SAQN www.saqn.org

Bringing together research, industry and policy to address air quality challenges

SAQN Awards End of Project Report

Please note: this report will be made publicly available on the SAQN website.
To complete the form, please make a copy of this Google doc, or download as a Word doc to edit.

Project Title	
Enabling the remote measurement of air pollution emissions in UK ports	
Project Team	
Name	Role (PI / Co-I)
James Lee	PI
Elin McCormack	Co_I
Dan Peters	Co_I
Connor McGurk	Co_I
James Thomas	Co_I
Vicky Naylor	Co_I

Proposed activities (copy from your project proposal)

The project is divided into a series of work packages:

WP1: Design of the package containing Low Cost Sensors (LCS) optimised for the buoy platform (milestone 1), including

- Choice of sensors.
- Optimised PM inlet using gravitational and aerodynamic sampling to filter out particles greater than the PM_{10} detection limit of the LCS package.
- A membrane filter to protect gas sensors from direct exposure to sea spray, but with sufficient gas permeability to aspirate the sensors.

WP2: Characterise the LCS package (from WP1). The package and inlet performance will initially be tested compared to suitable instruments at, e.g., the STFC Chilbolton Atmospheric Observatory to ensure gas and particle precision and accuracy, and assess inlet losses. The package will then be installed on the UoY van, which contains a suite of high sensitivity instruments to measure NO_x, CO_2, SO_2 and PM. The van will be taken to a UK port to measure both air pollution levels in and around the port and emission ratios from individual ships moving in and out of the port.

WP3: Data collected from the LCS package and the van (WP2) will be used to assess the potential of the sensor to both monitor air pollution in the port and calculate emissions from individual ships (milestone 2). Code will be developed to cross-correlate SO_2, NO_x and PM to CO_2 in order to calculate emission factors and in particular the sulfur fuel content, which is the main regulated parameter. Attention will also be given to identifying individual ships and relating them to the emission factors.

WP4: Outline ruggedization measures for each selected sensor, to a batch-production ready level. JET will assist with the design and implementation of a 3D printed proto-type. Ruggedisation of sensors should allow the sensor to maintain full function, while protecting it from dust, water and solid object ingress from all or selected directions (milestone 3). Consideration will be paid to the power system and integrating the sensor communication media with the buoy's. Final designs and specifications of the ruggedised sensors will be provided in this work package.

WP5: Demonstrate the integration of the identified air quality sensors into JETs 5G router. This will be done through the NMEA framework, ensuring data is recognised and transmitted successfully. This will deliver the outcomes of this project to a demonstration with a lab to TRL4.

Please report on the activities completed in the project

Work done on the different WPs is as follows:

WP1:

Early testing of the sensor range previously used by the STFC team indicated that these may not be sufficiently sensitive to capture the expected pollutant concentrations in shipping plumes. This led us to refocus the work done in WP1 towards achieving greater sensitivity with low-cost gas sensors.

We procured Alphasense B-series sensors for NO, NO_2 and SO_2, as well as a mid-cost smartGAS flow^{EVO} CO_2 sensor, having seen that this sensor type gives good accuracy for CO_2 measurements.

We produced a prototype sensor package designed to assess the sensitivity of the sensors and their viability for measuring shipping emissions. Building upon the experience gained in previous SAQN projects, we gave additional attention to minimising electrical noise in the instrument, ensuring the sensors were well shielded as well as testing higher resolution analog-to-digital converters.

The primary test instrument produced contains 9 electrochemical gas sensors (3 each for NO, NO_2 and SO_2), and 3 Alphasense NDIR CO_2 sensors, all of which are passively aspirated. Alongside this instrument, the smartGAS CO_2 sensor was run off a pumped sampling line, and OPC-R2 particulate sensors were run as part of instruments produced in a previous SAQN project.

WP2:

With the instrument enclosed in a bag, the sensors were exposed to calibration gases, producing the results shown in Figure 1.

