak values at 2.3 µgm^{-3}. UV measurements were slightly higher, both BC and UV remained elevated for approximately one hour before decreasing. BC and UV peaks were noted at 13:20 however there were no diary entries at this time. At 16:00 when cooking started BC and UV levels increased, with BC increasing from ~ 1.0 to 4.0µgm^{-3} over the course of 30 minutes, before decreasing. There was a larger increase in UV measured for this cooking event. From 17:52 there were a number of interactions with the stove. At 17:52 when the stove was relit there was a small increase in BC ~ 0.6 µgm^{-3}. The UV increase was broadly similar. When fuel was rearranged at 18:15 there was a slight increase in BC but a larger increase in UV measured. As the stove door was opened to add paper at 18:52 and fuel at 19:50 the BC continued to decrease gradually. Over this time there continued to be a higher proportion of UV absorbing particles measured, increasing slightly when fuel was added at 19:50, then continuing to also decrease along with BC.

Figure 4-4. BC & UV measurement data - Boat A - Day 2

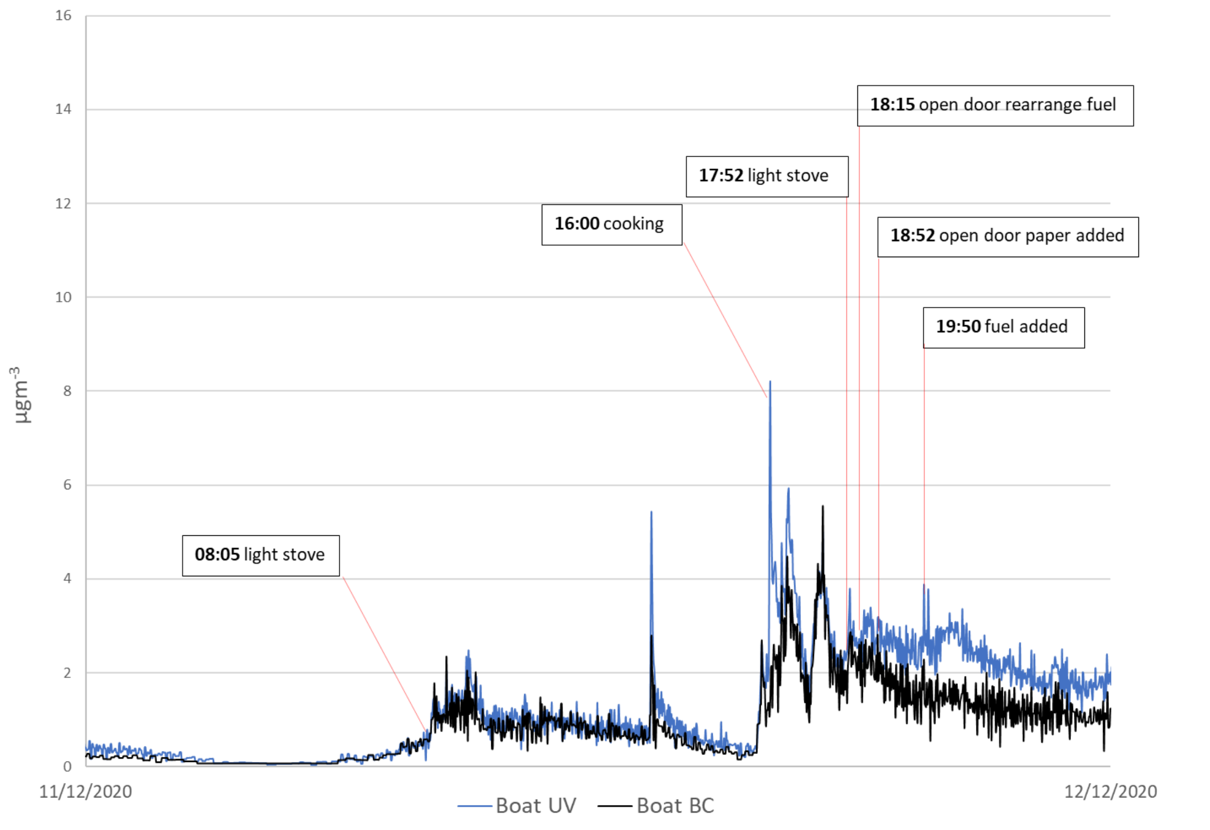
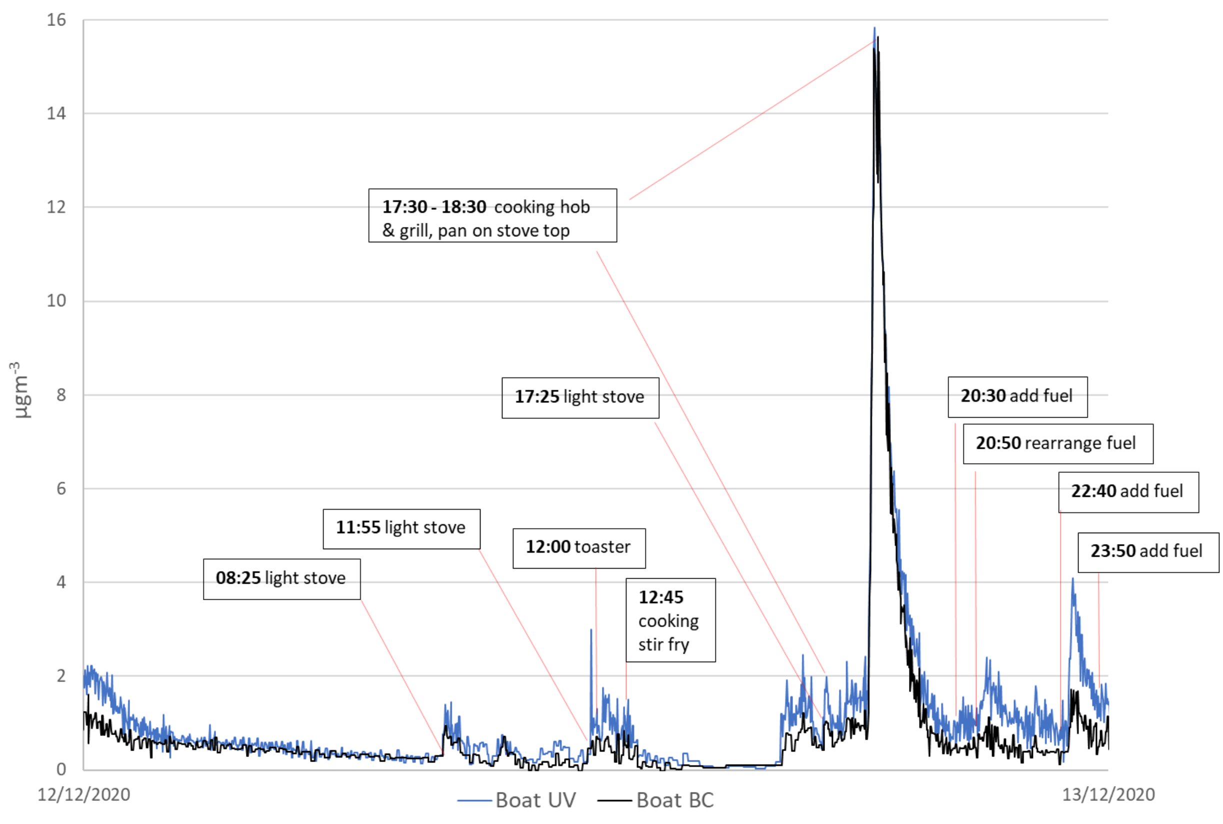


Figure 4-5 shows measurements for Day 3. Low levels of ~ 0.2 µgm^{-3} BC and UV were observed overnight until the stove was lit at 08:25 when BC increased from ~ 0.2 to 0.9 µgm^{-3} accompanied by a slightly larger increase in UV. Both measurements began to decrease after approximately 5 minutes. At 11:55 the stove was relit and there was an increase in UV but only a small BC increase from ~ 0.2 to 0.6 µgm^{-3}. The cooking events at 12:00 & 12:45 did not show any further increase in BC but UV levels were slightly higher. However, these cooking events were close to the previous stove activity and consequently it's not clear if the stove activity earlier at 11:55 was continuing to influence the measurements. At 17:25 the stove was relit, BC and UV measurements did not change significantly. Between 17:30 and 18:30 cooking activity took place, with high BC measurements ~ 16.0 µgm^{-3} from 18:20. This high BC concentration gradually decreased over the next 90 minutes. The was no added UV measured during this episode until 30 minutes after the peak as both BC and UV decreased. At 20:30 fuel was added to the stove which resulted in an increase in UV measured. At 20:50 fuel was rearranged, and BC increased slightly with a larger increase in UV. At 22:40 fuel was added and soon after BC increased from ~ 0.4 to 1.7 µgm^{-3} with a larger increase in the UV measurement.

Figure 4-5. BC & UV measurement data - Boat A - Day 3



Day 4 data is presented in Figure 4-6. Baking and grilling resulted in an increase in BC from ~ 0.3 to 7.8 μgm^{-3} over 30 minutes from 00:30, after which BC levels decreased over the next hour. There was a large extra UV measurement during this episode. There were a further two similar but smaller episodes at 02:45 and 03:00 but there were no diary entries for these smaller peaks. At 03:45 there was another baking peak with BC increasing from ~ 0.7 to 5.5 μgm^{-3} over five minutes with another large UV peak. It then took two hours for BC and UV measurements to return to similar levels as before these episodes began. At 09:10 we saw an increase in BC, ~ 1.0 μgm^{-3} and UV as the fire was lit. There were also two cooking activities, at 09:15 and 09:50 and there appeared to be a small increase in UV when the stove was used to heat up pastries. Fuel was added to the stove at 11:40 and BC increased from ~ 0.3 to 2.0 μgm^{-3} over 10 minutes. UV measurements were only very slightly higher but became more enhanced relative to BC after an hour and for the next two and half hours until fuel was added to the stove at 15:30. BC then increased from ~ 0.1 to 1.3 μgm^{-3} over 20 minutes. Again, UV measurements were only very slightly higher but became more enhanced relative to BC over the next half hour as levels decreased. Using the oven to roast vegetables between 17:00 and 18:00 showed a very slight BC increase but enhanced UV measurements. At 18:15 fuel was added to the stove and BC increased from ~ 0.3 to 1.2 μgm^{-3} over 20 minutes with enhanced UV measurement. BC and UV levels decreased over the next hour. There was a BC and enhanced UV peak at 21:15 but there was no diary entry.

Figure 4-6. BC & UV measurement data - Boat A - Day 4

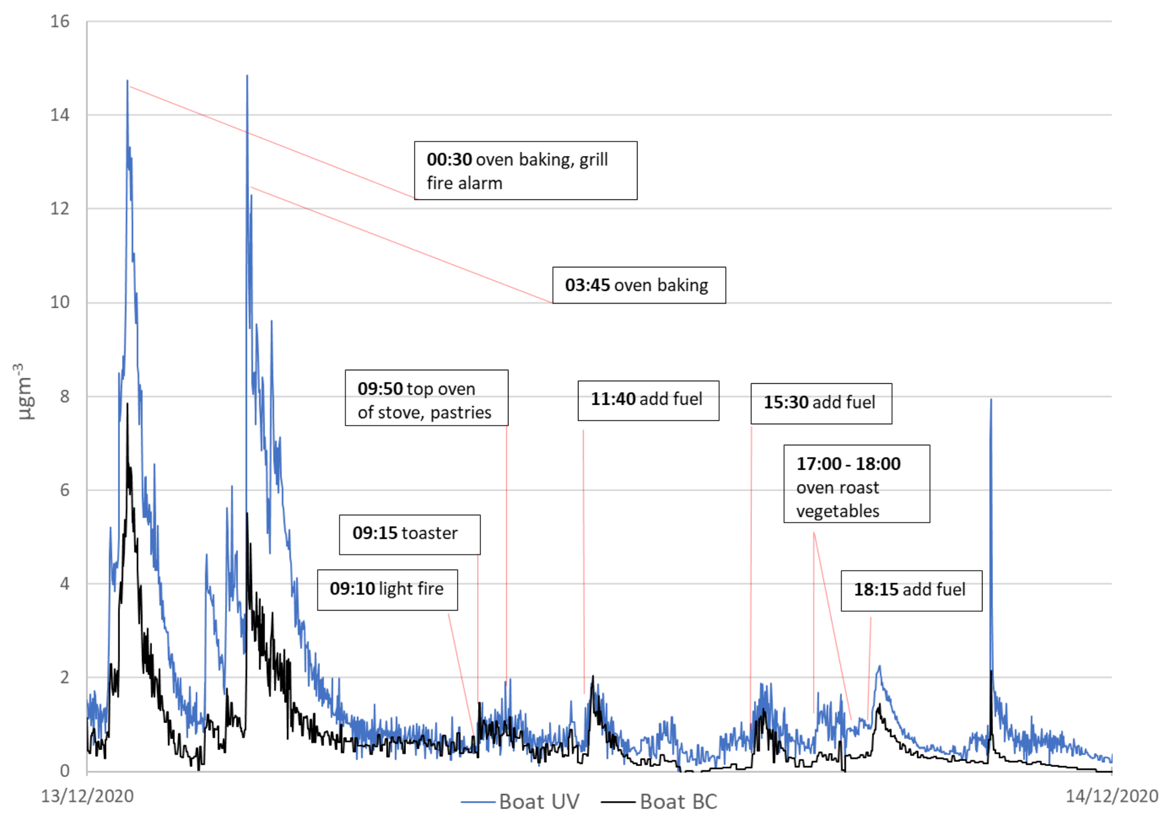


Figure 4-7 shows BC and UV measurements on Boat A for Day 5. BC and UV levels increased slightly as the stove was lit at 07:30. Before this measurement levels of both were very low overnight into early morning. Between 10:15 and 11:40 the front door was opened to allow extra ventilation and there was a noticeable drop in BC and UV measurement values albeit from a low level. At 13:35 the stove was lit again and there was an increase in BC from ~ 0.2 to 1.2 µgm^{-3} over three minutes. At 13:50 fuel was rearranged, and BC increased from ~ 0.5 to 5.2 µgm^{-3} over 10 minutes with enhanced UV measurement. Levels took an hour to decrease significantly and another hour to decrease back to pre-fire levels. Although BC levels began to increase again from 17:10, the diary noted cooking using the oven, hob for frying and grill at 17:40, when BC levels were then at up to 5.9 µgm^{-3} from a level of 0.2 µgm^{-3}. Throughout there was a slightly enhanced UV signal. At 21:20 the stove was relit, and BC increased from ~ 0.4 to 1.0 µgm^{-3} over three minutes and remained elevated for 30 minutes after which it decreased but at a lower rate than the UV measurement.

Figure 4-7. BC & UV measurement data - Boat A - Day 5

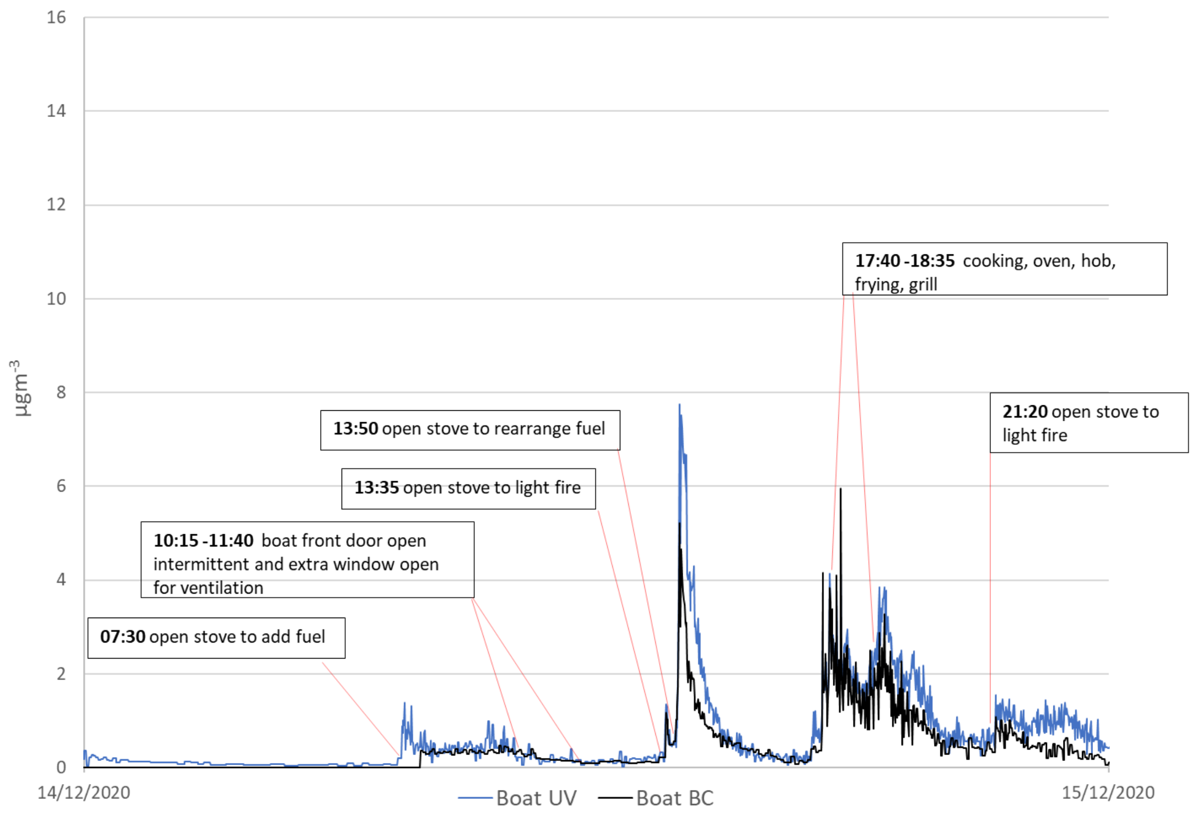
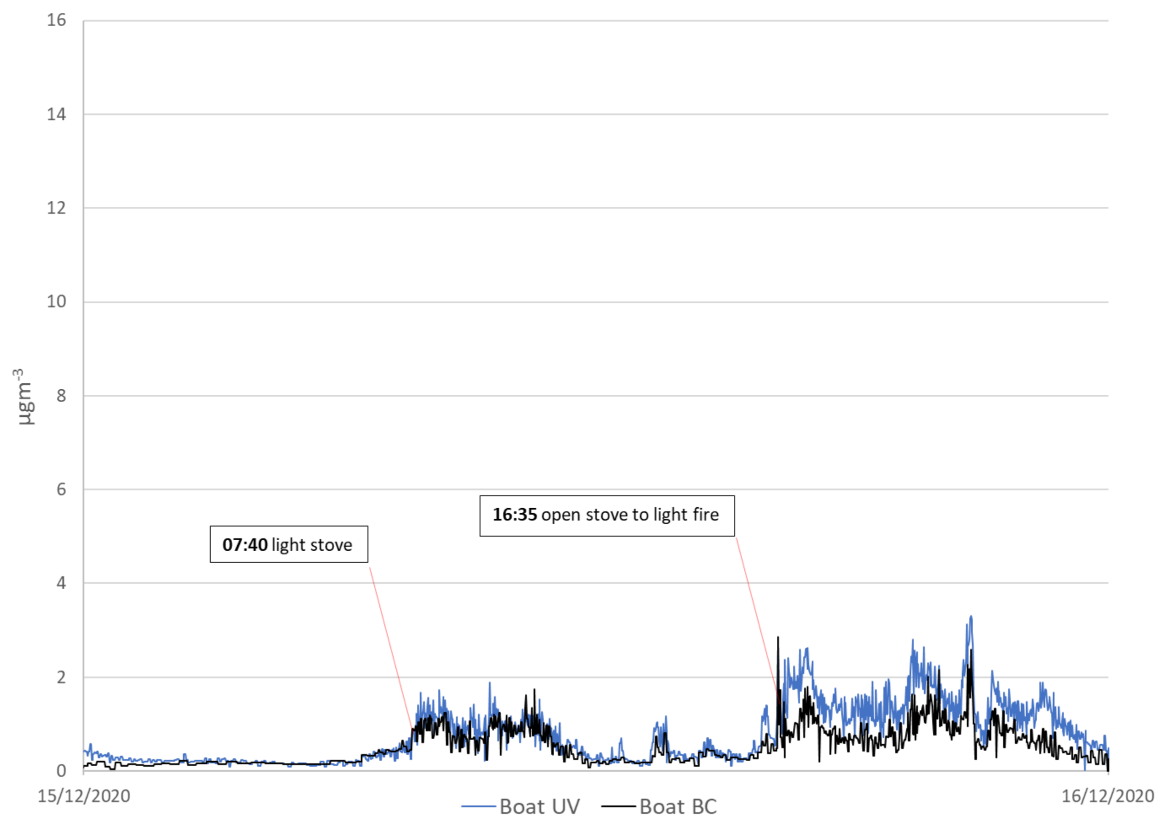


Figure 4-8 shows measurements for Day 6. Low background levels overnight increased when the stove was lit at 07:40. BC increased from ~ 0.4 to 1.2 μgm^{-3} and remained at ~ 1.0 μgm^{-3} for over three hours before decreasing and taking a further hour to get back to levels before the fire was lit. UV measurements were slightly enhanced relative to BC for the duration. At 16:35 the stove was lit again, there was an initial jump in BC measured from ~ 0.4 μgm^{-3}, peaking at 2.5 μgm^{-3}. For the rest of the day BC levels were elevated and fluctuated from ~ 0.5 to 1.5 μgm^{-3} with a couple of peaks > 2.0 μgm^{-3}. Throughout this period UV measurements were enhanced.