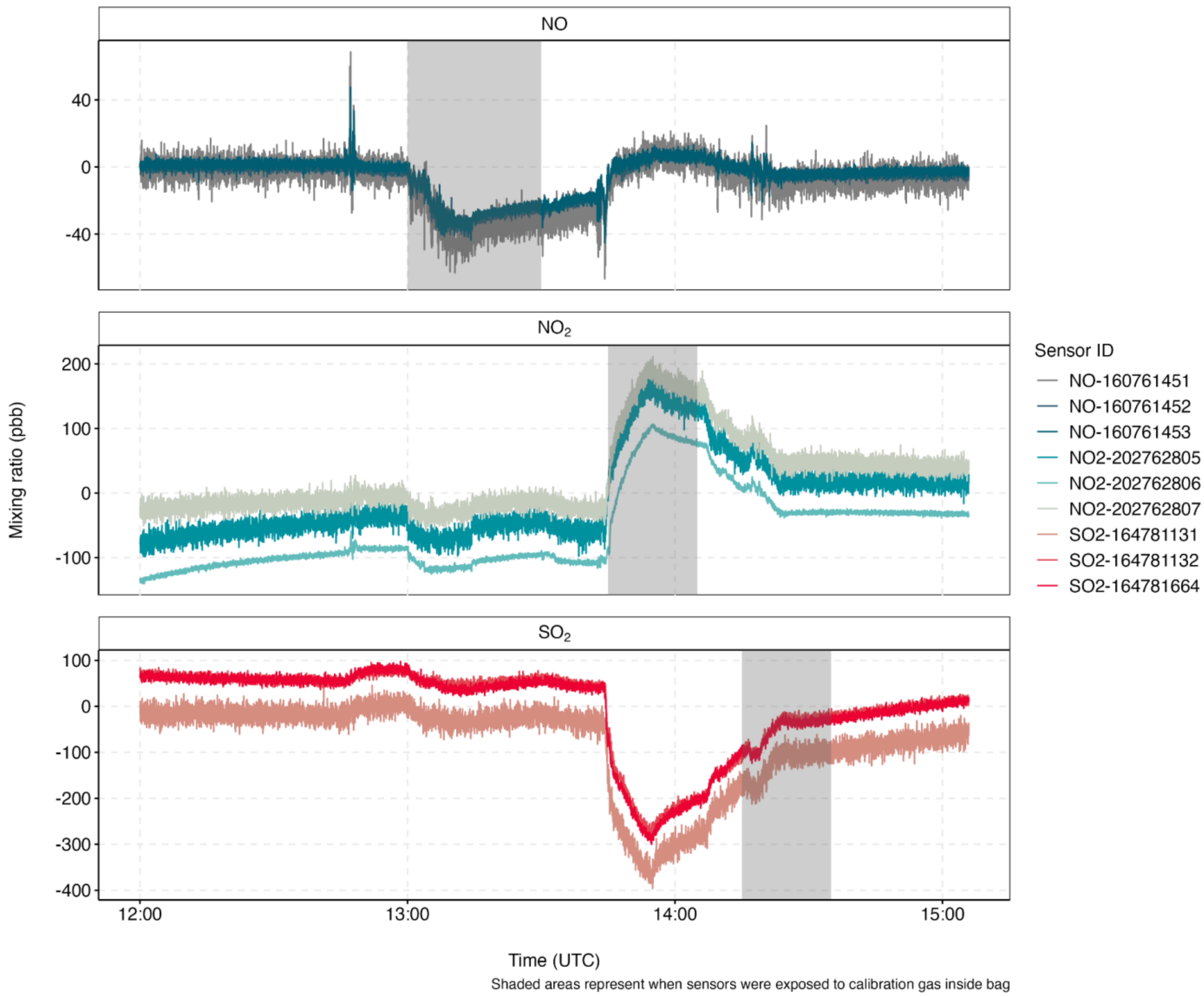

Figure 1: *Sensor responses to calibration gases.*

Measurements

The LCS package was taken, along with the University of York's mobile laboratory; the WACL Air Sampling Platform (WASP), to Newcastle for 5 days from 14th - 18th May to measure ships arriving and departing the Port of Tyne. Newcastle was chosen as the port sits 2-3 miles from the mouth of the river Tyne, meaning measurements can be made at a variety of locations along the river depending on the wind direction (Figure 2). The choice of location on a given day was made to ensure the mobile laboratory was positioned downwind of passing ship plumes based on forecast and observed wind direction. The schedule of ship movements were obtained from marinetraffic.com and the Port of Tyne ship movements website.

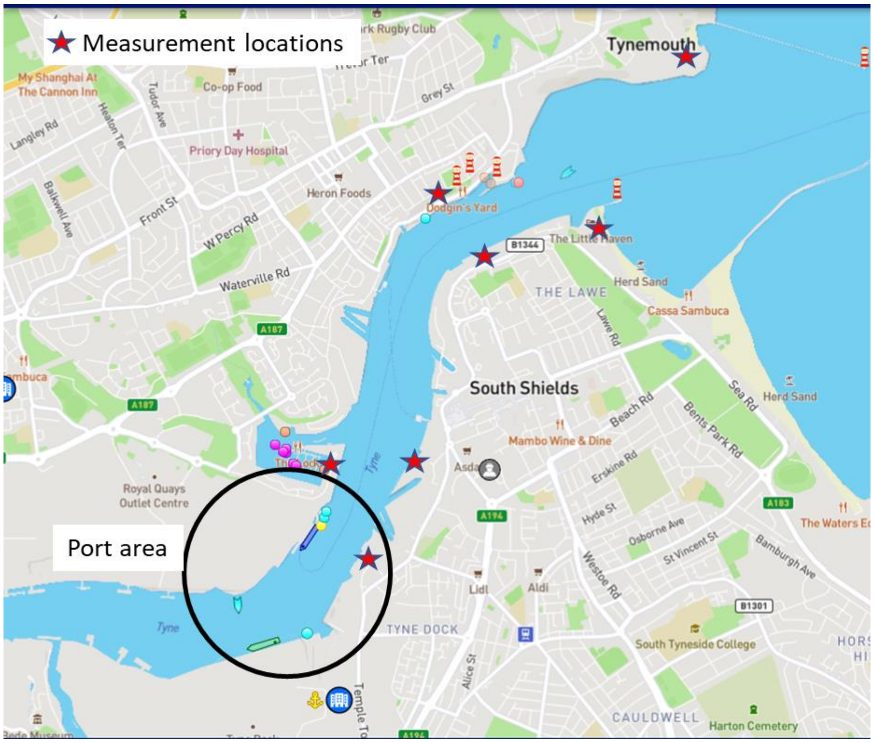

Figure 2: *Map showing the various sampling locations along the River Tyne (red stars). The black circle indicates the area where the ships actually dock.*

The WASP was deployed in Newcastle at the various sampling locations. The details of the instrumentation housed inside the mobile laboratory are provided in Table 1.

Table 1: *Details of the* reference *instrumentation on board the WASP.*

Species	**Instrument**	**Reference**
NO, NO_2	Airxy ICAD	Horbanski et al., AMT, 2019
CO_2, CH_4, H_2O	Los Gatos UGGA	Paul et al., Appl. Opt., 2001
SO_2	TEI 43i TLE	Luke et al., JGR, 1997
PM_1, $PM_{2.5}$, PM_4, PM_{10},PM_{TOTAL}	Palas AQGuard	Gilio et al., Env. Res., 2021
Wind speed, wind direction, air temperature	Gill windsonic 2D sonic anemometer	https://gillinstruments.com/compare-2-axis-anemometers/windsonic-2axis/

Figure 3: *Photograph showing the WASP sampling a passing cruise liner.*

A point-sampling strategy was implemented to sample ship plumes. The WASP was positioned downwind of passing ships, away from additional sources of interference such as vehicles. The typical sampling distance to the ship was 100-200 m (Figure 3).

WP3:

<u>Calculation of emission ratios</u>

The calculation of emission ratios requires the definition and subtraction of background concentrations. The background concentrations for NO_2, NO_x, SO_2 and CO_2 were calculated as the 1st percentile measurement in a rolling 2.5-minute, centered window. Once subtracted the remaining enhancement is attributed to fresh, local emissions from vessels passing upwind.

Enhancement ratios of $\Delta SO_2/\Delta CO_2$, $\Delta NO_2/\Delta CO_2$ and $\Delta NO_x/\Delta CO_2$ were calculated using ordinary least squares (OLS) regression. Prior to fitting the models, the time series of each variable (SO_2, NO_2, NO_x and CO_2) was aligned using cross correlation to account for differing response times of the instruments. For each plume, the time series was shifted to determine the offset which gave the strongest correlation with CO_2. The optimum offsets for NO_2, NO_x and SO_2 were then applied to the data for each plume. The linear models were then fitted to the aligned data and the sulfur fuel content (SFC) was calculated according to Equation 1. This procedure was performed independently for the reference instruments and the sensors.

$$SFC = \frac{\Delta SO_2\ (ppb)}{\Delta CO_2\ (ppm)} \times 0.232\%$$

Equation 1: *Equation to calculate the sulfur fuel content (SFC) within a plume.*

During the week-long campaign in Newcastle, 26 plumes were sampled from 18 unique vessels, 4 of which were tug boats. Figure 4 shows responses from the LCS package to a plume of pollutants. A 10-second rolling mean was applied to the sensor data to reduce the baseline noise. Aligned positive responses were seen from the NO_2, flow^{EVO} CO_2 and particulate sensors. A clear response on the NO sensor is seen at the same time, although, unexpectedly, this is negative. The cause of this is being investigated with the sensor manufacturer. The three low-cost NDIR CO_2 sensors failed entirely for this test, providing no useful data.

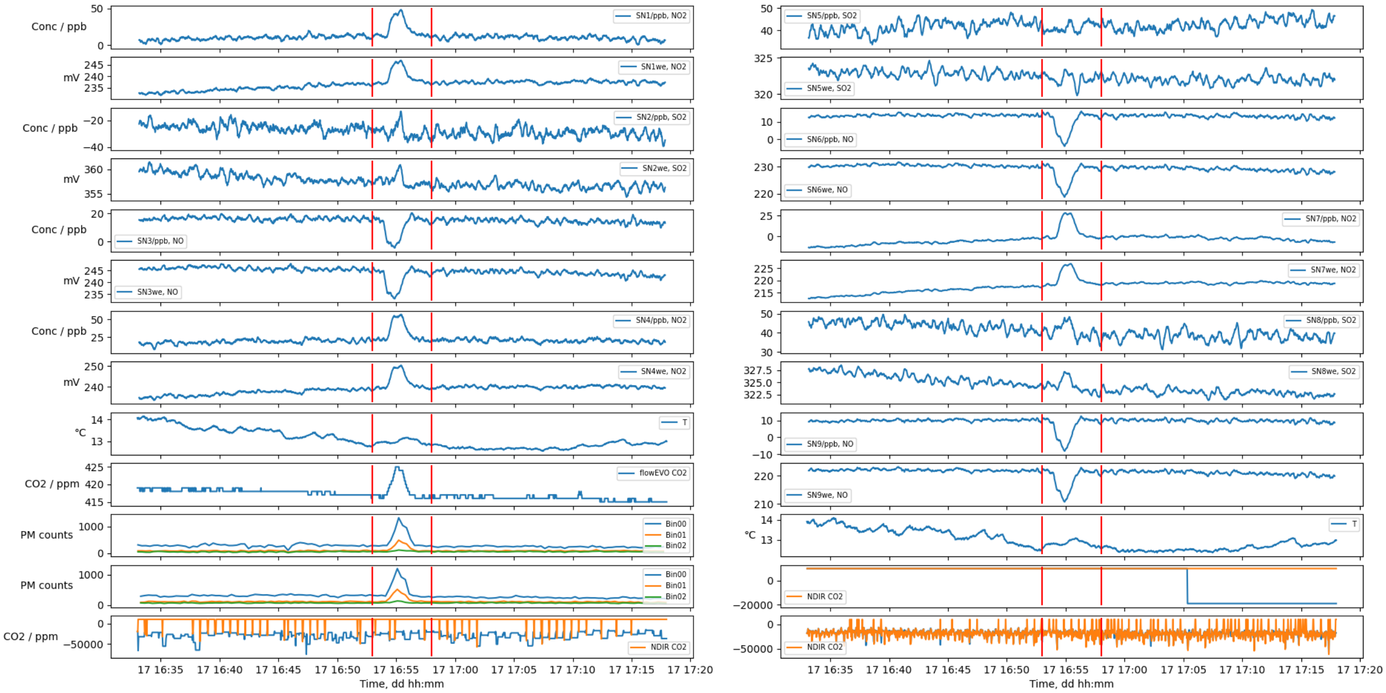

Figure 4: *Time series for a single ship plume showing the responses of the LCS package.*