Figure 4-8. BC & UV measurement data - Boat A - Day 6



Data from Day 7 on Boat A can be seen in Figure 4-9. The day began when the monitor was restarted for the second period of monitoring, during January 2021. The stove was not lit during Day 7 implying most probably that all the BC and UV episodes corresponded to cooking events. There was a BC peak at 12:30, presumed to be from cooking, with enhanced UV measurement, but no corresponding diary entry. At 17:30 frying increased BC from ~ 0.3 to 4.5 μgm^{-3} with a large, enhanced UV measurement. Levels continued to decrease for two hours before more frying and smoking oil at 20:00 increased BC concentrations from ~ 1.0 to 7.1 μgm^{-3} again with a large, enhanced UV signal relative to BC. Levels gradually decreased for two hours until 22:14 when there was another peak without a diary entry, which is presumed was cooking again. BC increased from 0.3 to 2.4 μgm^{-3} with a very large UV measurement compared to BC.

Figure 4-9. BC & UV measurement data - Boat A - Day 7

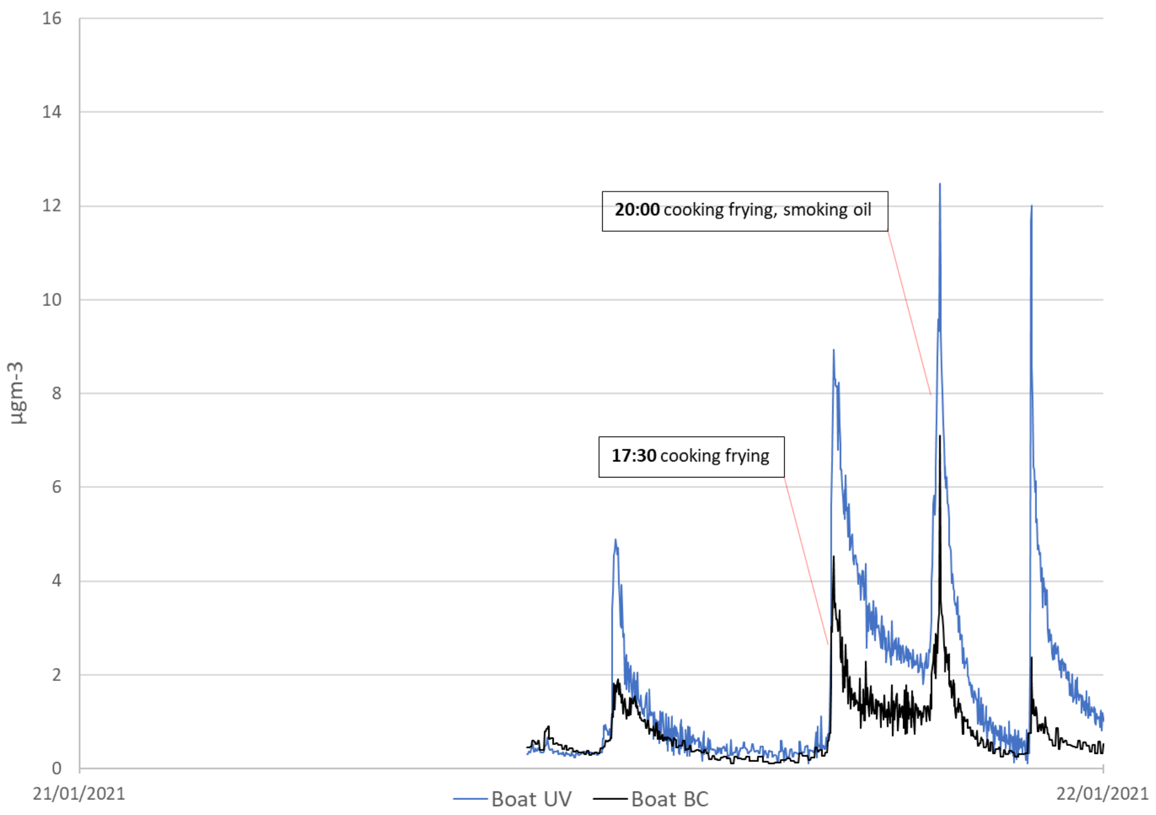
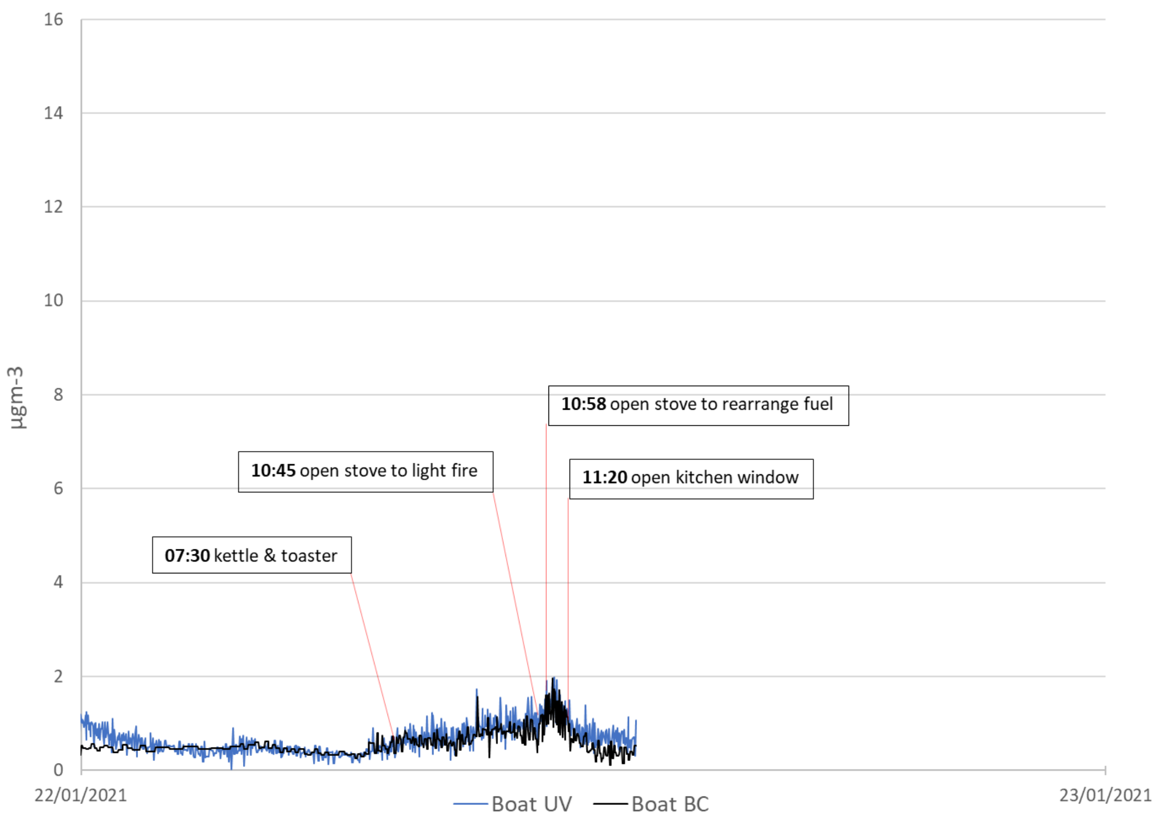


Figure 4-10 shows BC and UV measurements on Boat A for Day 8. There was a gradual increase in BC from very low levels ~ 0.2 μgm^{-3} from 07:30 when it is noted that a kettle and toaster were used. At 10:45 there was an increase in BC which continued when the fuel was rearranged in the stove at 10:58. The overall increase in BC over this time was from ~ 0.5 to 1.8 μgm^{-3}. BC and UV levels began to decrease 10 minutes after the fuel was rearranged in the stove. At 11:20 a window was opened, BC and UV measurements continued decreasing although an enhanced UV signal became more obvious.

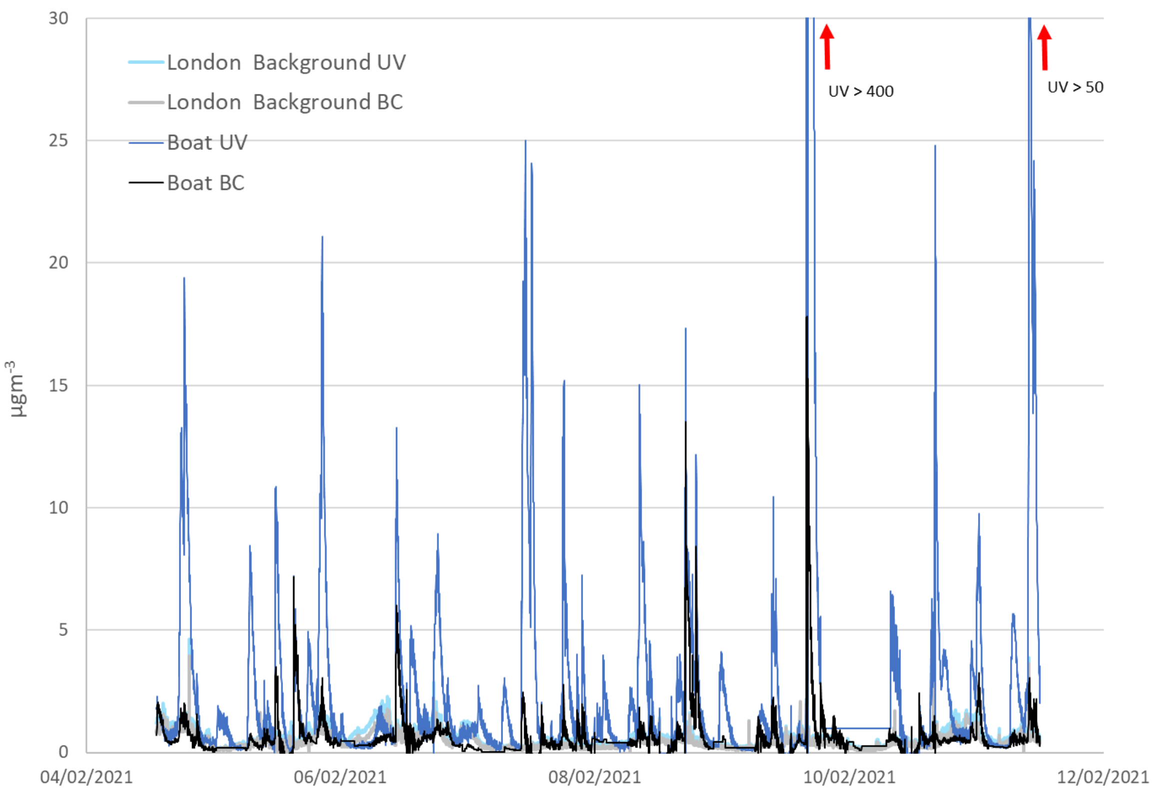
Figure 4-10. BC & UV measurement data - Boat A - Day 8



Boat B

A total of 167 hours of monitoring data from Boat B was analysed with reference to a diary of activities and times, as recorded by the boat's owner. Monitoring was carried out from Day 1 on 4th February to Day 8 on 11th February 2021. Figure 4-11 shows BC and UV measurements over the monitoring period on Boat B. BC measurements ranged from 0 to ~ 18 μgm^{-3} between Day 1 and Day 8. For context, London ambient background BC and UV measurements from the Air Quality Monitoring Station (AQMS) at North Kensington were plotted in addition to the boat BC and UV measurements.

Figure 4-11. BC & UV measurement data - Boat B - Monitoring Day 1- Day 8



Data from Day 1 is presented in Figure 4-12. On Day 1 the monitor was switched on at 13:15, the initial readings need to be treated with caution as the analyser takes a while to adjust to its new environment. After an hour BC and UV measurements were close to or below London background levels. At 16:15 the cooker was used to boil a kettle of water, however there was no significant change in either BC or UV measurements as a result. At 17:27 the stove was riddled and refuelled, BC increased from ~ 0.4 to 1.5 µgm^{-3} over 30 minutes. It then decreased for the following 30 minutes before increasing again from ~ 1.1 to 1.6 µgm^{-3} over 10 minutes before decreasing to background levels over the next 2 hours. UV during this time mirrored BC but with a much-enhanced response relative to BC. At 20:40 when the cooker was used to prepare dinner BC increased from 0.4 to ~ 1.3 µgm^{-3} over 10 minutes before gradually decreasing, aided by an extractor fan being switched on at 20:45. During this cooking episode there was a small increase in UV relative to BC measured.

Figure 4-12. BC & UV measurement data - Boat B - Day 1

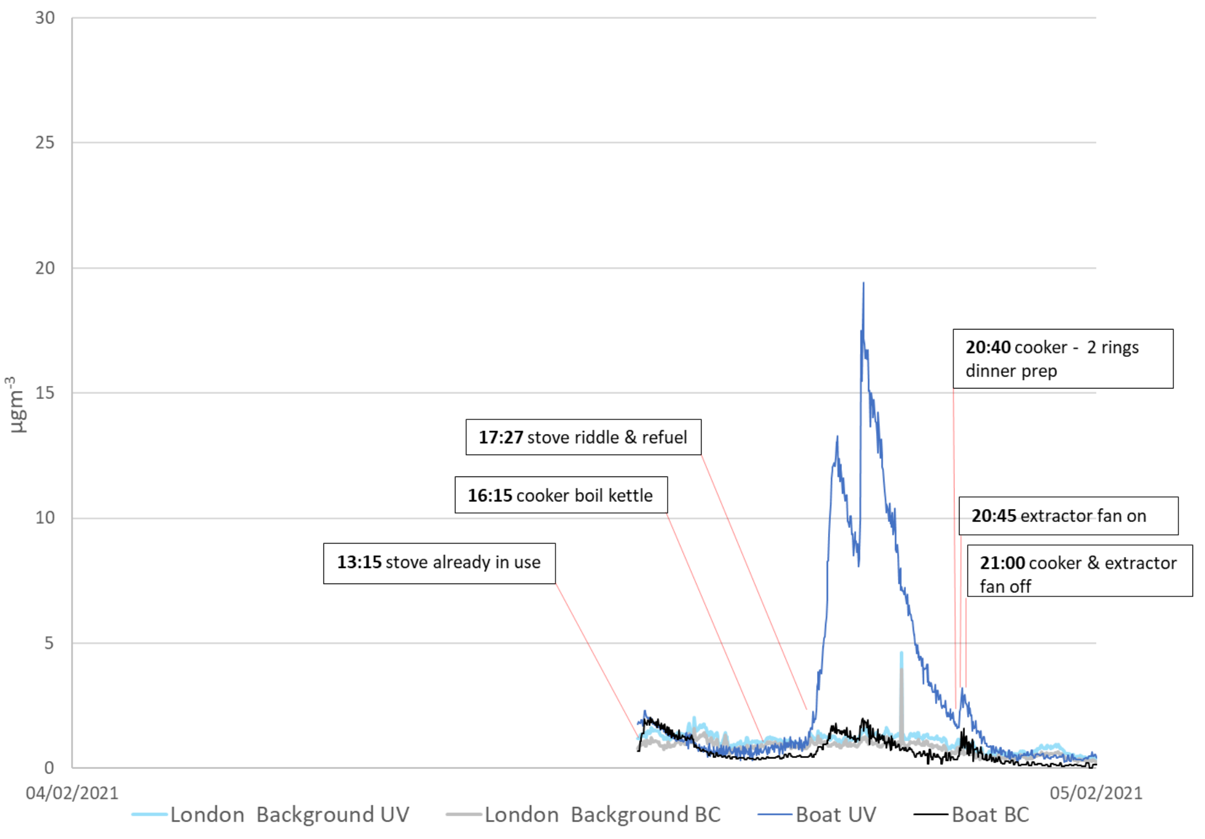
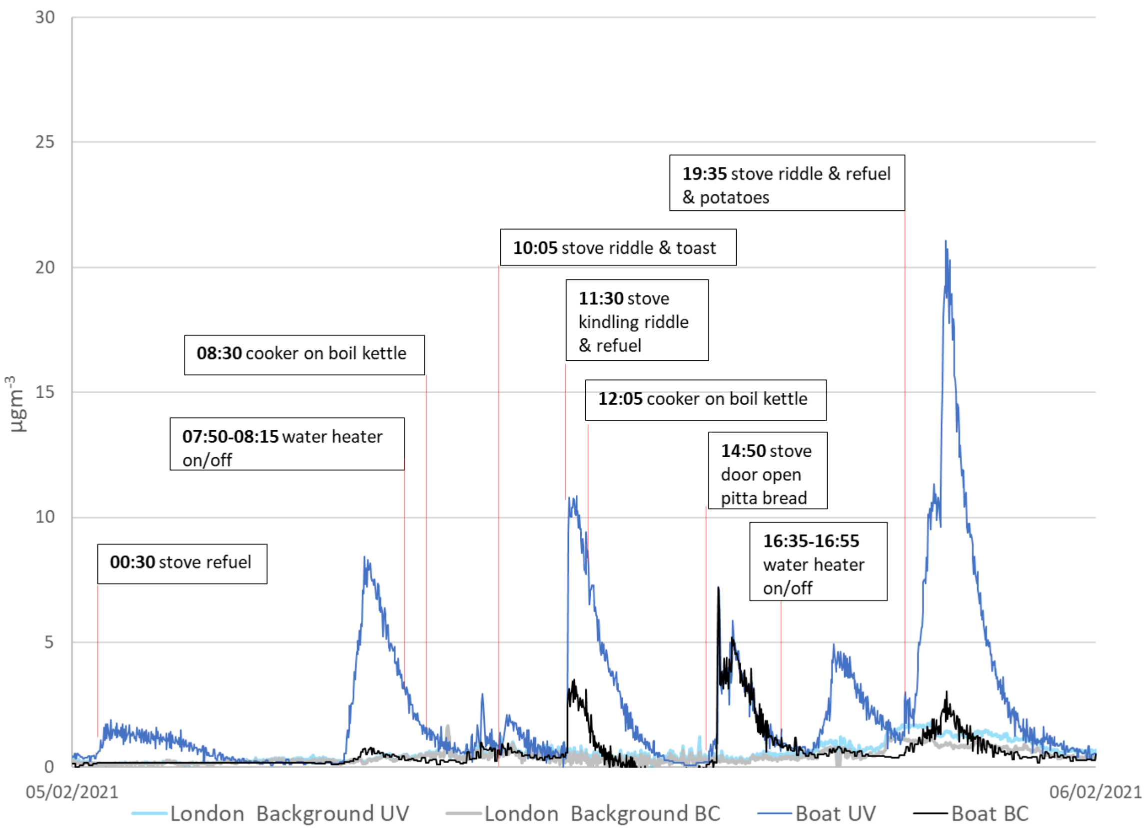


Figure 4-13 shows data from Day 2. An increase in UV measured at 00:30 corresponded to fuel being added to the stove. At 06:15 a peak appeared for both BC with enhanced UV measured. This peak re-occurred at the same time throughout the monitoring period and was not due to any activity on the boat. The use of the water heater from 07:50 to 08:15 and the use of the cooker to boil the kettle showed no significant change in BC or UV measurements. At 10:05 the stove was riddled, and bread was toasted. There was a small increase in UV measured but no significant change in BC which remained at background levels. At 11:30 the stove was riddled, kindling and fuel were added, BC increased from ~ 0.5 to 3.0µgm^{-3} over 20 minutes before decreasing to background levels over the next 40 minutes. There was a large corresponding increase in UV measured which took almost 2 hours to return to ambient background levels. At 14:50 the stove door was opened to warm pitta bread, there was an increase in BC over the next 40 minutes to ~ 5.1 µgm^{-3}, with a peak measurement of ~ 7.2 µgm^{-3}. There were no enhanced UV measurements during this episode, with levels decreasing to background levels after almost two hours. The use of the water heater between 16:35 and 16:55 did not show any significant increase in BC or UV measured. At 17:30 there was an increase in UV measured with no signal increase for BC. This event was not noted in the diary but had the same characteristic as adding fuel to the stove, as seen earlier in the day at 00:30. The increase in UV measurements was over 40 minutes and levels continued to decrease over the next hour. At 19:35 the stove was riddled and refuelled, and potatoes were cooked on the stove. There was an increase in BC from ~0.5 to 3.0 µgm^{-3} over an hour, decreasing to background levels over 90 minutes. There was a very large increase in UV over an hour, taking two hours to return to ambient background levels.