Figures 5-8 show the time series for plumes of SO_2, NO_x, CO_2 and particulate matter (PM) measured with the reference instrumentation in the WASP, respectively. Clear plumes of NO_x and CO_2 were observed from every ship, whereas SO_2 was only observed in approximately half the plumes. There was evidence of PM emissions from the majority of passing ships. However, it was difficult to isolate the enhancement from the ship plumes due to the complex source characteristics of PM in urban areas.

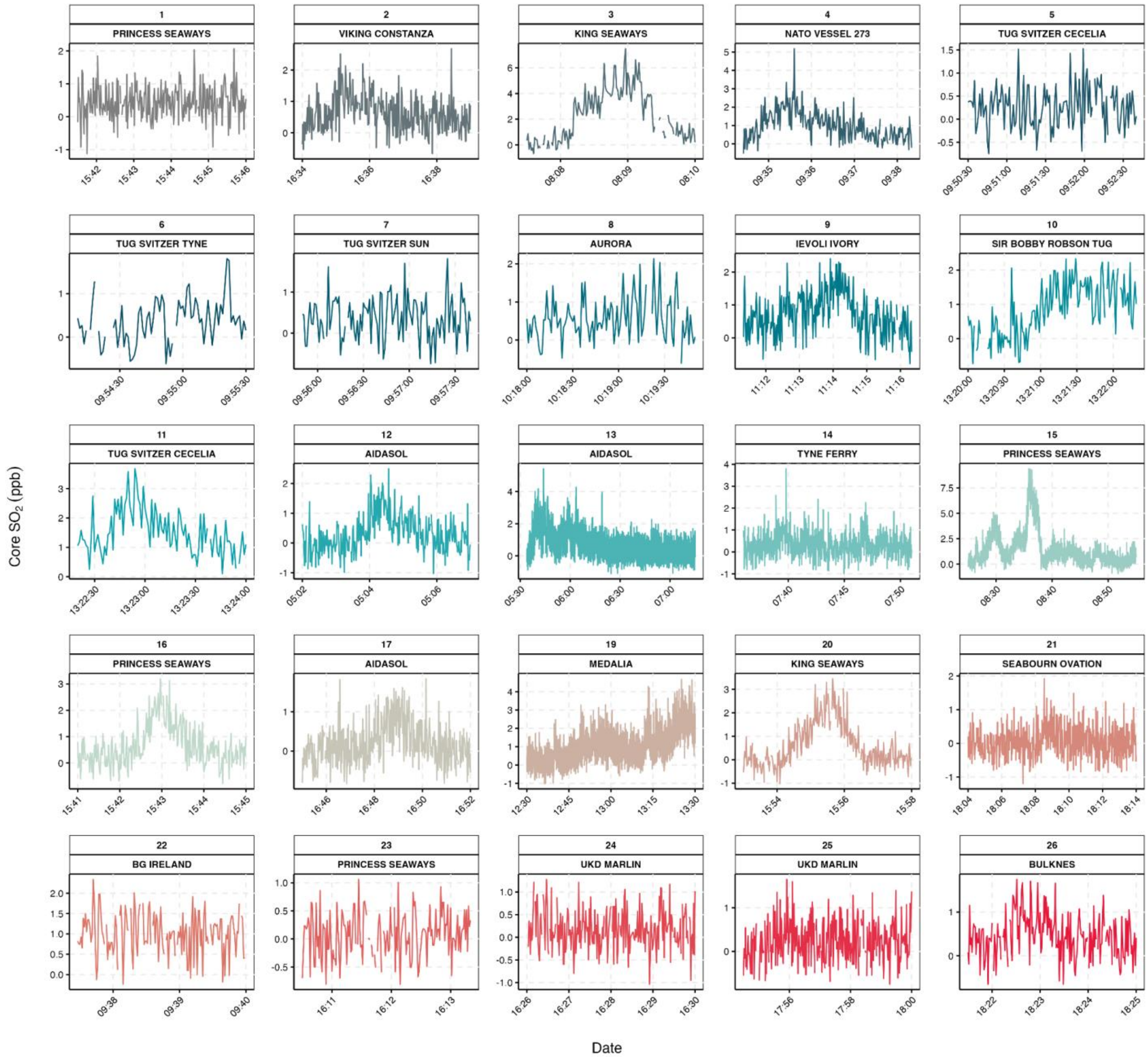

Figure 5: *Time series of SO_2 for individual plumes measured using reference instrumentation.*

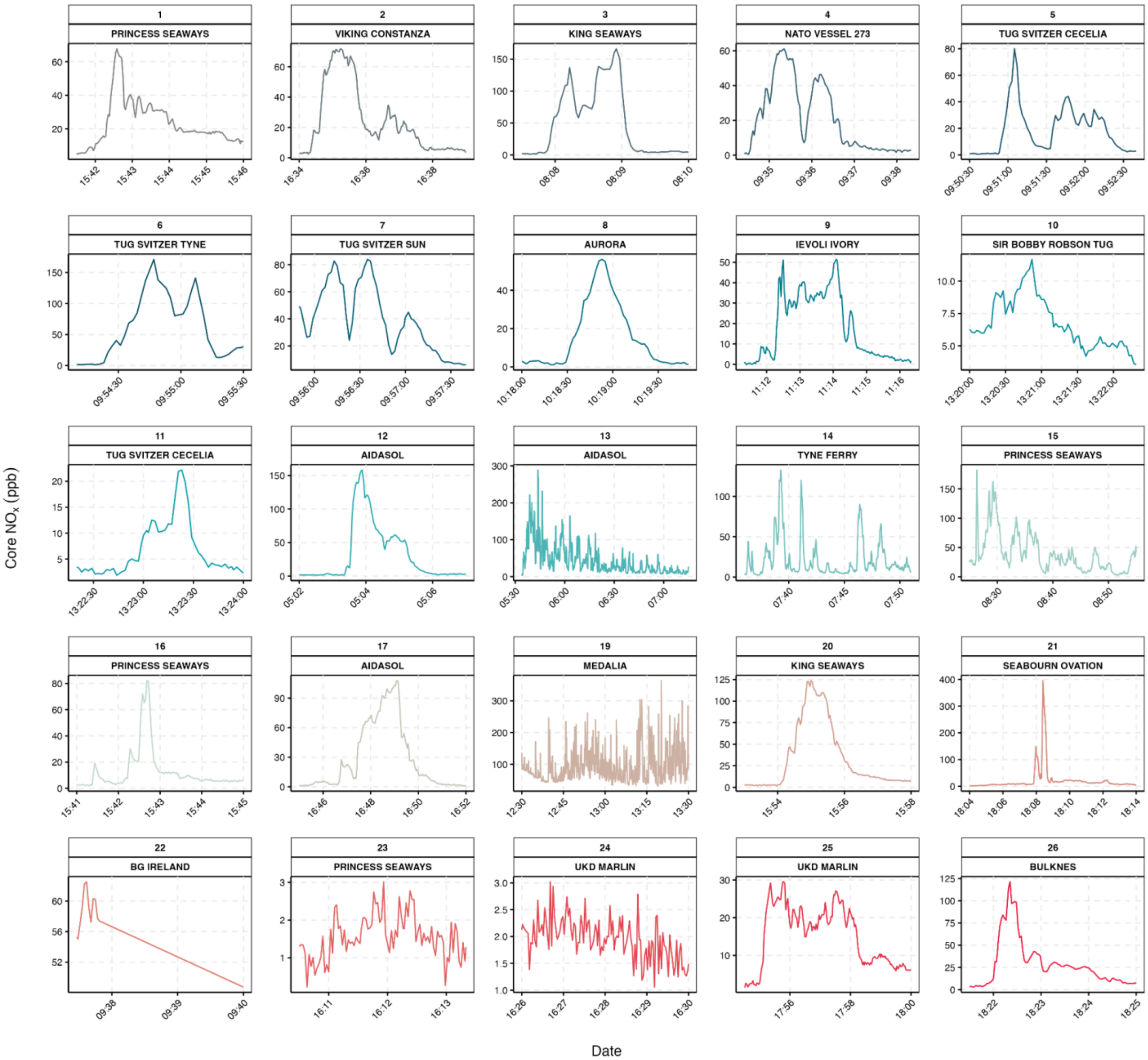

Figure 6: *Time series of NO_x for individual plumes measured using reference instrumentation.*