Figure 4-13. BC & UV measurement data - Boat B - Day 2



Data for day 3 can be seen in Figure 4-14. At 00:00 there was a small increase in UV as the stove was opened to remove ash. Again, there was mostly enhanced UV at the reoccurring unexplained episode at the regular time of 06:15. At 10:20 the stove was riddled, refuelled and kindling used. BC increased from ~0.4 to 6.0 µgm^{-3} over 10 minutes and decreased to background levels over 2 hours. There was a large UV measurement for this event over 10 minutes, also decreasing to background levels over 2 hours. At 12:50 the stove was opened to toast bread, there was an increase in the UV signal and a small BC increase. At 13:10 the stove was refuelled, UV measurements continued to increase, and BC increased to ~ 1.0 µgm^{-3}. The UV measurement took almost 2 hours to return to background levels. At 15:40 the stove was used to heat pitta bread and there was a small increase in UV and a very small increase in BC ~ 0.3 µgm^{-3}. At 17:15 the UV measurement began to increase. The increase continued for just over an hour and decreased over the next 90 minutes. There was a slight BC increase at the same time from ~0.5 to 1.1 µgm^{-3} over 40 minutes. This event did not have a diary entry. The use of the cooker oven from 19:15 to 19:45 did not lead to an increase in BC or UV measurements. A small BC peak ~ 0.3 µgm^{-3} with an enhanced UV peak at 20:00 did not have a diary entry to explain it. The stove was refuelled at 23:50 and there was a slight BC increase and a gradual UV increase throughout the night.

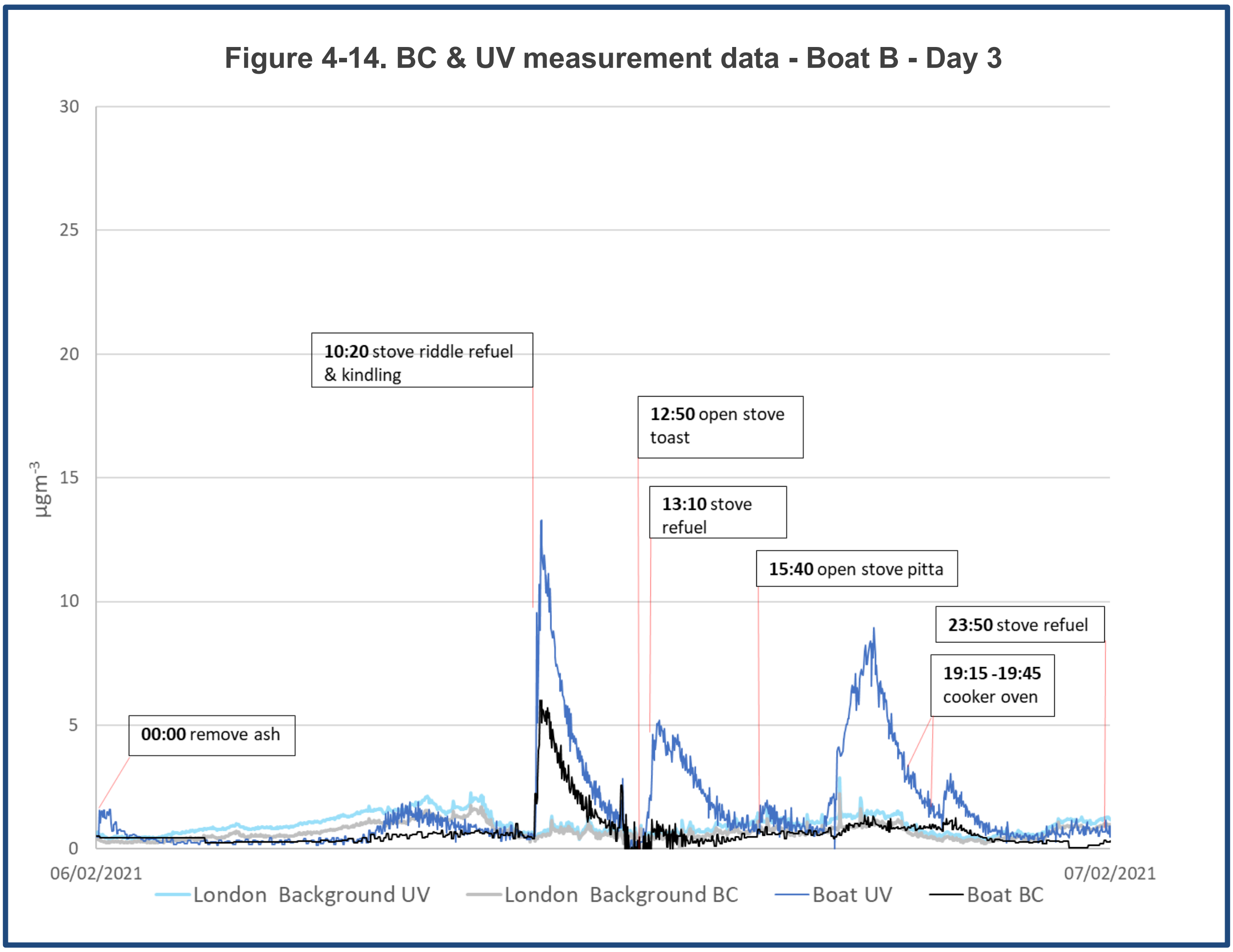


Figure 4-15 shows measurements for Day 4. Beginning at 06:15 there was the usual unexplained regular peak, this time almost completely a UV measurement with only a very slight BC increase. At 10:00 the stove was riddled and refuelled, BC increased from ~0.2 to 2.4 μgm^{-3} over 30 minutes. There was a very large, enhanced UV measurement increasing for over an hour. At 11:50 the door of the stove was opened to toast some bread, UV measured levels increased for 15 minutes before decreasing to background levels in just under two hours. At 17:10 the stove was riddled, and refuelled BC increased from ~0.1 to 1.4 μgm^{-3} over 30 minutes. BC measurements peaked at ~ 2.7 μgm^{-3} an hour after the stove was refuelled. Similarly, there was an enhanced UV measurement which peaks an hour after the fuel was added. BC levels then returned to background levels after an hour whereas UV measurements remained above background levels over two and a half hours later. At 20:30 two gas rings were used to prepare dinner, BC increased from ~0.3 to 1.5 μgm^{-3}. There was also an enhanced UV measurement. Both BC and UV measurements decreased at the time the extraction fan was switched on. There was no diary entry for the increase in BC and enhanced UV measured at 21:25.

Figure 4-15. BC & UV measurement data - Boat B - Day 4

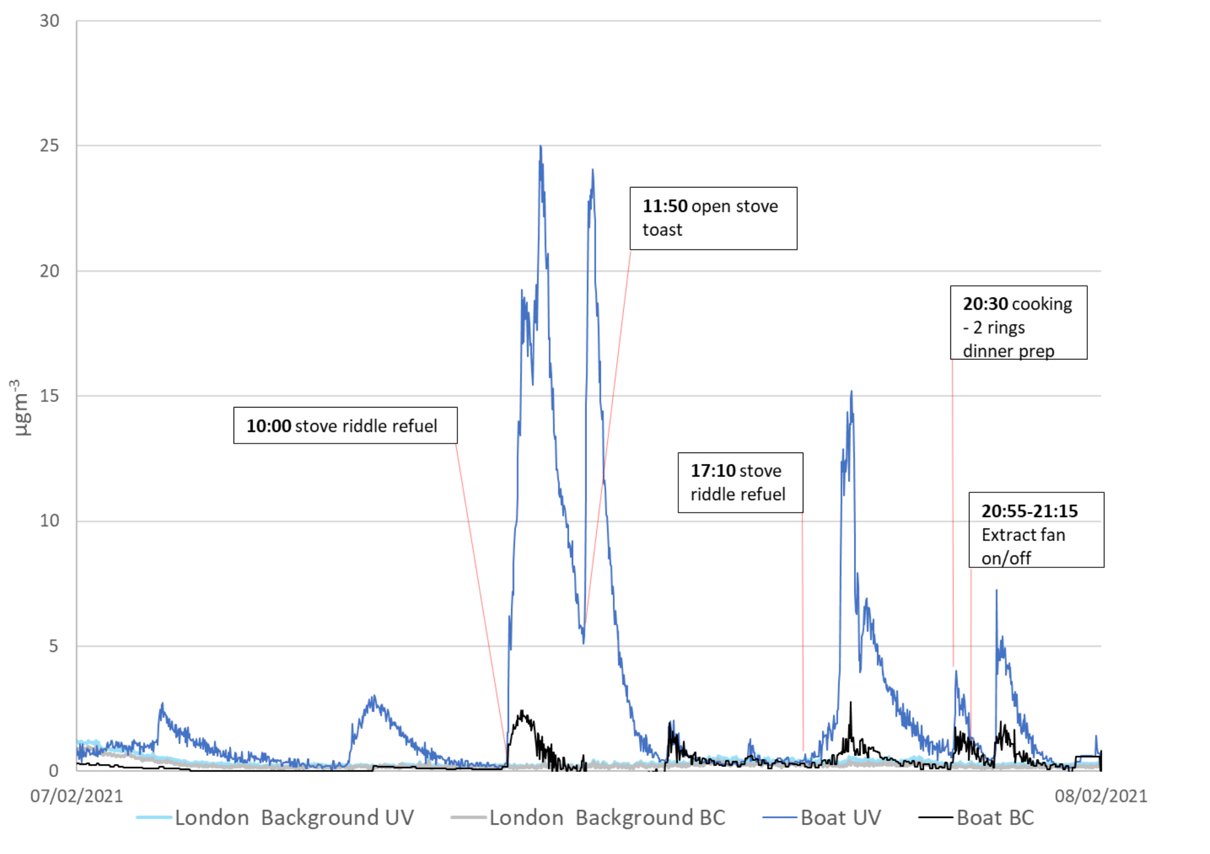
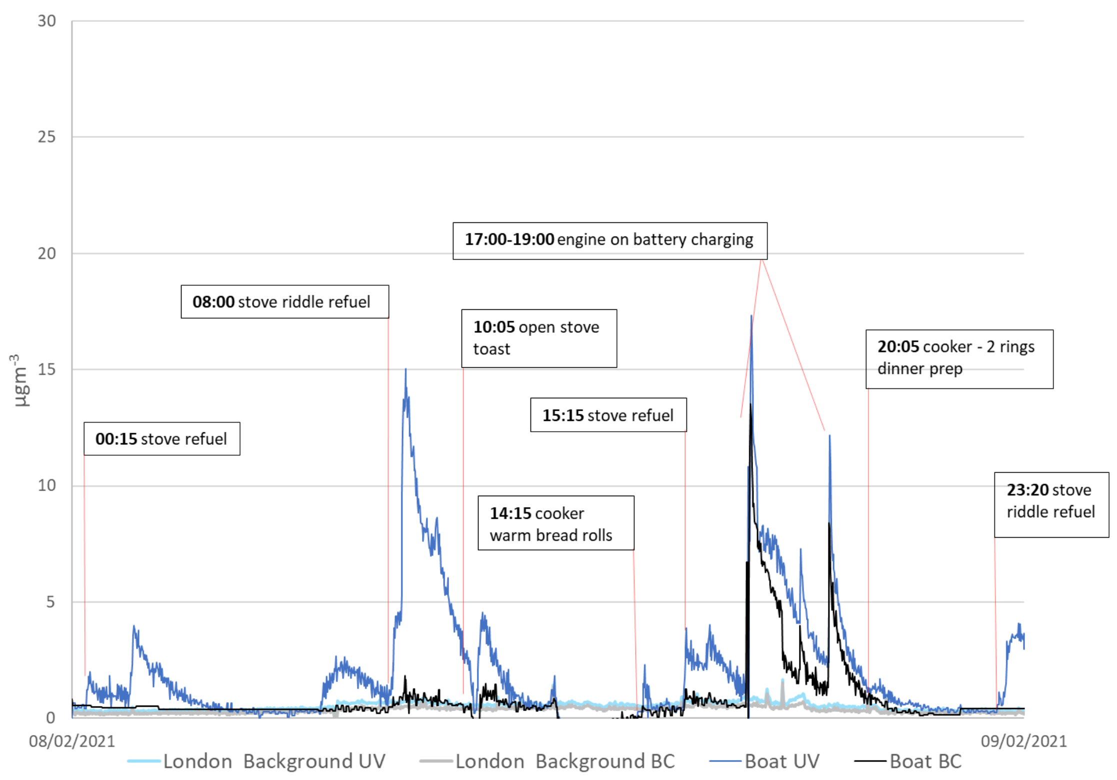


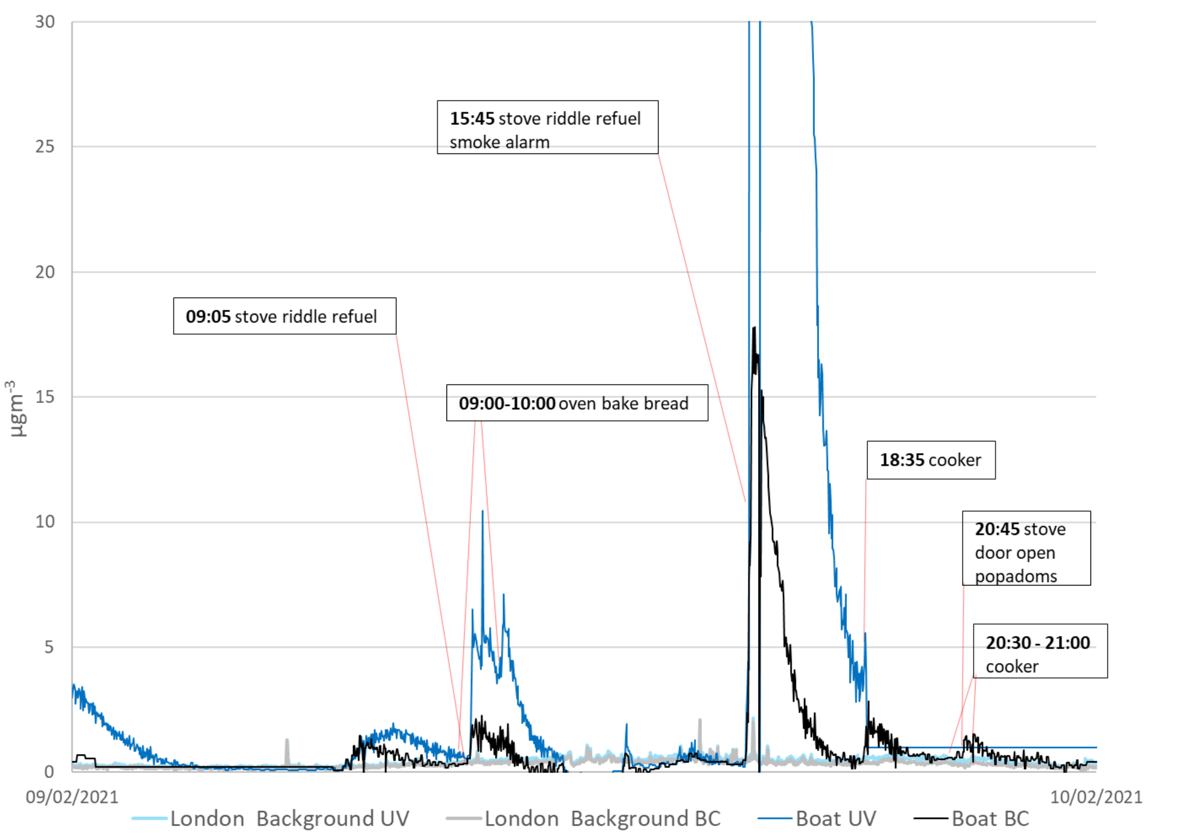
Figure 4-16 shows measurements for Day 5. UV increased from 00:15 when the stove was refuelled. There was no BC signal. At 06:15 there was the regular increase in UV measured but this time no significant BC increase. At 08:00 The stove was riddled and refuelled, there was an increase in BC from ~0.2 to 1.2 μgm^{-3} with a peak at ~1.8 μgm^{-3}, the increase was sustained over 30 minutes. This was accompanied by a very large UV measurement which decreased to background levels over 90 minutes. At 10:05 the stove door was opened to toast bread, BC increased to 1.2 μgm^{-3} from background levels. Further increases in BC and UV measurements occurred at 14:15 when the cooker was used to warm bread and at 15:15 when the stove was refuelled. The BC increase in both cases was small <0.3 and 0.5 respectively with enhanced UV. Between 17:00 and 19:00 the diesel engine was started and run for battery charging. A large increase in BC from background levels ~0.5 μgm^{-3} to 13.5 μgm^{-3} was observed six minutes later. There was slightly enhanced UV, but most of the measurement was BC. BC levels decreased gradually to ~6.0 μgm^{-3}after 30 minutes and ~2.0 μgm^{-3}after an hour. There were further increases however to ~4.0 μgm^{-3}after 75 minutes and ~8.0 μgm^{-3}after two hours when the engine was switched off. This final BC peak decreased to background levels over 90 minutes. The steady decrease in BC and UV was interrupted slightly at 20:05 when the cooker was used to prepare dinner. At 23:20 the stove was riddled and refuelled and there was a UV measurement without a BC increase. This UV measurement continued to increase over 20 minutes, decreased after 40 minutes and returned to background levels 150 minutes later, on Day 6.

Figure 4-16. BC & UV measurement data - Boat B - Day 5



Data from Day 6 is presented in Figure 4-17. At 06:15 there was the regular UV and BC increase. BC increased from ~0.1 to 1.0 μgm^{-3} with an enhanced UV measurement. From 09:00 to 10:00 the oven was used to bake bread and BC increased from ~0.4 to 2.3 μgm^{-3} with an increase in the UV measurement. At 15:45 the stove was riddled and refuelled and there was enough smoke in the living area to set off the smoke alarm. BC levels peaked at 17.8 μgm^{-3} returning to background levels after two hours. UV measurements remained elevated after two and a half hours. Both BC and UV measurement data are shown scaled in Figure 4-18. The high UV measurements affected the micro-aethalometer data and UV measurements did not return to background until later in the morning of Day 7. Use of the cooker at 18:35 and 20:30 as well as opening the stove door to heat food at 20:45 resulted in increases in the BC measurement.