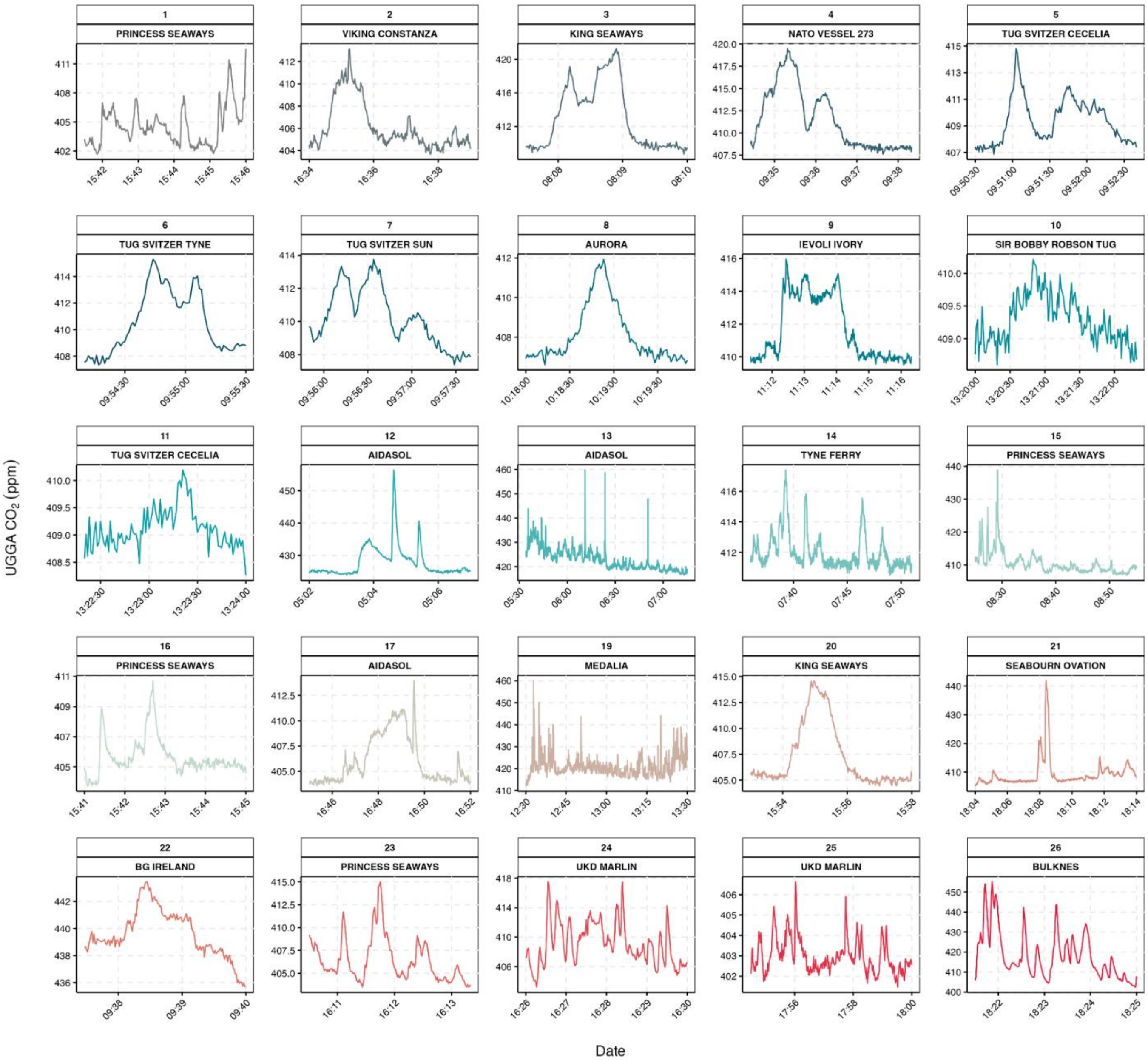

Figure 7: *Time series of CO_2 for individual plumes measured using reference instrumentation.*

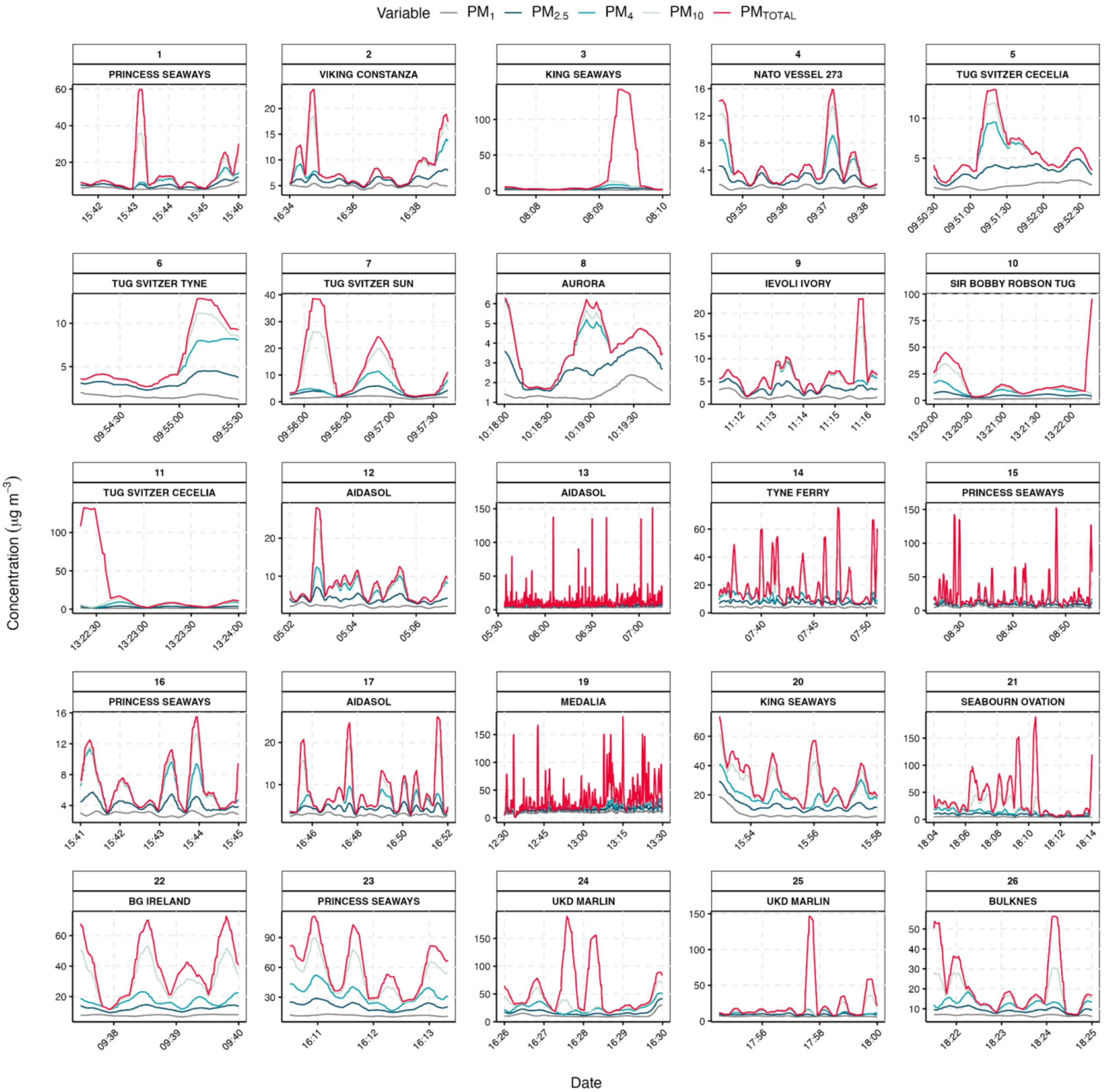

Figure 8: *Time series of PM size fractions for individual plumes measured using reference instrumentation.*

Figure 9 shows an example of a single plume measured using the reference instruments and the LCS. Due to the small magnitude of enhancements in SO_2, typically ranging from 1-2 ppb, the plumes were difficult to resolve even with the high-sensitivity commercial instrument in the WASP. Consequently, the low sensitivity and low-signal-to noise ratio of the SO_2 LCS limited their ability to detect highly dispersed plumes of SO_2 effectively. The NO_2 sensor showed more promising results, clearly responding to enhancements in NO_2 but also suffered from a low signal-to-noise ratio. The mid-cost CO_2 sensor performed very well, as expected, agreeing well with the reference CO_2 measurements from the UGGA and ICAD.

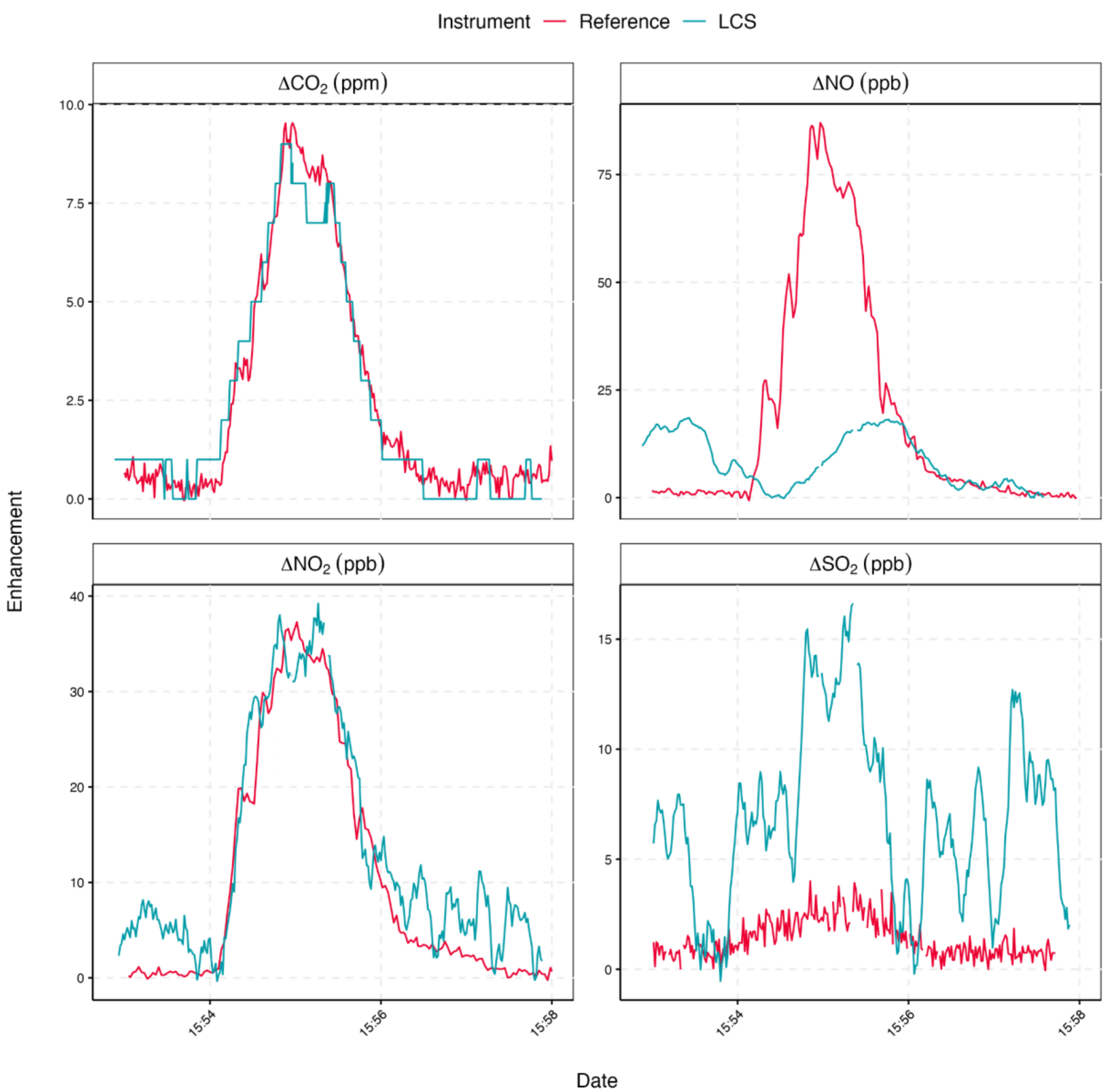

Figure 9: *Time series of enhancements in CO_2, NO, NO_2 and SO_2 for a single ship plume measured by the* reference *instrumentation and LCS.*