Figure 4-17. BC & UV measurement data - Boat B - Day 6



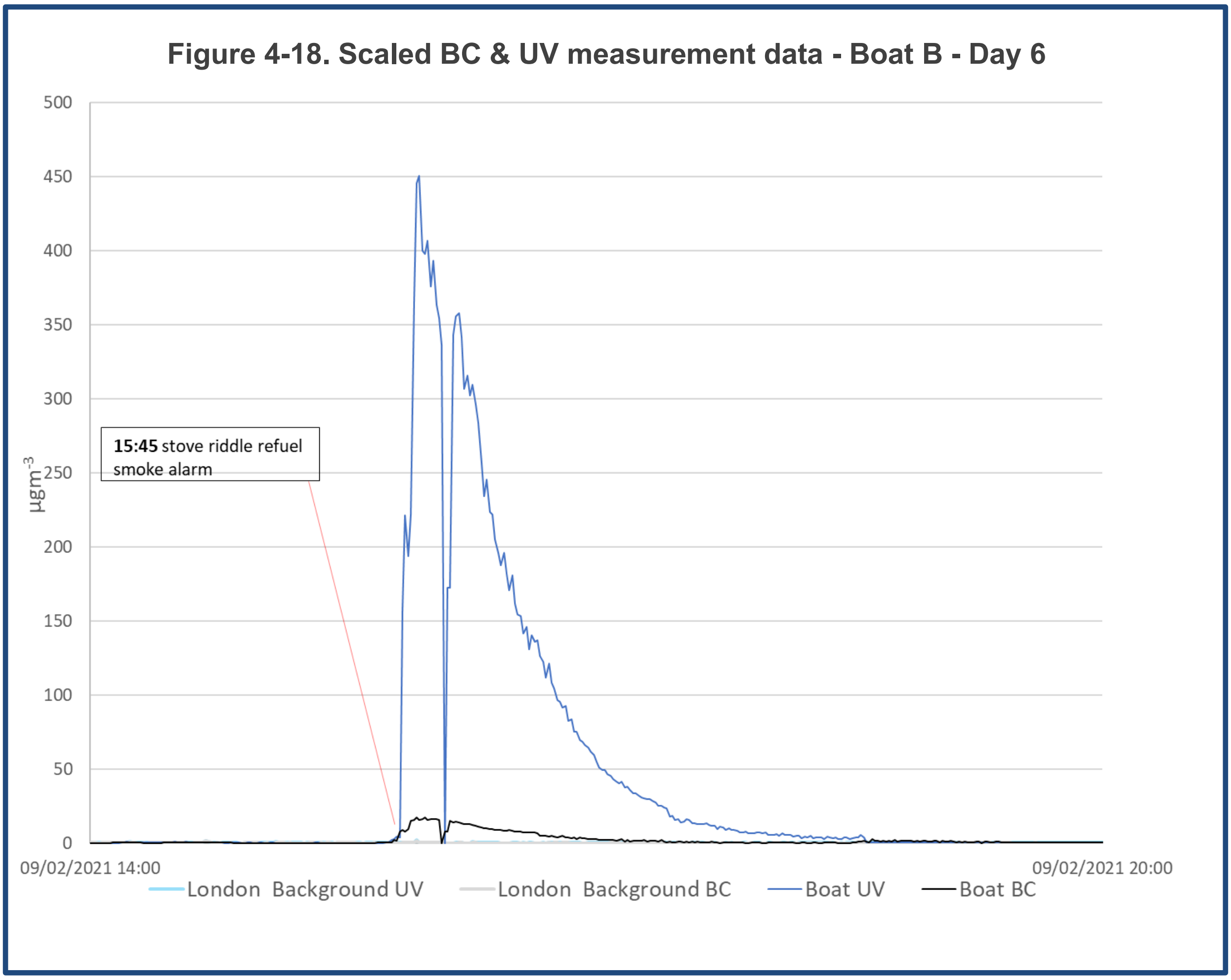
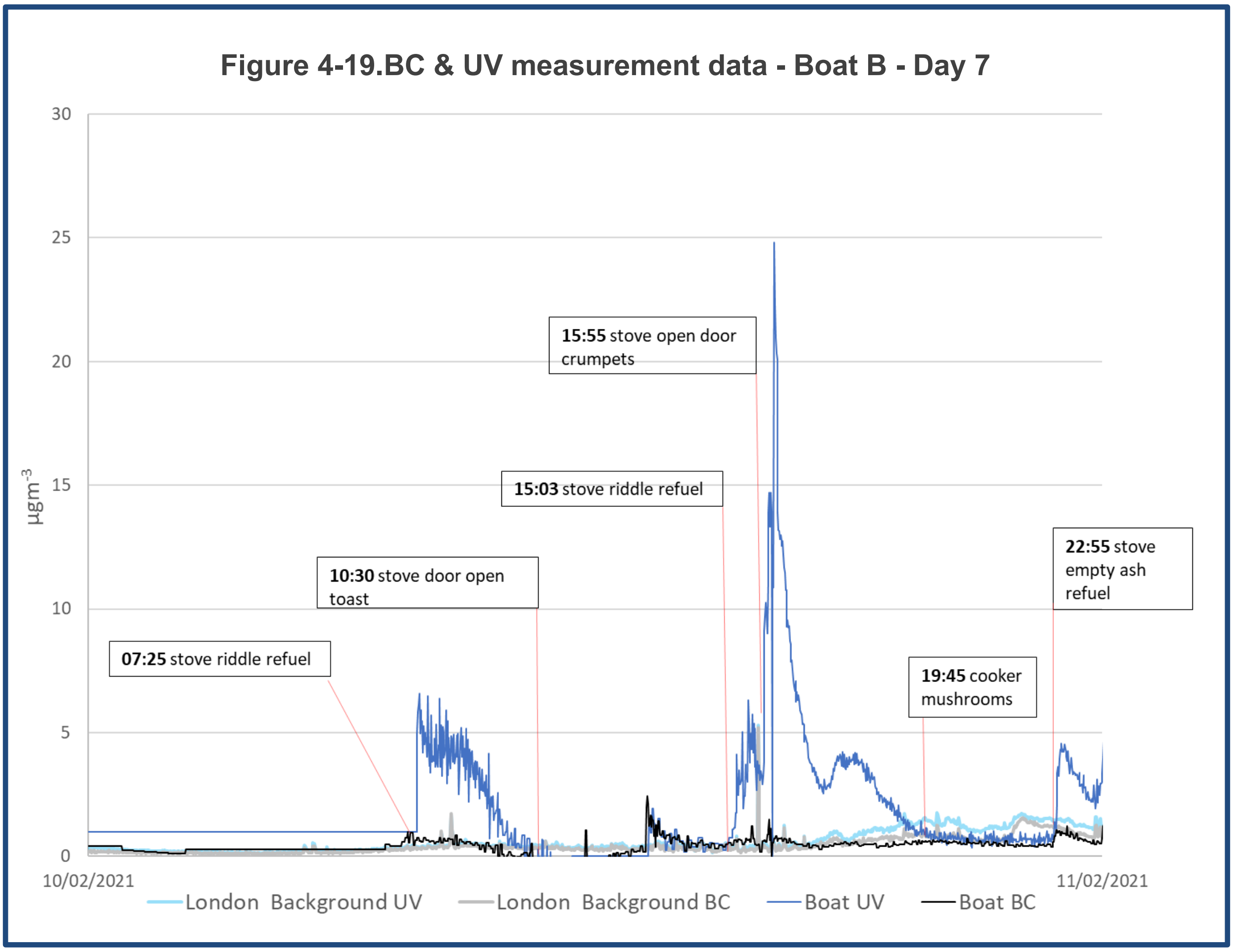


Figure 4-18. Scaled BC & UV measurement data - Boat B - Day 6
500
450
400
350
300
250
200
150
100
50
0
µgm-3
15:45 stove riddle refuel smoke alarm
09/02/2021 14:00
09/02/2021 20:00
London Background UV
London Background BC
Boat UV
Boat BC

Day 7 data is shown in Figure 4-19. UV measurements returned to near background concentrations soon after the stove was riddled and refuelled at 07:25. There was also a small increase in BC. At 10:30 the stove door was opened to toast bread but there was no increase in BC or UV measurements. At 15:03 the stove was riddled and refuelled with only a slight increase in BC measurements but enhanced UV. At 15:55 the stove door was opened again with a slight blip in BC but a large increase in UV measurement, which only returned to background levels after three and a half hours. At 19:45 the cooker was used to cook mushrooms but there was no BC or UV increase. At 22:55 when the stove was refuelled, BC increased from ~0.4 to 0.9 μgm^{-3} with increased UV measurements.



Data from Day 8 on Boat B is displayed in Figure 4-20 and Figure 4-21 . In what looks like a continuation of the riddling and refueling of the stove from Day 7, BC increased to ~ 3.0 μgm^{-3} with increased UV measurements. The regular peak at 06:15 was evident again, this time with a very small BC increase of ~ 0.5 μgm^{-3} with a larger UV measurement. The stove was riddled and refuelled at 08:55, the UV signal increased gradually over the following 45 minutes before a very large increase. At the same time as the very large UV increase, BC increased from background levels of ~ 0.5 μgm^{-3} to peak at ~ 2.8 μgm^{-3}. The full scaling for this UV peak can be seen in Figure 4-21. At 10:40 the stove door was opened again to toast bread and there was another large UV measurement with BC levels also increasing slightly from ~1.0 to 1.7 μgm^{-3}. Monitoring finished on Day 8 at 12:00.

Figure 4-20. BC & UV measurement data - Boat B - Day 8

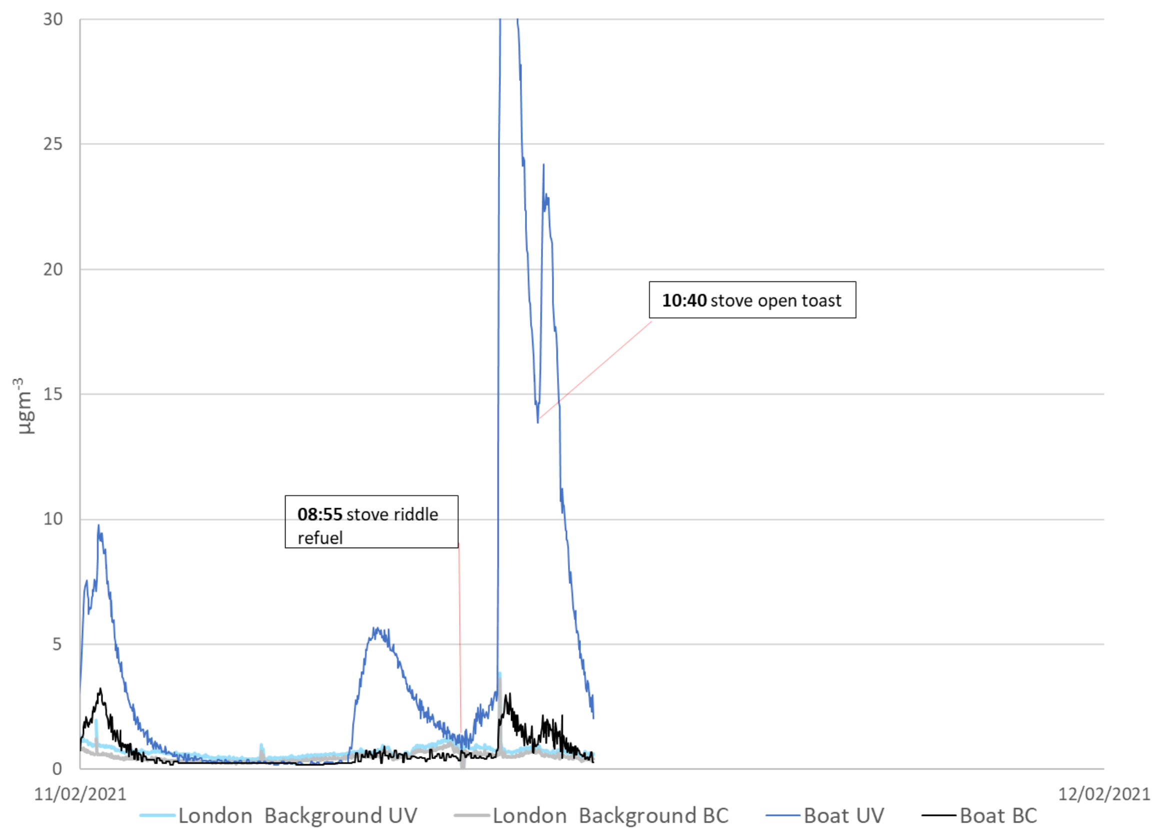
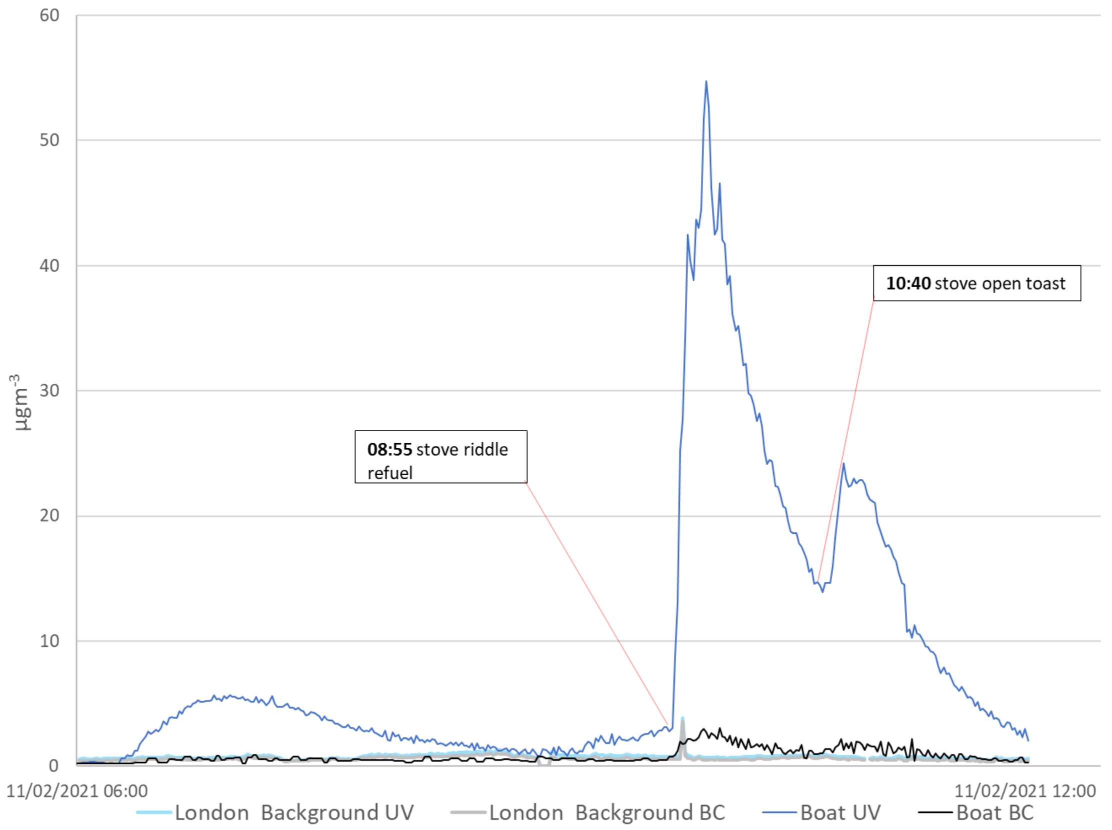


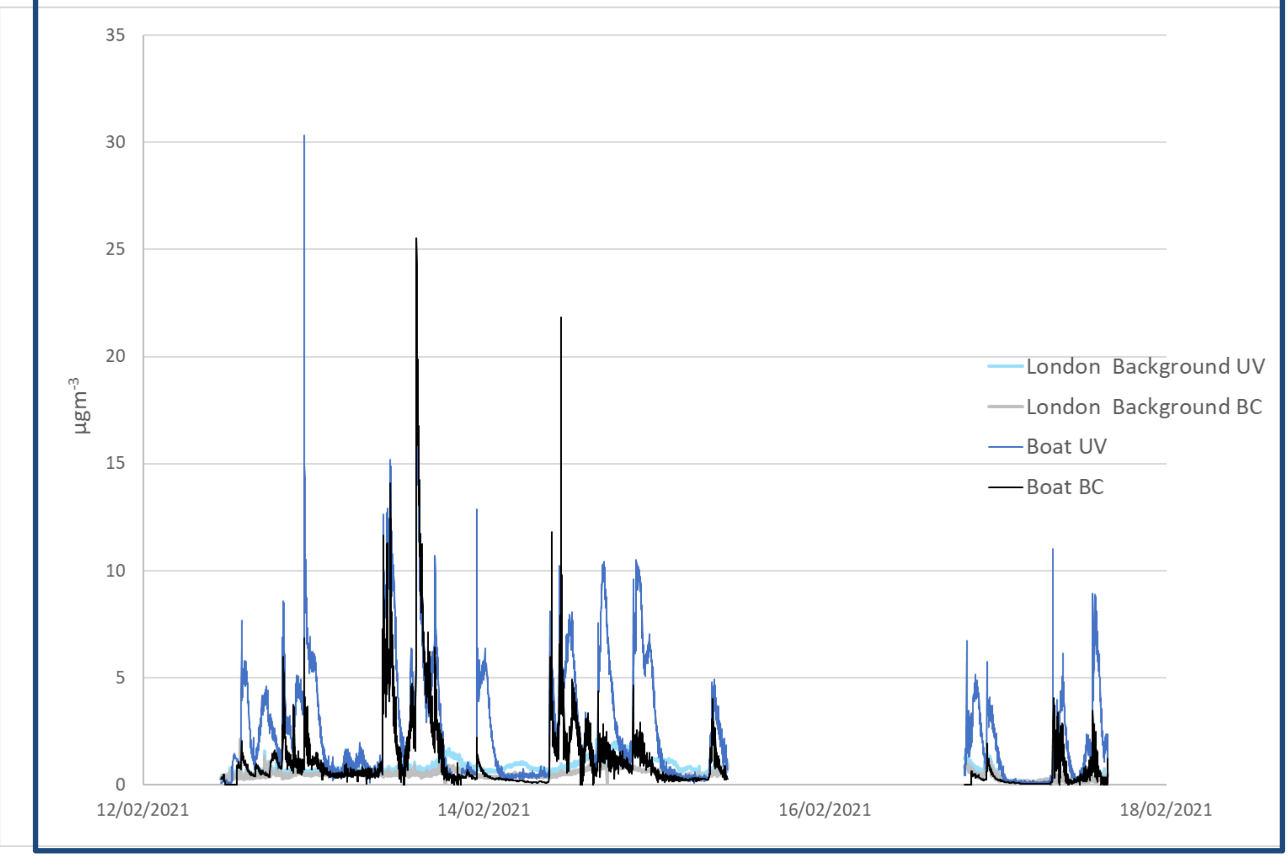
Figure 4-21. Scaled BC & UV measurement data - Boat B - Day 8



Boat C

A total of 91 hours of monitoring data was analysed from Boat C, with reference to a diary of activities and times, as recorded by the boat's owner. Monitoring was carried out from Day 1 on 12th February to Day 6 on 17th February 2021. Figure 4-22 shows BC and UV measurements over the monitoring period. BC measurements ranged from 0 to ~ 26 µgm^{-3} between Day 1 and Day 6. For context, London ambient background BC and UV measurements from the Air Quality Monitoring Station (AQMS) at North Kensington are plotted in addition to the boat BC and UV measurements. This boat moved location during the monitoring period. Monitoring continued while the boat was moving and after it reached its new location. The boat is also different in another aspect in that it uses two stoves, often lit at the same time.

Figure 4-22. BC & UV measurement data - Boat C - Monitoring Day 1- Day 6



Data from Day 1 is presented in Figure 4-23. BC increased from ~0.8 to 1.9 μgm^{-3}, four minutes after both stoves were refuelled. This was accompanied by an increase in the UV measurement. However, UV measurements continued increasing for 30 minutes after refueling. BC decreased to background levels after an hour whereas UV levels were still above background when stove 2 was refuelled nearly two hours later at 15:48. BC increased from ~0.5 to 1.0 μgm^{-3}, 3 minutes after fuel was added. UV continued to increase 90 minutes after refueling. UV measurement levels then decreased over the following 2 hours. From 18:30 to 19:40 cooking took place and immediately after there was a BC peak > 5.0 μgm^{-3} along with some increase in UV measurement. A BC peak from background to 3.7 μgm^{-3} at 21:08 corresponded to refueling stove 1. There was associated UV measured which remained elevated until the next time stove 1 was refuelled at 22:40. At this time BC levels increased from ~0.7 to 6.9 μgm^{-3} over 5 minutes. Stove 2 was refuelled at 22:55 and BC spiked at ~ 3.3 μgm^{-3} and 2.9 μgm^{-3}. BC levels started decreasing almost immediately following these peaks but only returned to background levels more than 90 minutes later, early in Day 2. UV measurements for these events were high and took two hours to decrease to background levels.

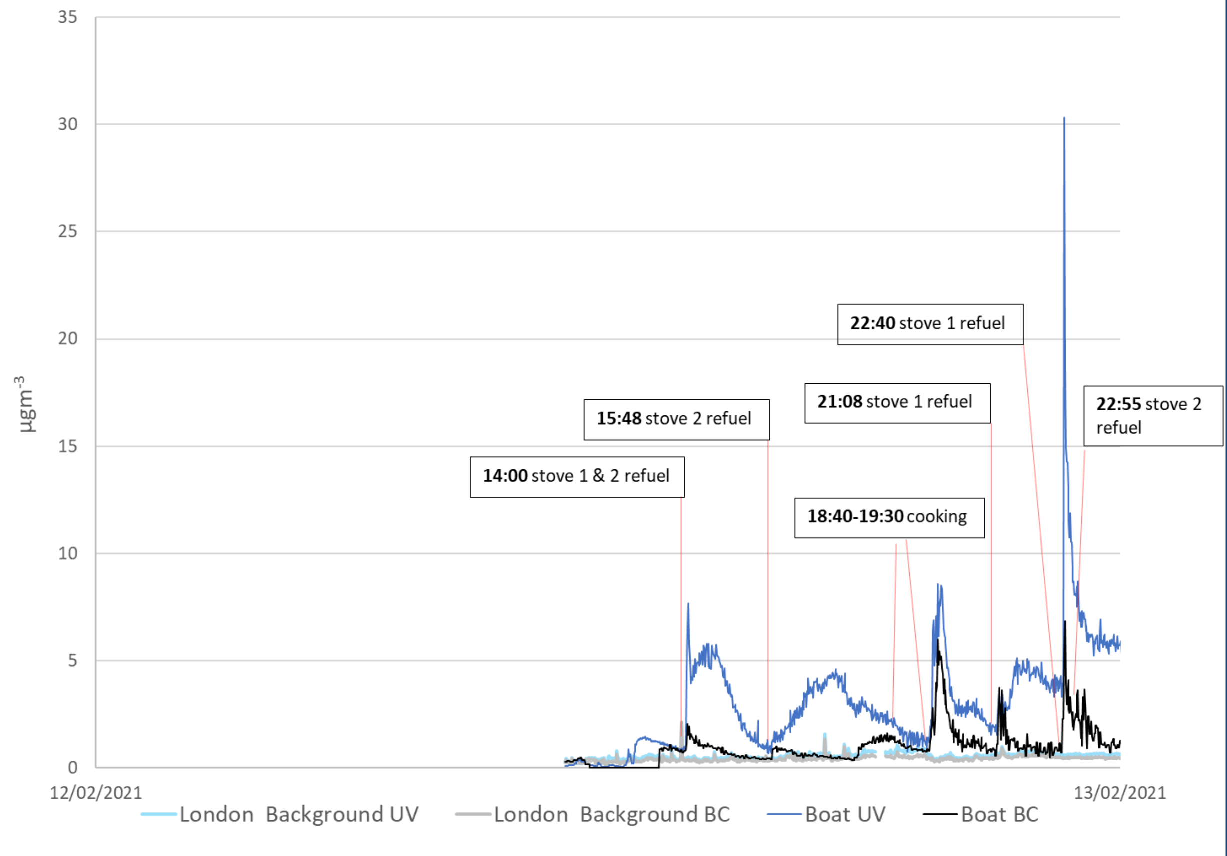
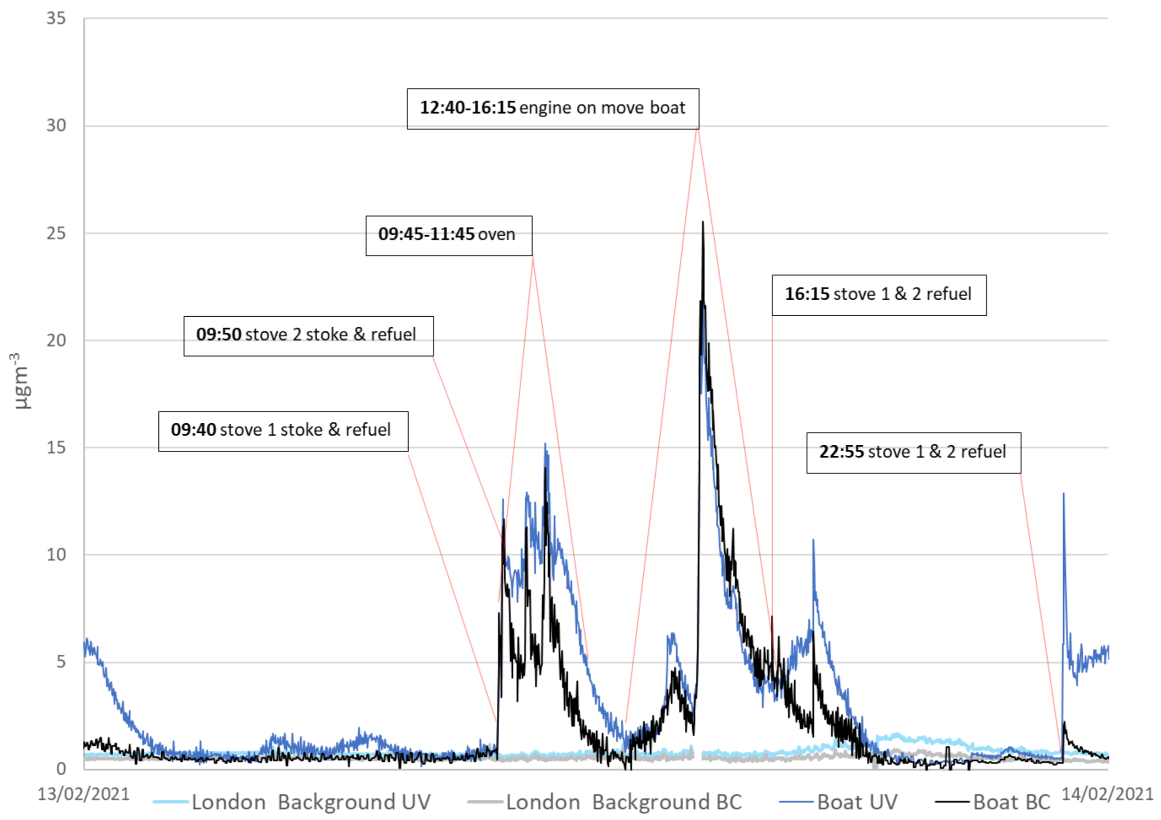


Figure 4-23. BC & UV measurement data - Boat C - Day 1

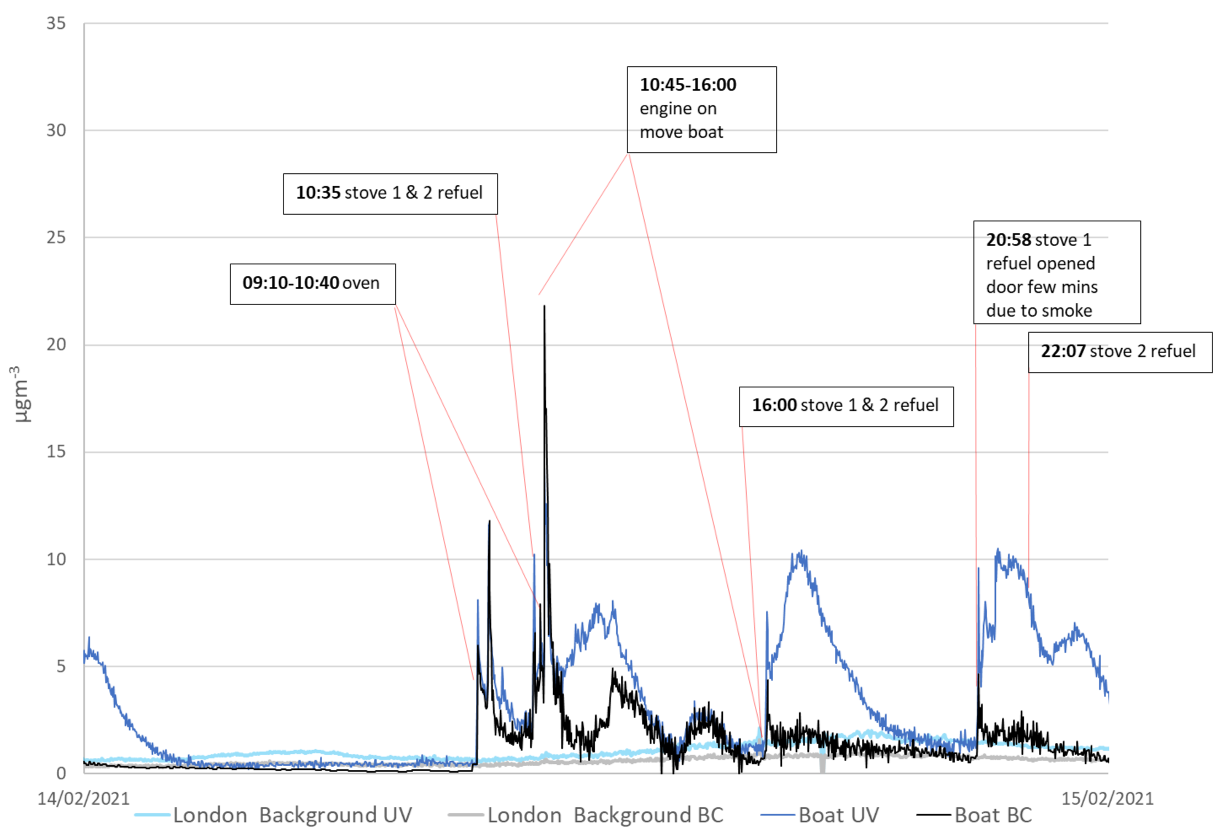
Figure 4-24 shows measurements for Day 2. At 09:40 stove 1 was stoked and refuelled. At 09:50 stove 2 was stoked and refuelled. BC levels begin to increase from 09:40 but as the oven was then in use from 09:45 to 11:45 it's not obvious which event was responsible for the high BC levels, up to 11.6 μgm^{-3} at 09:51 and up to 14.1 μgm^{-3} later at 10:49. UV measurements remained enhanced throughout this period although not hugely increased. From 12:40 to 16:15 the boat moved location. The engine was in use and a number of high BC measurements were observed. From 12:40, BC steadily increased from background levels, peaking at ~ 4.3 μgm^{-3}, one hour later. At 14:30 there was a large BC peak of 25.5 μgm^{-3}. There was very little, or no additional UV measured for these peaks, as expected from diesel exhaust emissions. More than 90 minutes after the large BC peak, BC levels were still > 4.0 μgm^{-3}. At 16:15 stoves 1 and 2 were refuelled and there were some small spikes in BC measured. There was enhanced UV, which continued to increase for 50 minutes, before a large peak at 17:06. There was also a BC peak at 17:06, with BC increasing from ~1.7 to 6.4 μgm^{-3}. There was no diary entry for this peak at 17:06. Later at 22:55 both stoves were refuelled, and BC increased from background levels of ~0.2 to 2.2 μgm^{-3} in a few minutes. A large, elevated UV measurement was also noted. BC levels decreased to background levels after an hour, with UV measurements remaining above background concentrations for over 3 hours, into Day 3.

Figure 4-24. BC & UV measurement data - Boat C - Day 2



Data from Day 3 on Boat C is presented in Figure 4-25. The oven was in use between 09:10 and 10:40. BC increased immediately when the oven was used. An initial spike of 6.0 μgm^{-3} was followed by a spike of 11.8 μgm^{-3}. As measurement values decreased from 09:30, an enhanced UV trace was visible. At 10:40 there were some more BC peaks but this period overlaps when the stove was refuelled at 10:35. It's difficult to determine which event was responsible for which peak around this time. A BC concentration of 6.6 μgm^{-3} was measured at 10:34, one minute before the stoves were refuelled. At 10:42 there was a BC concentration of 7.9 μgm^{-3}. There was very little enhanced UV measured over this period to 10:40. From 10:45 to 16:00 the engine was in use as the boat was being moved. At 10:48 there was a large BC peak measuring 21.8 μgm^{-3}. This high BC concentration fell away rapidly, however a number of smaller BC peaks were noted until the engine was turned off at 16:00. BC concentration was measured at 4.9 μgm^{-3} at 12:23 and at 3.3 μgm^{-3} at 14:38. An enhanced UV measurement occurred shortly after fuel was added to the stoves at 10:35 however measurements that followed while the engine was in use are almost completely BC. At 16:00 when the engine was switched off the stoves were refuelled, BC increased to ~ 2.0 μgm^{-3} with a high associated UV measurement. The levels increased for almost an hour after fuel was added and then decreased to background levels over the next two hours. At 20:58 stove 1 was refuelled and the boat's door was opened for a few minutes due to smoke. Measurements are similar to the previous episode at 16:00, with a spike in BC to 4.7 μgm^{-3} and a levelling off at concentrations of ~ 2.5 μgm^{-3}, over an hour later. A high associated UV measurement also occurred. At 22:07 stove 2 was refuelled and there was another increase in the UV measurement but no significant change to BC.

Figure 4-25. BC & UV measurement data - Boat C - Day 3



Monitoring data from Day 4 is presented in Figure 4-26. This was a short measurement day as the monitor's battery completely discharged and needed to be taken off site to recharge. Overnight measurement levels of BC and UV returned to very low levels. UV measurement returning to background levels at 02:00 on Day 4, four hours after stove 2 was refuelled and five hours after stove 1 was refuelled. BC levels returned to background concentrations quicker, an hour and a half after fuel was added to stove 2. At 08:03 when both stoves were refuelled, BC peaked at 4.0 μgm^{-3} minutes later. BC levels returned to background concentrations after an hour. There was an enhanced UV measurement for this event with UV measurements taking almost two hours to return to background levels. The battery ran out on the monitor at 10:14.

Figure 4-26. BC & UV measurement data - Boat C - Day 4

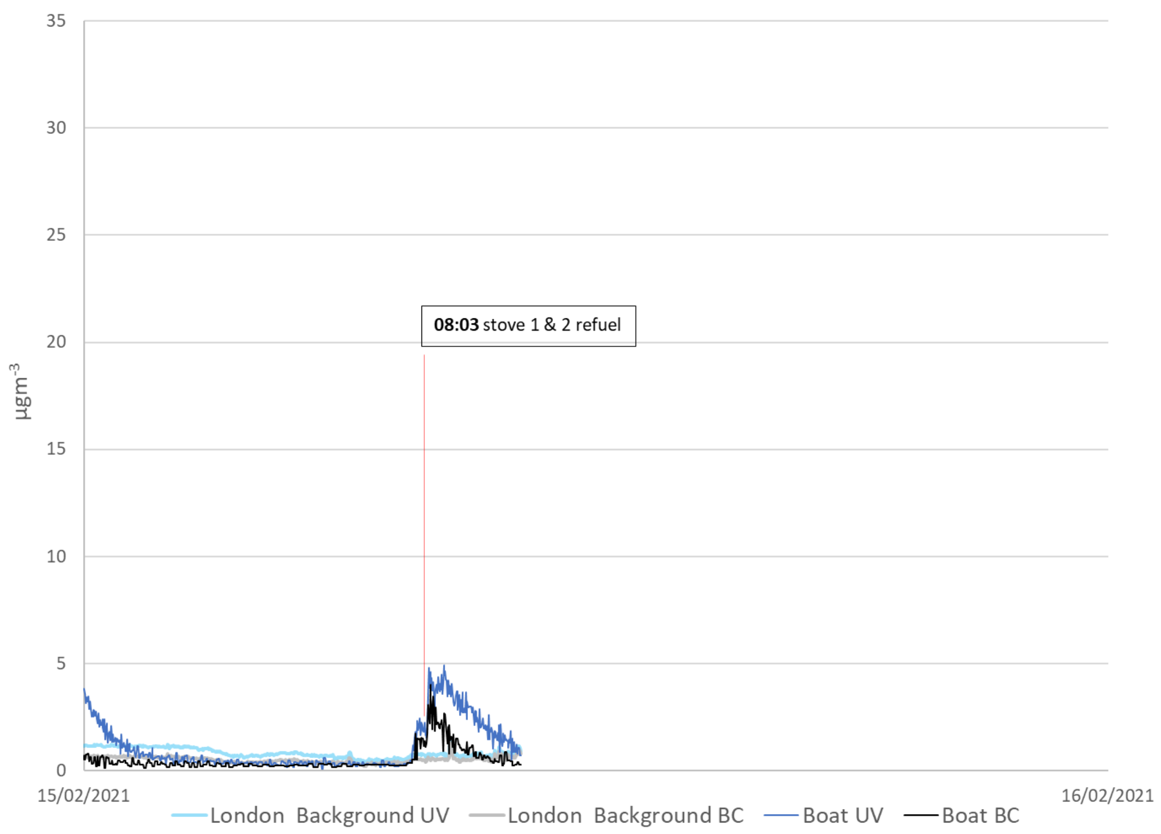
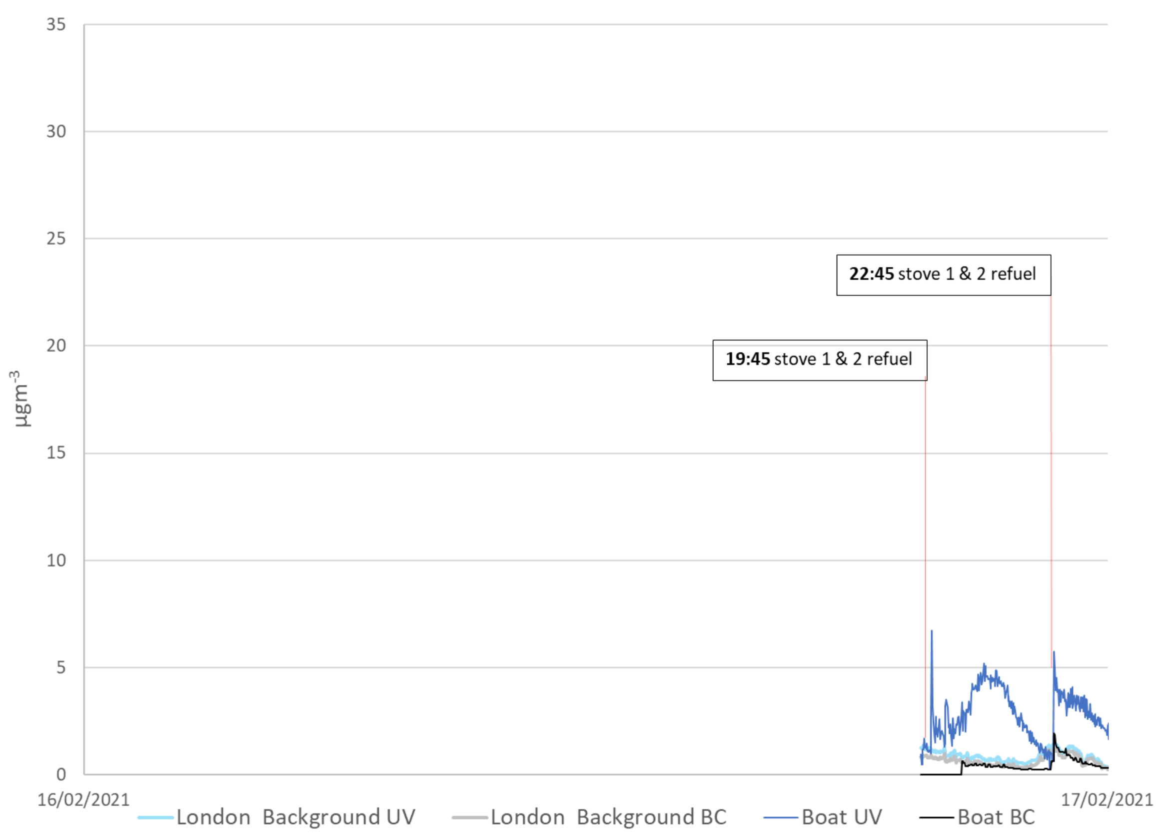


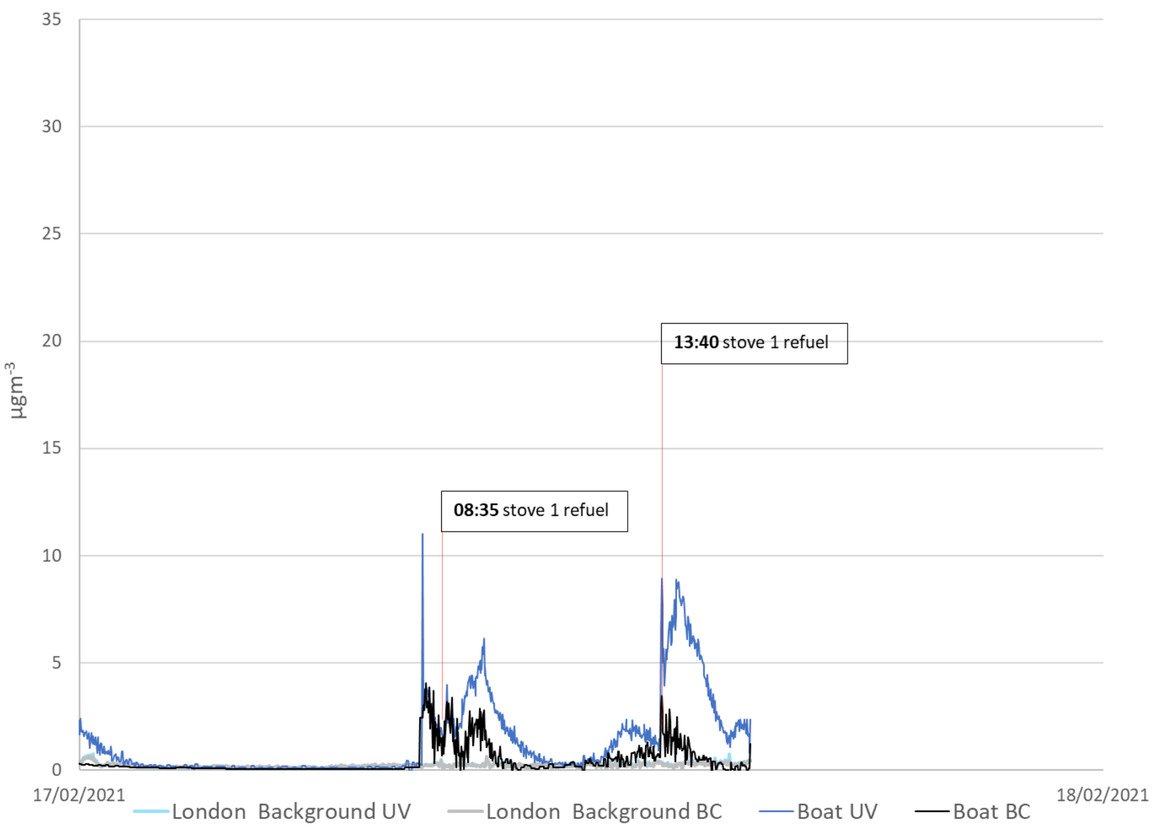
Figure 4-27 shows data from Day 5. The monitor was restarted at 19:37, after recharging. Initially BC measurements appeared to be unresponsive. Both stoves were refuelled at 19:45, BC measurements did not respond but this must be treated with caution as the analyser had just restarted. There was an enhanced UV measurement. UV measurements peaked after just over an hour before decreasing 40 minutes later to background levels after a further hour. At 22:45 both stoves were refuelled. BC increased over a few minutes to 1.9 µgm^{-3}. There was also an increase in UV associated with this event. BC levels decreased over the next hour to background levels. UV decreased for over two and a half hours returning to background levels the following day.

Figure 4-27. BC & UV measurement data - Boat C - Day 5



Data from the final day's monitoring, Day 6 on Boat C, is displayed in Figure 38. Two events were noted in the diary. Refueling stove 1 only at 08:35 and again at 13:40. There was an unidentified BC peak beginning at 08:00. At 08:35 BC increased again when the stove was refuelled, BC peaked at 3.1 μgm^{-3} five minutes later before dropping to near background levels before it increased again to ~ 2.3 μgm^{-3}, 30 minutes later. BC returned to background concentrations an hour after the stove was refuelled. UV measurements peaked 50 minutes after the stove was refuelled, returning to background levels 90 minutes later. At 12:25 there was a small unidentified BC and enhanced UV signal. At 13:40 the stove was refuelled, BC increased to 3.5 μgm^{-3} within two minutes and decreased to background levels 50 minutes after fuel was added. The UV measurement peaked 20 minutes after fuel was added and had not returned to background levels by the time the monitor was switched off at 15:44, two hours after fuel was added to the stove.

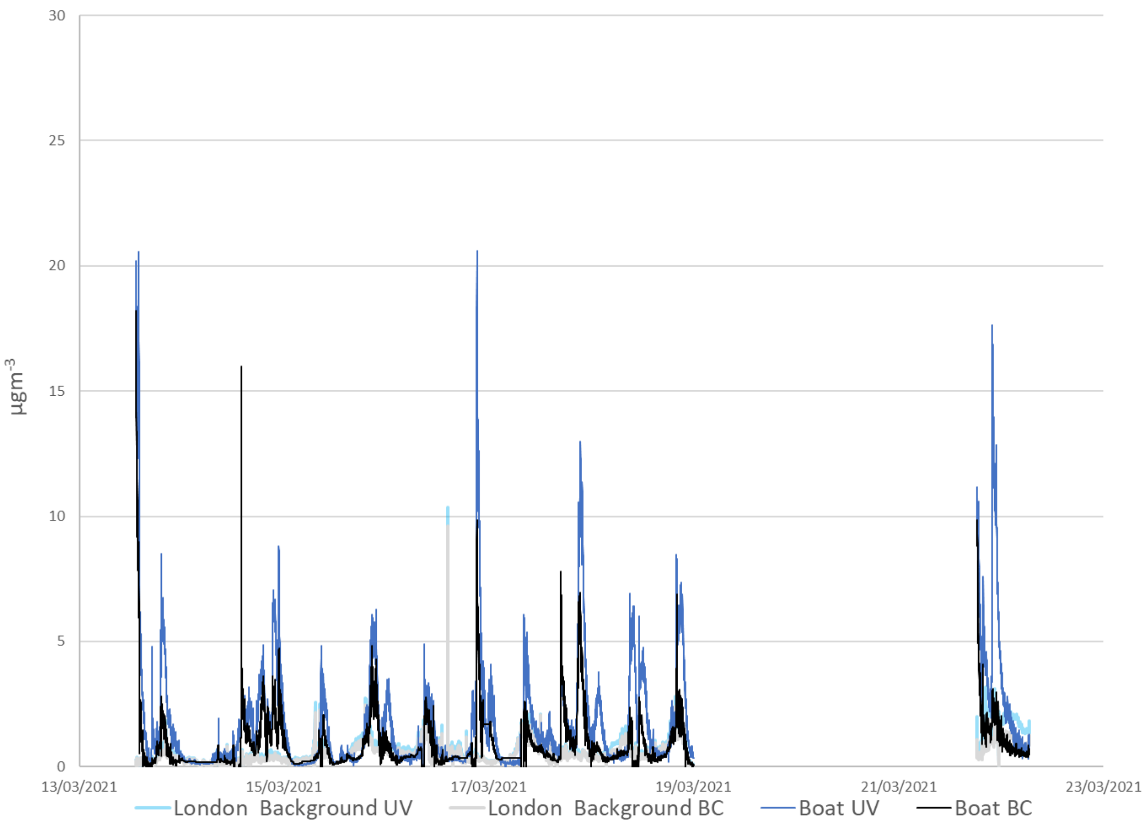
Figure 4-28. BC & UV measurement data - Boat C - Day 6



Boat D

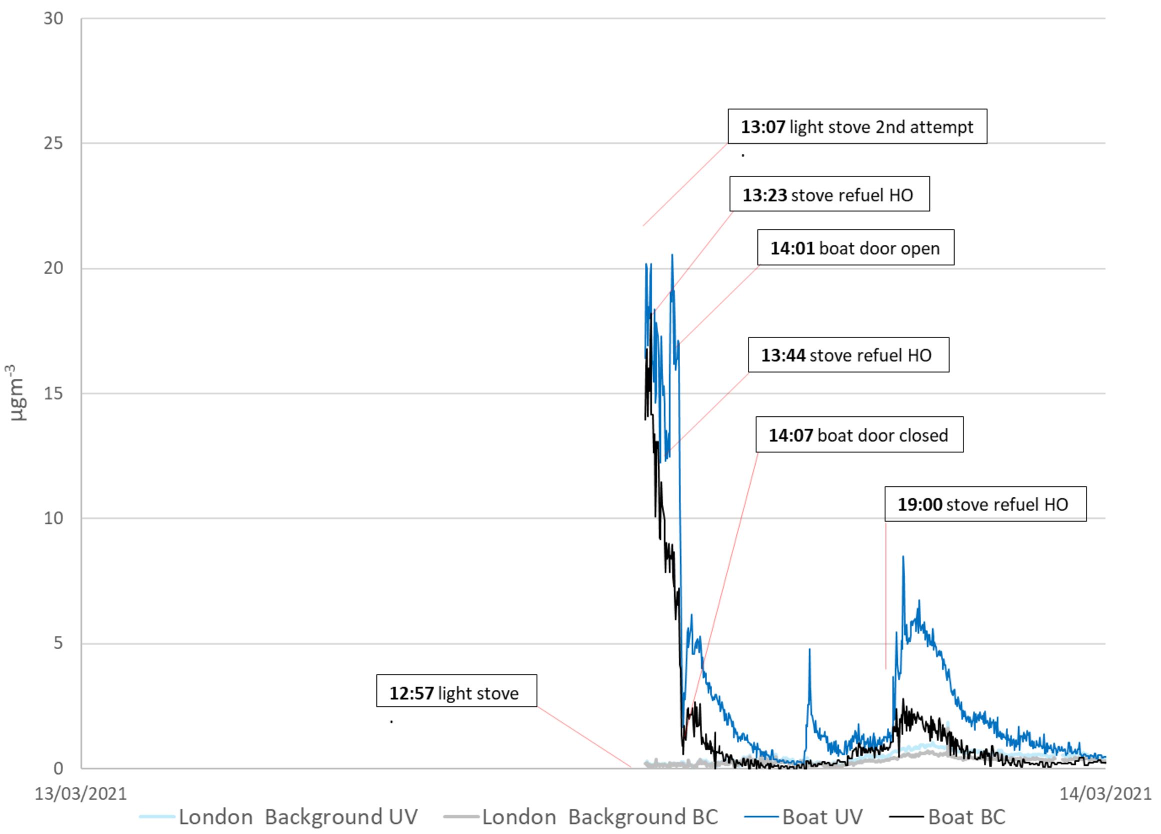
A total of 144 hours of monitoring data was analysed from Boat D, with reference to a diary of activities and times, as recorded by the boat's owner. Monitoring was carried out from Day 1 on 13th March to Day 6 on 18th March 2021, and from Day 7 on 21st March to Day 8 on 22nd March 2021. Figure 4-29 shows BC and UV measurements over the monitoring period. BC measurements ranged from 0 to ~ 16 µgm^{-3} between Day 1 and Day 8. As the boat was in London, for context, London ambient background BC and UV measurements from the Air Quality Monitoring Station (AQMS) at North Kensington are plotted in addition to the boat BC and UV measurements. Unlike other boats in the study, Boat D used different fuels. Mostly Homefire Ovals (HO) are used, but at times Homefire ECO (HE) and also seasoned logs. The fuel type used at any time was noted on the monitoring timeline.

Figure 4-29 . BC & UV measurement data – Boat D – Monitoring Day 1- Day 8



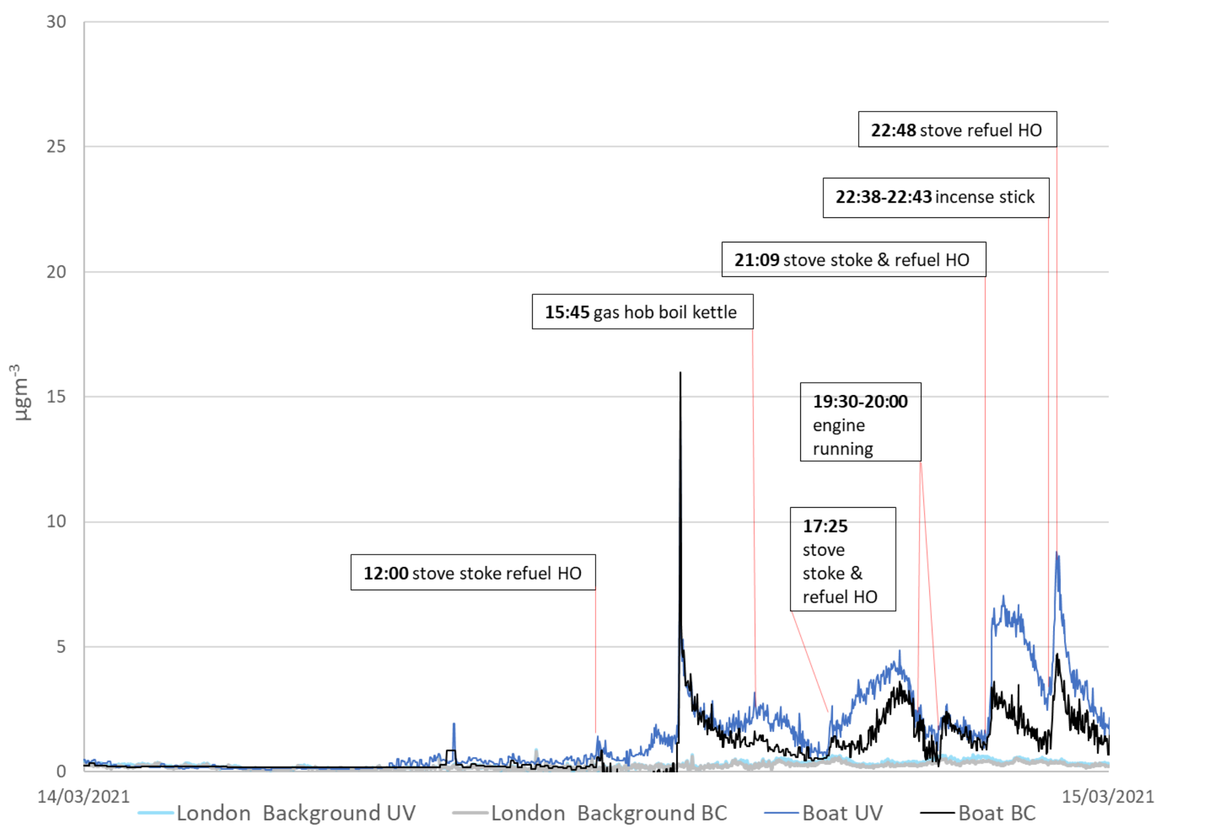
Data from Day 1 on Boat D is displayed in Figure 4-30. After two attempts to light the stove BC levels were initially measured at 18.2 μgm^{-3} as the stove was refuelled. There was an enhanced UV measurement that continued to increase 30 minutes after the stove was refuelled. When the boat door was opened at 14:01, BC and UV measurements dropped off very quickly to low levels until the door was closed again at 14:07 and levels increased slightly. BC then decreasing to background levels an hour later and UV almost two hours later. There was an unidentified event at 16:55 leading to a UV measurement. At 19:00 the stove was refuelled, BC increased from ~ 0.7 to 2.0 μgm^{-3} over 10 minutes, remaining elevated for 30 minutes and peaking at ~2.5 μgm^{-3}. BC decreased to background levels over 70 minutes. There were enhanced UV measurements associated with BC. The UV measurements peaked after 40 minutes and only returned to background levels three and a half hours later.

Figure 4-30. BC & UV measurement data - Boat D - Day 1



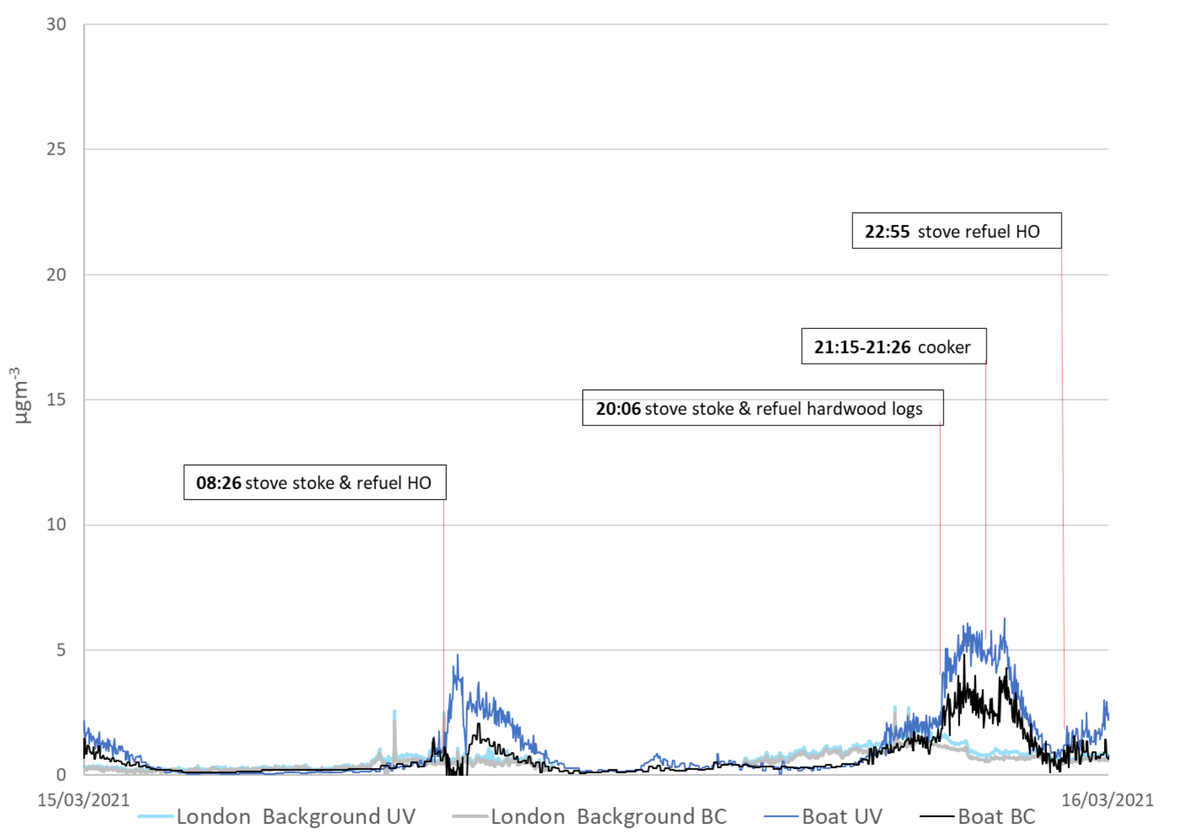
Data from Day 2 is shown in Figure 4-31. Very low background levels were observed overnight. At 12:00 the stove was refuelled, there followed an increase in the UV signal measured. BC after an initial increase appeared negative and was unreliable for this event. At 14:00 there was a high BC episode but it was not noted in the boat's diary. At 15:45 there appeared to be a very slight increase in BC and associated UV as the kettle was boiled on the gas hob. At 17:35 the stove was stoked and refuelled, there followed an increase in the BC measurement peaking at 3.3 µgm^{-3} 100 minutes later with enhanced UV following the same pattern. The engine was run between 19:30 and 20:00 and there was a slight increase in BC initially. At 21:09 the stove was stoked and refuelled, BC increased from ~ 0.8 to 3.6 µgm^{-3} over 10 minutes with elevated UV also measured. Whereas BC measurement levels begin to decrease after 10 minutes, UV measurements remained elevated for 50 minutes after refuelling. From 22:38 to 22:43 an incense stick was lit, both the BC and UV enhanced measurement increased, with BC concentration increasing from ~ 1.0 to 4.0 µgm^{-3} before fuel was added to the stove at 22:48. It was difficult to differentiate between both events after this time as they both occurred so close together.

Figure 4-31. BC & UV measurement data - Boat D - Day 2



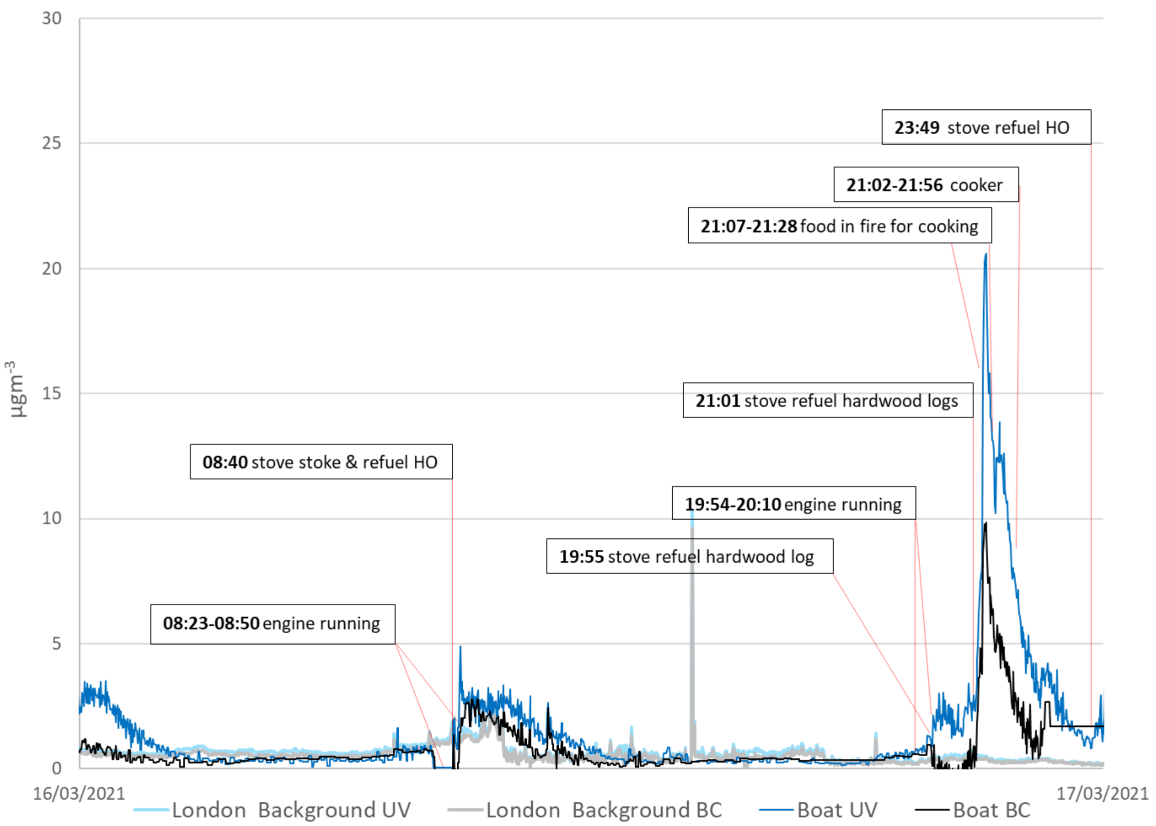
Boat D Day 3 data is displayed in Figure 4-32. After very low measurements overnight there was an initial increase in BC and enhanced UV measurement when the stove was lit at 08:26. There was some interference with the BC measurement, but elevated UV measurement increased for 20 minutes before decreasing to previous background levels after a further two hours and 10 minutes. BC decreased to previous background levels almost two hours after the stove was refuelled. At 20.06 the stove was stoked and refuelled with hardwood seasoned logs. BC increased from ~ 1.3 to 3.3 μgm^{-3} over the next 45 minutes with peaks measured at up to 4.8μgm^{-3}. BC began to decrease after 45 minutes but the decrease was interrupted by the end of a cooking episode at 21:26, when BC increased by ~ 1.5μgm^{-3} over 10 minutes. BC then returned to background levels over the next hour. An enhanced UV measurement followed the same pattern as BC. The stove was refuelled at 22:55 and there was a very slight increase in BC with a slight increase also in UV measured. BC returned to background levels around midnight but UV measurements only returned to background levels into Day 4, three hours after the fuel was added.

Figure 4-32. BC & UV measurement data - Boat D - Day 3



Day 4 data is displayed in Figure 4-33. There was interference in both BC and UV channels during the initial event when the engine was running between 08:23 and 08:50, and data could not be accurately interpreted. At 08:40 the stove was stoked and refuelled, BC increased to ~ 2.5 µgm^{-3} after 15 minutes and remained elevated for a further 20 minutes before decreasing to background levels over the next two hours. A slightly enhanced corresponding UV measurement stayed elevated for an hour and decreased at a slower rate. Background onboard BC and UV levels decreased to very low levels during the day with no further events until 19:54 when the engine was started, and any increase in BC and UV measurement was barely noticeable. There was an increase in UV measurements appearing to be from when hardwood logs were added to the stove at 19:55. At 21:01 hardwood logs were added to the stove, the BC concentration increased to 9.8 µgm^{-3} over the next 15 minutes, with a corresponding large increase in UV measured. The event was complicated however by the stove being used from 21:07 to 21:28 for cooking food in the fire. It was most likely that the prolonged period when the stove door was open led to the higher emissions from the stove in the living area. Between 21:02 and 21:56 the cooker was also in use. It was difficult to find any affect on the data from the cooker being used. Just before midnight at 23:49 the stove was refuelled, BC and UV measurements increased, BC had only a very slight increase with UV measurements returning to background two hours later in Day 5.

Figure 4-33. BC & UV measurement data - Boat D - Day 4



Data from Day 5 on Boat C is presented in Figure 4-34. Increased UV was observed at 08:03 when the stove was stoked and refuelled. There was also an increase in BC although it's difficult to quantify due to interference in the data. BC levels returned to background concentrations 90 minutes afterwards and UV measurements returned to background levels three hours after fuel was added. A BC peak was observed at 16:55 but there was no diary entry for this. At 21:01 the stove was stoked and refuelled, and hardwood logs were added. There was a clear increase in BC from ~ 0.8 to 6.8 μgm^{-3} over 15 minutes, with BC levels taking two and a half hours to return to background levels. There was a corresponding increase in UV measurements although these peaked 30 minutes after fuel was added and decreased at a slower pace. Two events occurred soon after both BC and UV begin to decrease. The cooker was in use from 21:30 to 21:45 and the stove door was opened briefly at 21:47. It appeared that the brief opening of the stove door was observed in the data with a very slight increase at this time. However, both events were very close together and it's difficult to be sure the degree to which each event was responsible.

Figure 4-34. BC & UV measurement data - Boat D - Day 5

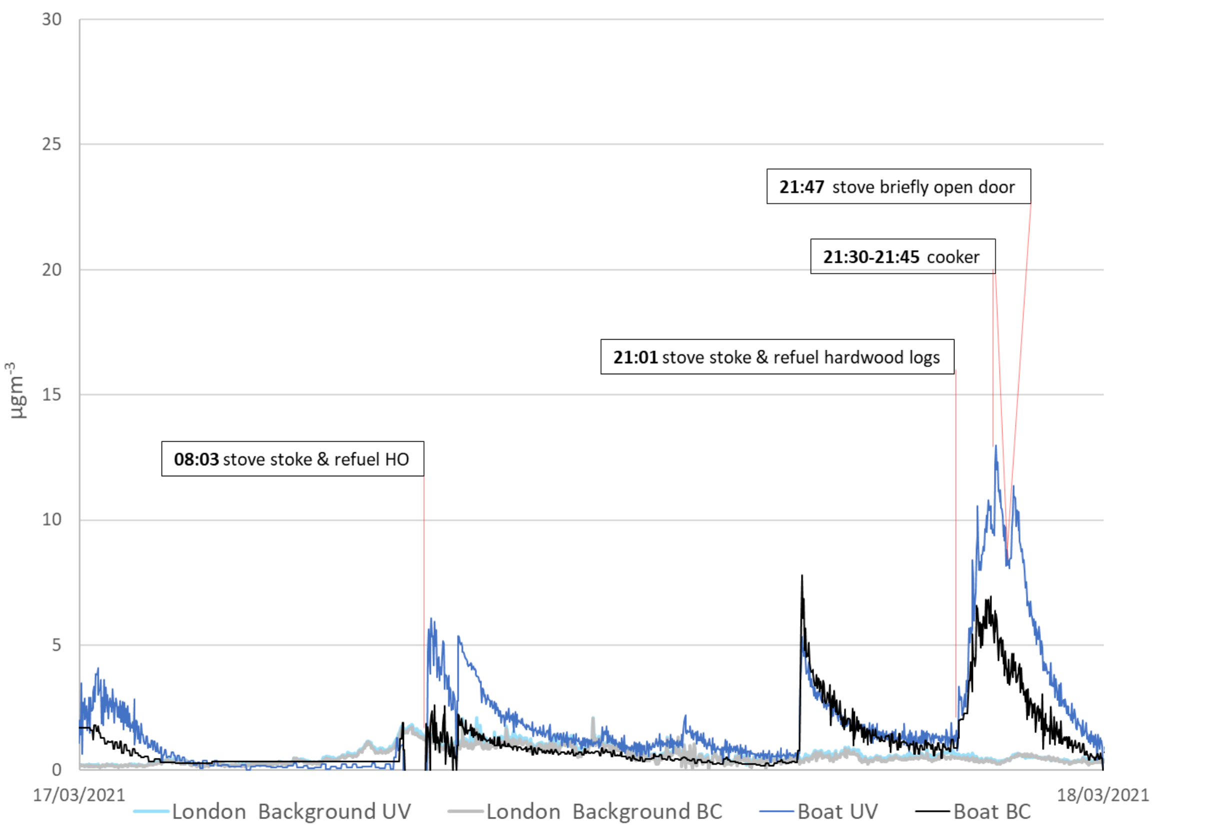
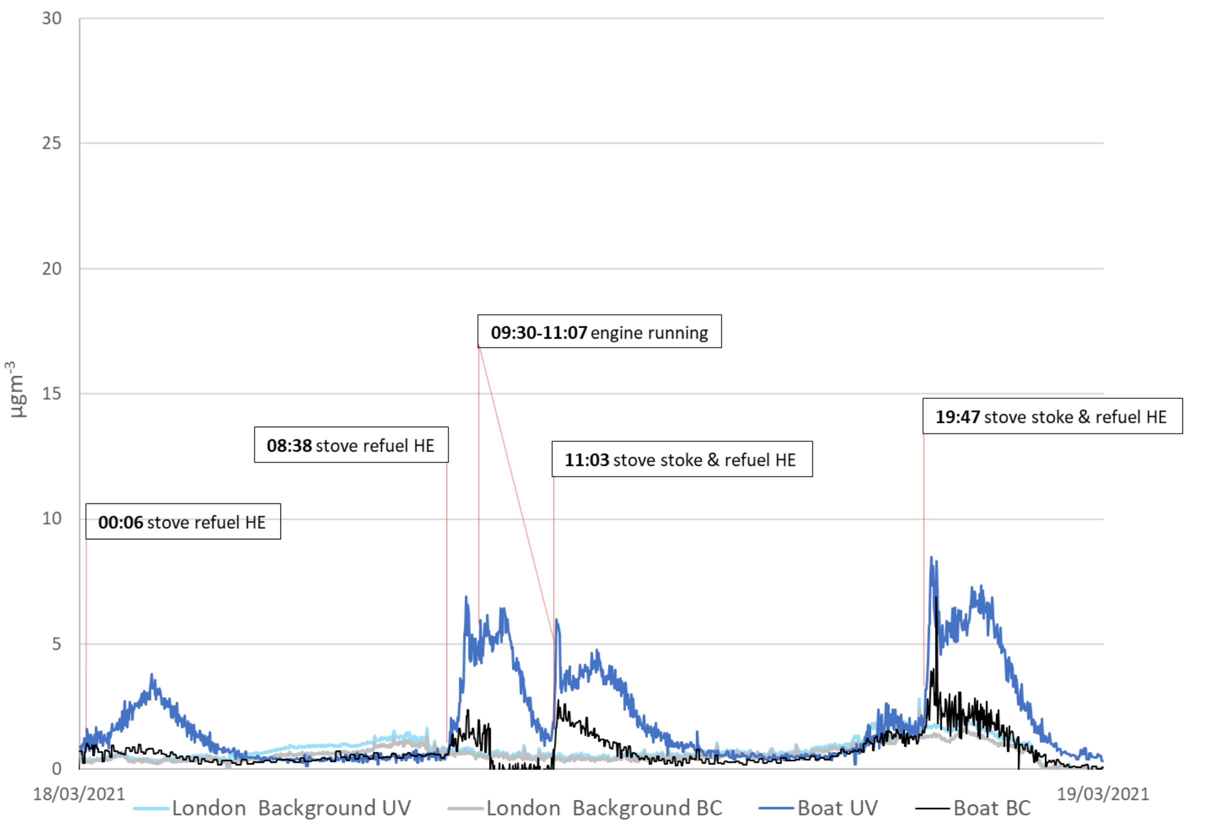


Figure 4-35 shows data from Day 6. The stove was refuelled with Homefire Ecoal (HE) at 00:06. The increase in BC was barely noticeable, UV measurements though continued to increase for almost two hours before taking almost a further two hours to decrease to background levels. BC and UV measurements then remained lower than London background levels until the stove was refuelled again with HE. BC increased after 30 minutes from ~ 0.5 to 2.3 µgm^{-3}. At 09:30 the engine was started, and BC levels decreased until the engine was turned off at 11:07. There was an increase in UV after the engine was started but it's difficult to determine if this was just a normal effect from the burning of the HE fuel in the stove. UV measurements began to decrease shortly afterwards, while the engine was still running. At 11:03 the stove was stoked and refuelled again with HE fuel. BC concentrations increased to 2.6 µgm^{-3} over the next 20 minutes with elevated UV measurements for 90 minutes after fuel was added. BC levels were back at background concentration just under two hours after fuel was added. UV measurements took about three and a half hours to return to background levels after the fuel had been added. At 19:47 the stove was stoked and HE fuel was added. BC increased from ~ 1.4 to 3.6 µgm^{-3} peaking at 6.8 µgm^{-3} over the next 20 minutes. BC levels decreased to background levels two hours after fuel was added. There was an elevated UV measurement observed also, remaining elevated for 90 minutes before decreasing over the next two and a half hours.

Figure 4-35. BC & UV measurement data - Boat D - Day 6



Data from Day 7 is presented in Figure 4-36. The stove was lit at 18:03 with the engine also running between 18:00 and 19:00. The monitor was restarted and began measuring data at 18:22. BC levels were elevated when monitoring started but because both events overlapped it was not possible to attribute increases definitively to either event. At 19:37 the stove was refuelled with seasoned hardwood logs. BC increased from ~ 0.9 to 4.1 µgm^{-3} over the next 10 minutes, a corresponding elevated UV measurement remained elevated for 15-20 minutes. At 21:52 more fuel was added this time HE. BC increased from ~ 1.0 to 2.9 µgm^{-3} over 10 minutes with a corresponding very large UV measurement increase over the same time. BC levels returned to background concentrations less than two hours after refuelling, whereas UV measurements remained elevated into the early morning of Day 8, as observed in Figure 4-37. Monitoring finished on Boat D at 06:40 on Day 8.

Figure 4-36. BC & UV measurement data - Boat D - Day 7

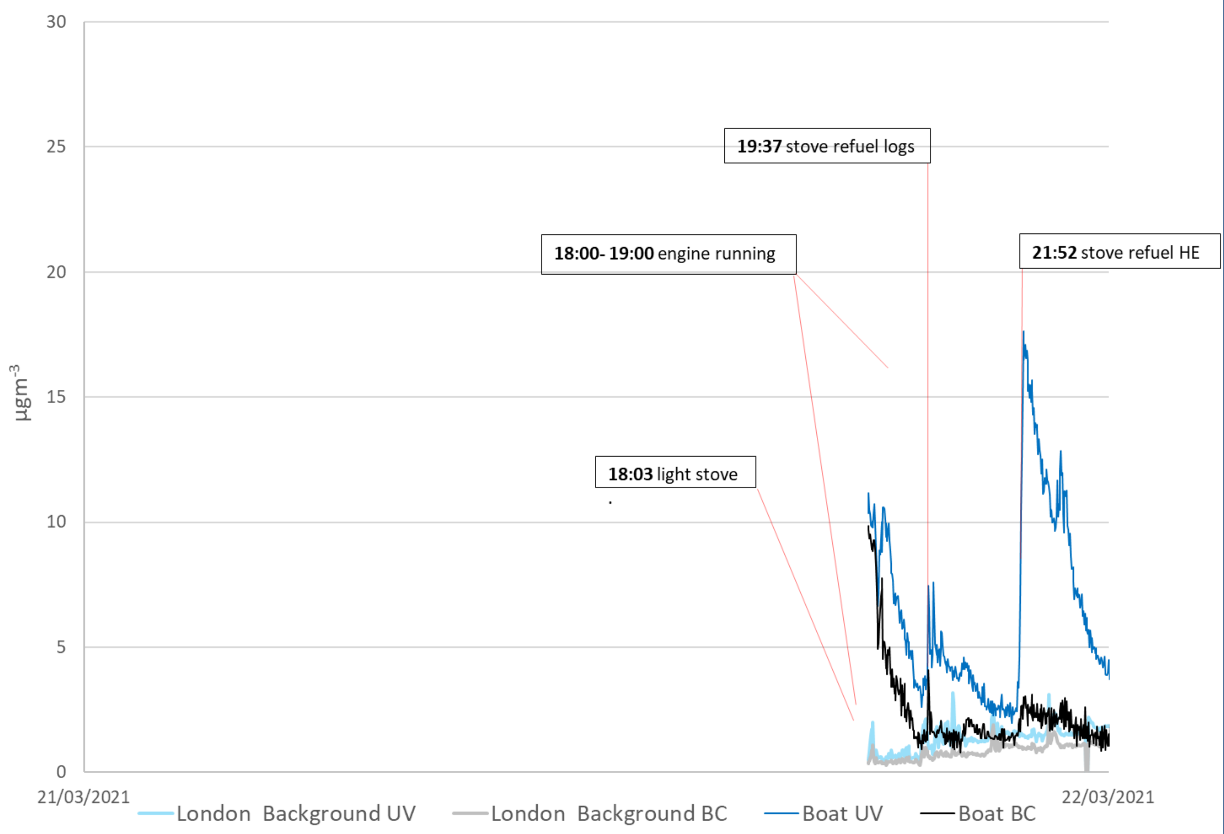
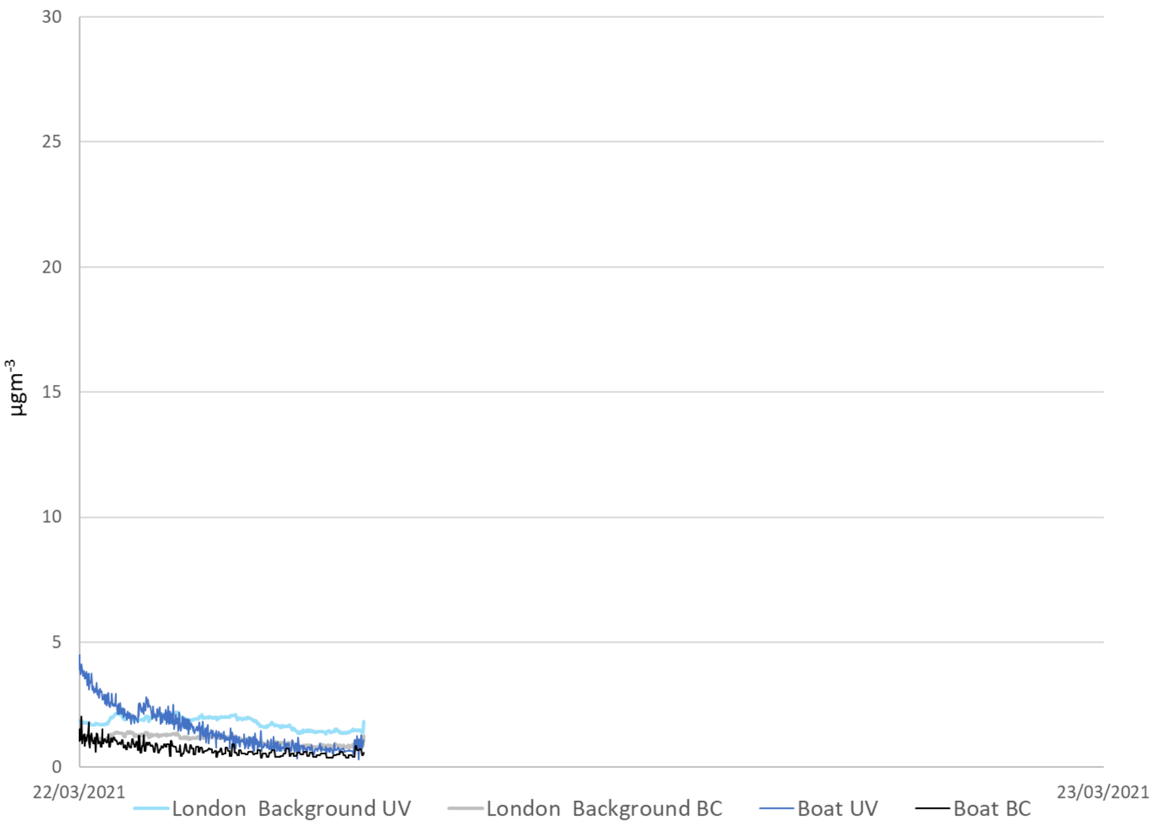


Figure 4-37. BC & UV measurement data - Boat D - Day 8



5. Discussion

The highest black carbon measurements were most often linked to a boat's diesel engine emissions, cooking activities, the use of kindling and firelighters and the burning of seasoned wood in stoves.

The highest UV measurements were generally observed when manufactured smokeless briquettes were used as fuel in stove.

A summary of the top 5 peak BC and UV measurements on each boat, their source and the activity that gave rise to each is displayed in Table 3.

Table 3. Peak BC and UV measurements and their sources on each boat

Boat	Peak Measurements BC (μgm^{-3})	UV (μgm^{-3})	Source	Activity
Boat A	**15.6**	15.6	Cooking	Grill, Pan, Top Oven
	7.8	**14.7**	Cooking	Oven, Baking, Grill
	7.1	**12.5**	Cooking	Frying
	5.9	5.9	Cooking	Oven, Hob, Frying,Gill
	5.5	**14.8**	Cooking	Oven, Baking
	4.5	**8.9**	Cooking	Frying
	4.5	**8.2**	Cooking	
Boat B	**17.8**	**450.5**	Stove	Riddle & Refuel
	13.5	17.3	Engine	Battery Charging
	8.4	12.2	Engine	Battery Charging
	6.0	13.3	Stove	Kindling, Riddle & Refuel
	5.1	5.1	Stove	Door Open , Heat Pitta Bread
	3.0	**54.7**	Stove	Riddle & Refuel
	1.5	**24.8**	Stove	Door Open, Heat Crumpets
	2.4	**25.0**	Stove	Riddle & Refuel
	3.0	**21.0**	Stove	Riddle & Refuel
Boat C	**25.5**	25.5	Engine	Boat Travelling
	21.8	21.8	Engine	Boat Travelling
	14.8	15.1	Cooking	Oven
	11.8	11.8	Cooking	Oven
	6.9	**30.3**	Stove	Refuel Stove 1
	2.2	**12.9**	Stove	Refuel Stove 1 & 2
	2.9	**10.2**	Stove	Refuel Stove 1 & 2
	4.7	**10.4**	Stove	Refuel Stove 1
	3.5	**8.9**	Stove	Refuel Stove 1
Boat D	**18.2**	20.6	Stove	Light
	9.8	**20.5**	Stove	Stoke & Refuel Hardwood Logs
	7.0	10.6	Stove	Stoke & Refuel Hardwood Logs
	6.9	8.3	Stove	Stoke & Refuel, HE
	6.8	10.6	Stove	Stoke & Refuel Hardwood Logs
	3.0	**17.6**	Stove	Refuel HE
	2.8	**8.5**	Stove	Refuel, HO
	2.3	**6.9**	Stove	Refuel, HE
	4.7	**8.8**	Stove	Refuel, HO

Top 5 UV peak measurements highlighted in bold are those that are most enhanced from BC measurements.

On Boat A the DEFRA approved stove was fuelled by recycled hardwood briquettes, with Eco firelighters used to help light the stove. Over the monitoring duration of eight days the main incidences of high BC and elevated UV measurements were as a result of cooking emissions. Table 3. Shows the top five BC peak measurements were from cooking activities. Seven of the nine highest emission events for BC can be attributed to a cooking activity. The highest is ~16 ugm^{-3} when the hob, grill, pan and stove top were used. UV measurement levels for the event were similar to BC and using the Delta-C method, PM2.5 concentrations were estimated at ~ 160 ugm^{-3}. Both BC and UV decreased to low levels after about an hour. BC measurements for the remaining six highest cooking events ranged from ~4 ugm^{-3} to 8 4 ugm^{-3}.

A largely elevated UV measurement was also a feature of the cooking events with five of the highest enhanced UV measurements resulting from cooking events, as displayed in Table 3. There was an equivalent PM2.5 measurement of up to 110 ugm^{-3} estimated for two baking events using the Delta-C method. Significant increases in BC were measured for two events when the stove was lit. Both times the door was opened soon after to rearrange fuel. BC measurements increased to ~4 ugm^{-3} on both occasions with an elevated UV signal and estimated PM2.5 concentration of ~55 ugm^{-3}.

Interactions with the stove which involved opening the stove door to add fuel or rearrange fuel generally led to an increase in BC concentrations over a range ~0 to 1.5 ugm^{-3}. UV measurements were usually slightly elevated compared to BC measurements for these events. Both BC and UV levels generally increased quickly after interaction, 10-20 minutes, and decayed relatively quickly also, very often returning to previous concentrations after about an hour. There were a number of peaks that were not accounted for by diary entries. BC levels often returned to low levels < 0.3 ugm^{-3} overnight into early morning or when there were periods of no activity on the boat.

Boats B,C & D were located in London and London background data was added to their timeline graphs to provide some context to the BC and UV measurements onboard during the study.

The stove on Boat B burned smokeless briquettes which comprised 60-65% petroleum coke and 30-35% anthracite by weight. Over eight monitoring days the highest emissions can be traced to interactions with the stove. Table 3 shows that three of the top five BC measurements occurred when the door of the stove was opened, two of these involved the addition of fuel with one also involving the addition of kindling. There was one very high measurement of BC of 18 ugm^{-3} and PM2.5 estimated at >3,000 ugm^{-3} – using the 'Delta-C' method - when the stove is riddled and refuelled, and the door left open to toast marshmallows. This event also resulted in the fire alarm being activated. Riddling and refuelling the stove generally resulted in an increase of BC in the range ~0.5 to 2.6 ugm^{-3}.

The increased UV measurements really stood out on Boat B. Table 3 shows that four of the top five enhanced UV measurements on Boat B were as a result of opening the stove door to riddle the stove and add fuel. UV was seen to be very elevated compared to BC, with associated PM2.5 values using the 'Delta-C' method, ranging from ~24 to 400 ugm^{-3}, the majority > 100 ugm^{-3} estimated PM2.5. It was also noted that there was quiet a long build up to the highest concentrations being measured after the stove had been riddled and refuelled. This was anywhere from 10 minutes to greater than one hour, usually greater than 30 minutes after fuel was added. The time it took for measured BC and UV to return to pre interaction levels was also significant, ranging from one to two hours for BC and often greater than three hours for UV, to return to background levels.

It was possible that the elevated UV signal measured was due to the high petroleum coke content of the smokeless fuel being burned. It was also possible that there may have been emissions escaping from the stove or not being extracted by the flue due to a poor draw, this may help explain why levels took so long to reach a peak after fuel was added. It should also be noted that the decay rate for BC and UV measurements was long, with often over 3 hrs before UV levels were back to pre-intervention levels.

When kindling was added to riddling and refuelling of the stove, higher BC values were usually measured afterwards, ranging from ~3.0 to 5.5 ugm^{-3} with estimates using the 'Delta-C' method of ~75 to 85 ugm^{-3}. Peak measurement for these events was quicker than when kindling was not used, taking only 10-20 mins after fuel and kindling had been added to measure maximum response. When only fuel was added to the stove and riddling was not performed then there was generally no increase in BC and a smaller increase in UV levels than was seen when riddling was also carried out.

There was one period when the diesel engine was run over two hours, to charge the boat's battery. From Table 3, two of the five highest BC measurements can be sourced to this episode. When the engine was started there was an almost instant increase in BC measured to ~ 13.5 ugm^{-3} and just as the engine was turned off there was an increase in BC measured to ~ 8.4 ugm^{-}3. This indicates that emissions from the engine entered the living area from the time the engine was started. For the duration of time that the engine was running there were elevated BC concentrations measured. There was generally a decrease following the initial BC peak indicating that emissions probably entered the living area in a single episode maybe with a door opening and closing. The decrease over the two hours was interrupted a couple of times with smaller peaks, likely also due to a one-off addition of diesel engine emissions to the living area. The BC measurements for this event had an enhanced UV measurement associated with them, with PM2.5 estimated by the 'Delta-C' method of ~ 130 ugm^{-3} for the initial peak and ~ 91.5 ugm^{-3} for the second peak.

Cooking activities and toasting bread generally resulted in small increases in BC and UV measurements. There was one occasion when bread was baked and both BC and UV increased, however it was very close to riddling and refuelling the stove, so it was not possible to be certain if the increases were due to baking or the stove activity.

It was often apparent looking at the data to see how activities on the boat caused BC and UV levels to increase relative to London ambient background levels. Likewise, it was possible to see how measurement levels onboard dropped off to background levels and below when there were extended periods of no interaction with the stove.

Every morning at 06:15 there was a regular BC and associated UV enhanced peak which did not appear in the activity diary. This was followed up with the owner of the boat who was not aware of any activity on the monitored boat that would be causing it. It was thought to be most likely due to emissions from a heating appliance on a boat alongside. The heater was likely to be on an automatic timer, switching on at the same time every morning. These emissions appeared to be finding their way into the living area of Boat B. BC increases were small, ranging from ~ 0.1 to 1.0 ugm^{-3} with an elevated UV signal indicating an increase of PM2.5 up to 60 ugm^{-3} as estimated by the 'Delta-C' method. The low BC and elevated UV signal would indicate the source of emissions to be from combustion of a fuel other than diesel. The fluctuation in measurement values for this event would most likely have been because as an outside source, emissions entering boat B would have been affected by ambient weather and wind activity.

Boat C had two stoves, one located in the main living area and one located at the back of the boat. Both stoves were often lit at the same time but there were instances when only one of the two was in operation. The fuel used for the stoves was Excel briquettes comprising 65% to 70% petroleum coke and 25% anthracite by weight.

Table 3 shows only one of the top 5 BC measured peaks could be attributed to refuelling the stove. BC tended to increase almost immediately when fuel was added and took about one hour to decay to background levels. There was an enhanced UV measurement for the stove refuelling activity. Table 3 shows that the top 5 measurement peaks for enhanced UV were as a result of opening the stove door and adding fuel to the stove. With an estimated increase of PM2.5 ranging from 30 to 90 ugm^{-3}, using the 'Delta-C' method. UV measurements increased for fuel additions, from almost immediately to approximately an hour and a half after fuel was added to both stoves. The monitor was located closest to stove 1 and this stove features in all top 5 enhanced UV measurement peaks in Table 3.

The profile of the stove UV peak was similar to that seen on Boat B, with usually 30 minutes to an hour passing before the UV signal peaked and began to decay. Levels of UV were much lower than measured on Boat B however. This was interesting as both boats used very similar fuel, with a high petroleum coke content. It would seem to indicate that this type of fuel may be producing more UV absorbing compounds. PAHs are one group of compounds that are absorbed in the UV range. The higher levels measured on Boat B would seem to indicate that higher emissions are entering that boat from the stove, possibly due to stove design or flue conditions on Boat B.

Boat C was the only boat that moved location during the monitoring period, having its diesel engine running for significant periods of time on Day 2 and Day 3. From Table 3, the two highest peak measurements for BC were noted when the engine was in use. These two measurements were recorded on separate days. BC measurement peaked at > 25 ugm^{-3} on Day 2. It appeared within the time window when the boat was being moved and it looked like there were a series of instances where emissions entered the cabin and slowly dispersed. There was another BC peak > 20 ugm^{-3} on Day 3 when the boat was moved again. This peak occurred at the beginning of the period when the engine was in use and again looked like some emissions entered the cabin in one instance and then dispersed over time. There were also a number of smaller peaks within the time that the engine was in use. All but one of these diesel emission BC peaks had little or no UV enhancement. One of the peaks appeared to have a UV enhanced peak but this was likely from adding fuel to a stove, which occurred a little earlier in the timeline.

The oven was used and appeared to generate BC emissions with peaks at concentrations ~ 10.0 to 15.0 ugm^{-3}. From Table 3, two of the top 5 peak measurements for BC on Boat C resulted from oven baking events. There was fuel added to a stove at a similar time to the oven being in use so there needed to be some caution with interpreting the data. However, it seemed likely adding fuel to the stove contributed to the UV measurement rather than BC, as can be seen with other fuel addition peaks. There was one other cooking event noted in the diary which didn't register either a BC or UV increase.

Boat D used a few different fuels in the stove over the monitoring period. Homefire Ovals (HO) comprised anthracite fines (as to approximately 50 to 75% of the total weight), petroleum coke (as to approximately 20 to 45% of the total weight), bituminous coal (as to approximately 5 to 17% of the total weight). Homefire Ecoal (HE) briquettes had a similar composition with the addition of biomass (as to approximately 5 to 20% of the total weight) and biomass char (as to approximately 0 to 10% of the total weight). Seasoned logs were also used as fuel. Fuel was not combined when burned. Similar to other boats there were a number of activities that overlapped each day and made individual analysis of some events difficult. It was however possible to analyse many individual events, where no overlapping of activities took place.

Lighting the stove at the beginning of the monitoring period involved placing a fire lighter below softwood kindling below HO fuel. This was attempted twice and after the initial suspect data was removed due to the analyser settling, very high BC concentrations of up to 18.2 ugm^{-3} were measured. As observed from Table 3 this was the highest BC concentration measured over the monitoring period on Boat D. There was a small, elevated UV signal which increased when the stove was refuelled with HO. It was interesting to note how ventilation introduced by opening the boat door caused an immediate drop in both BC and UV levels. BC dropped from ~ 7.0 to 0.9 ugm^{-3} over 6 minutes and UV showed the equivalent of a PM2.5 – from 'Delta-C' method - drop from ~ 125 to 7.5 ugm^{-3} over the same time.

Generally, when the stove was stoked before fuel was added, emissions into the boat tended to be higher with increased BC and UV measurements. When HO fuel was added without stoking the stove beforehand, BC increased by ~ 0.7 to 1.5 ugm^{-3} but when stoked beforehand the increases in BC were ~ 1.4 to 2.6 ugm^{-3}. PM2.5 levels, calculated using the 'Delta-C' method, showed a corresponding increase of PM2.5 particles of ~ 12.0 to 36.0 ugm^{-3} as opposed to an increase of ~ 28.0 to 41.2 ugm^{-3} when the stove was stoked beforehand.

The highest UV measurements were observed when HO or HE fuel was added to the stove. Table 3 shows that four of the top 5 UV enhanced measurement peaks were as a result of adding either HO or HE fuel to the stove, with little distinction between UV measurements for either fuel. On one occasion the addition of HE fuel led to an estimated PM2.5 increase of > 100 ugm^{-3} using the 'Delta-C' method.

Burning hardwood logs also increased both BC and UV when used as a fuel. The BC trace observed appeared to be higher for this type of fuel that the others. From Table 3 it's observed that three of the top 5 BC measurement peaks and one of the top 5 UV measurement peaks resulted after hardwood logs were added to the stove.

The engine was run on four occasions for periods of time ranging from 30 minutes to an hour. On one occasion during Day 6 there appeared to be an increase in BC around the same time, but there was stove activity overlapping. Nevertheless, it appears that the increased BC measured at this time was more than likely due to diesel burning emissions entering the boat. BC concentrations of ~ 10ugm^{-3} were observed after analyser settling data was discounted.

There were two occasions when the cooker was used, on one occasion there appears to be a small increase in both BC and UV measurements, for the other there were overlapping activities that made it difficult to definitively attribute observed increases to cooker use.

6. Conclusion

Burning of solid fuels and fossil fuels onboard boats contributed pollution to the indoor environment, increasing the occupant's pollution exposure.

The report aims to help boaters manage indoor pollution by providing information on the type and quantity of pollution from different sources and activities.

Pollution and the health impacts of emissions generated from the combustion of solid and fossil fuels and cooking are well documented and understood. This project aimed to gain an understanding of indoor pollution arising from these activities, inside typical liveaboard boats located on London's canals and rivers. The investigation was carried out in real world conditions and provided a snapshot of carbon particulate pollution in the main living area, over approximately one week, in each of four boats.

BC is a measure of airborne soot-like carbon and an indicator of harmful particulate substances from combustion that can include known carcinogens and other toxic species. UV measurements give an indication of organic carbon particles, some of which have no toxicity, but others with a firmly established toxicity, including many types of poly-aromatic hydrocarbons (PAHs).

Some of the highest BC measurements were recorded when emissions from a boat's diesel engine entered the living area over a period when the engine was in use for either charging batteries or moving the boat. Cooking activities, most notably baking, grilling and frying with hot oil were a significant contributor of BC to the indoor environment. The use of kindling and firelighters to light a fire as well as the use of seasoned hardwood logs and briquettes were notable contributions of BC, being emitted when the door of the stove was open.

Generally, the highest UV measurements were observed when the door of a stove was opened, and manufactured smokeless briquettes were re-arranged or added to the stove. These measurements tended to be slightly higher if the stove was riddled or stoked before fuel was added. There was also evidence that the type and the setup of a stove can affect its indoor emissions. The rate of decay of particle pollution after a door is opened on a stove and fuel added or rearranged, varied across boats. Ventilation was observed to reduce pollution measurements. BC and UV measurements almost always returned to ambient background levels, sometimes lower, overnight, and early in the morning, during periods of no stove interaction and no cooking.

Significant combustion emissions, likely from another boat alongside, were detected inside one canal boat.

By highlighting indoor pollution levels onboard boats. This study would aim to help in the management of indoor air pollution for boaters. The provision of electrical charging points for boats to connect to, is one means to facilitate a switch from solid or fossil fuels to electricity, to provide heat and power on a boat. Good ventilation could also help to significantly decrease pollution levels that arise from cooking and combustion sources.

7. References

Abdel-Shafy, H. and Mansour,M., 2016. **A review on polycyclic aromatic hydrocarbons: Source, environmental impact, effect on human health and remediation.** Egyptian Journal of Petroleum, 25, 107–123

Air Quailty Expert Group, 2012. **Fine Particulate Matter (PM2.5) in the United Kingdom**, Defra, London

Andreae, M., and Gelencsér, A., 2006. **Black carbon or brown carbon? The nature of light-absorbing carbonaceous aerosols.** Atmos. Chem. Phys., 6, 3131–3148

Brown, R., Butterfield, D., Goddard, S., Hussain, D., Quincey, P., Fuller, G., 2016. **Wavelength dependent light absorption as a cost effective, real-time surrogate for ambient concentrations of polycyclic aromatic hydrocarbons** Atmospheric Environment., 127, 125-132

Chakraborty, R., Heydon, J., Mayfield, M. and Mihaylova, L., 2020. **Indoor Air Pollution from Residential Stoves: Examining the Flooding of Particulate Matter into Homes during Real-World Use.** Atmosphere, 11, 1326

DEFRA, *https://smokecontrol.defra.gov.uk/fuel-details.php?id=52*

Drinovec, L., Močnik, G., Zotter, P., Prévôt, A. S. H., Ruckstuhl, C., Coz, E., Rupakheti, M., Sciare, J., Müller, T., Wiedensohler, A., and Hansen, A. D. A, 2015: **The "dual-spot" Aethalometer: an improved measurement of aerosol black carbon with real-time loading compensation**, Atmos. Meas. Tech., 8, 1965–1979

European Environment Agency (EEA) 2013. Technical report No 18/2013 **Status of black carbon monitoring in ambient air in Europe,** Publications Office of the European Union, Luxembourg

Fuller, G., Tremper, A., Baker, T., Espen, Y., Butterfield, D., 2014. **Contribution of wood burning to PM10 in London.** Atmospheric Environment., 87, 87-94

Hagler, G., Yelverton, T., Vedantham, R., Hansen, A., Turner, J., 2011**. Post-processing Method to Reduce Noise while Preserving High Time Resolution in Aethalometer Real-time Black Carbon Data.** Aerosol and Air Quality Research, 11: 539–546.

Kumar, P., Patton, A.P., Durant, J.L. and Frey, H.C., 2018. **A review of factors impacting exposure to $PM_{2.5}$, ultra-fine particles and black carbon in Asian transport microenvironments**. Atmospheric Environment, 187, pp. 301-316

Magee Scientific Company, 2005. The Aethalometer ™

Aethlabs, 2018. microAeth®MA Series MA200, MA300, MA350 Operating Manual- AethLabs, December 2018, rev03

The United Nations Environment Programme (UNEP)and World Meteorological Organization (WMO), 2011 **Integrated Assessment of Black Carbon and Tropospheric Ozone,** UNON Publishing Services Section, Nairobi

Wang, H., Nie, L., Liu, D., Gao, M., Wang, M. and Hao, Z., 2015. **Physico-chemical characterization and source tracking of black carbon at a suburban site in Beijing**. Journal of Environmental Sciences,33, pp.188-194

Wang, Y., Hopke, P., Rattigan, O., Xia, X., Chalupa, D., and Utell, M., 2011. **Characterization of Residential Wood Combustion Particles Using the Two-Wavelength Aethalometer.** Environ. Sci. Technol., 45, 7387–7393

WHO, 2012, **Health effects of black carbon**, World Health Organisation, WHO Regional Office for Europe, Copenhagen

WHO, 2021, **Global Air Quality Guidelines**, World Health Organisation (WHO), WHO, Geneva

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