Figure 10 shows an example of the correlation of each species (NO, NO_2 and SO_2) with CO_2 for the single ship plume shown in Figure 9. Enhancements in all 3 species were evident from the reference instrumentation. Positive slopes were obtained from all the LCS, suggesting they did at least respond to the enhancements in the plume. The strongest response was seen by the NO_2 sensor, which produced a similar slope value to the reference instrument. For SO_2, the high degree of noise resulted in a steeper slope and larger uncertainty (shaded region in Figure 9) compared to the reference instruments. For NO, a large response was seen by the reference instruments which was not replicated by the sensors. In all cases, there was a clear offset between the absolute concentrations reported by the LCS compared to the reference instruments. However, given more time to develop a robust calibration procedure, this could likely be improved.

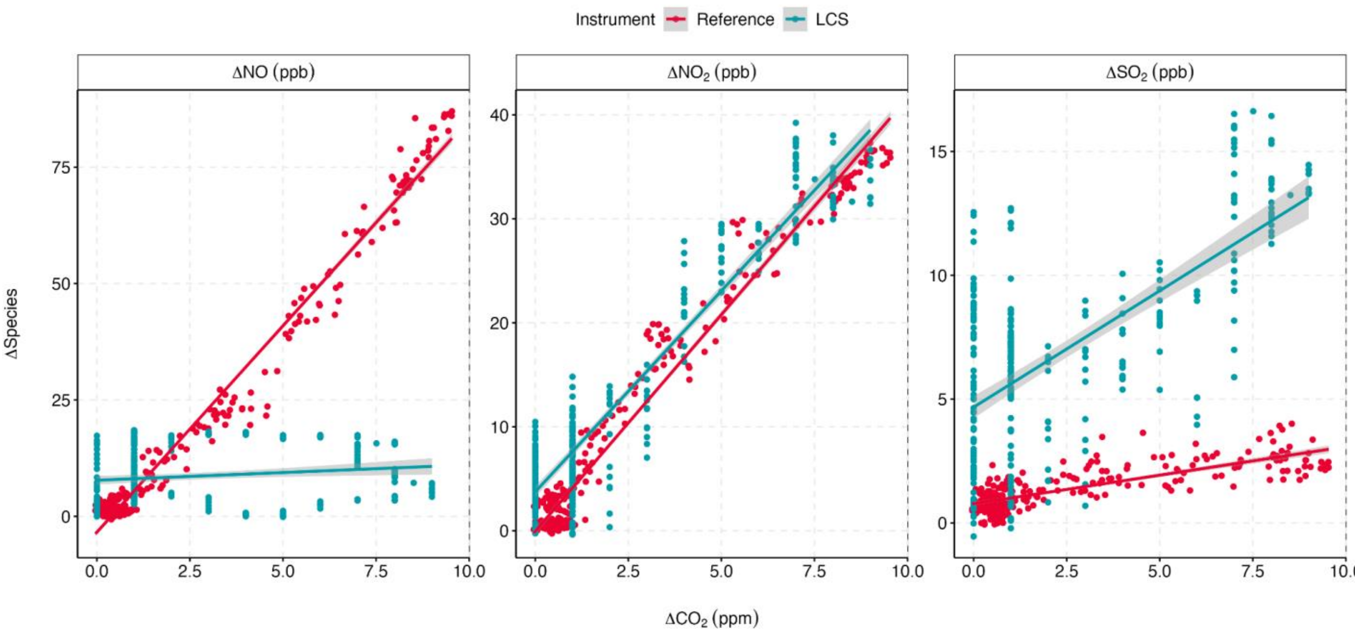

Figure 10: *Scatter plot of enhancements in NO, NO_2 and SO_2 against the CO_2 enhancement for a single ship plume (see Figure 9) measured by the reference instrumentation and LCS. The solid line shows the fit obtained from a linear regression. The shading represents the standard error of the slope.*

Figure 11 shows the calculated SFC, $\Delta NO_2/\Delta CO_2$ and $\Delta NO_x/\Delta CO_2$ ratios for the ships measured during the campaign. For cases where a vessel was measured more than once the result is represented by multiple points on the plot. The average SFC is 0.04 ± 0.03%, which is significantly lower than the 0.1% stipulated by IMO regulations inside the sulfur control zone of the English Channel and North Sea. Only two vessels (not shown) breach this limit (albeit with a large error on the measurement) and these are both tug boats. It is interesting to note that two other tugs do not breach the limit. $\Delta NO_x/\Delta CO_2$ ratios varied from 0.0001 - 0.021 ppb / ppb, with an average of 0.008 ± 0.0002. There are not currently easily definable regulations of NO_x emissions from ships, however for context recent remote sensing measurements of road vehicles have shown that Euro 4 standard and above petrol vehicles have a NO_x/CO_2 emission ratio of 0.0003 - 0.001 ppb ppb^{-1} with Euro 6 diesel vehicles having a range of 0.0017 - 0.0026 ppb ppb^{-1}. This shows that ships on the Tyne typically have a higher NO_x/CO_2 ratio than road vehicles. This is important, especially for a city like Newcastle where the ships sail down the river to access the port, making them a potentially significant source of NO_x to the city.

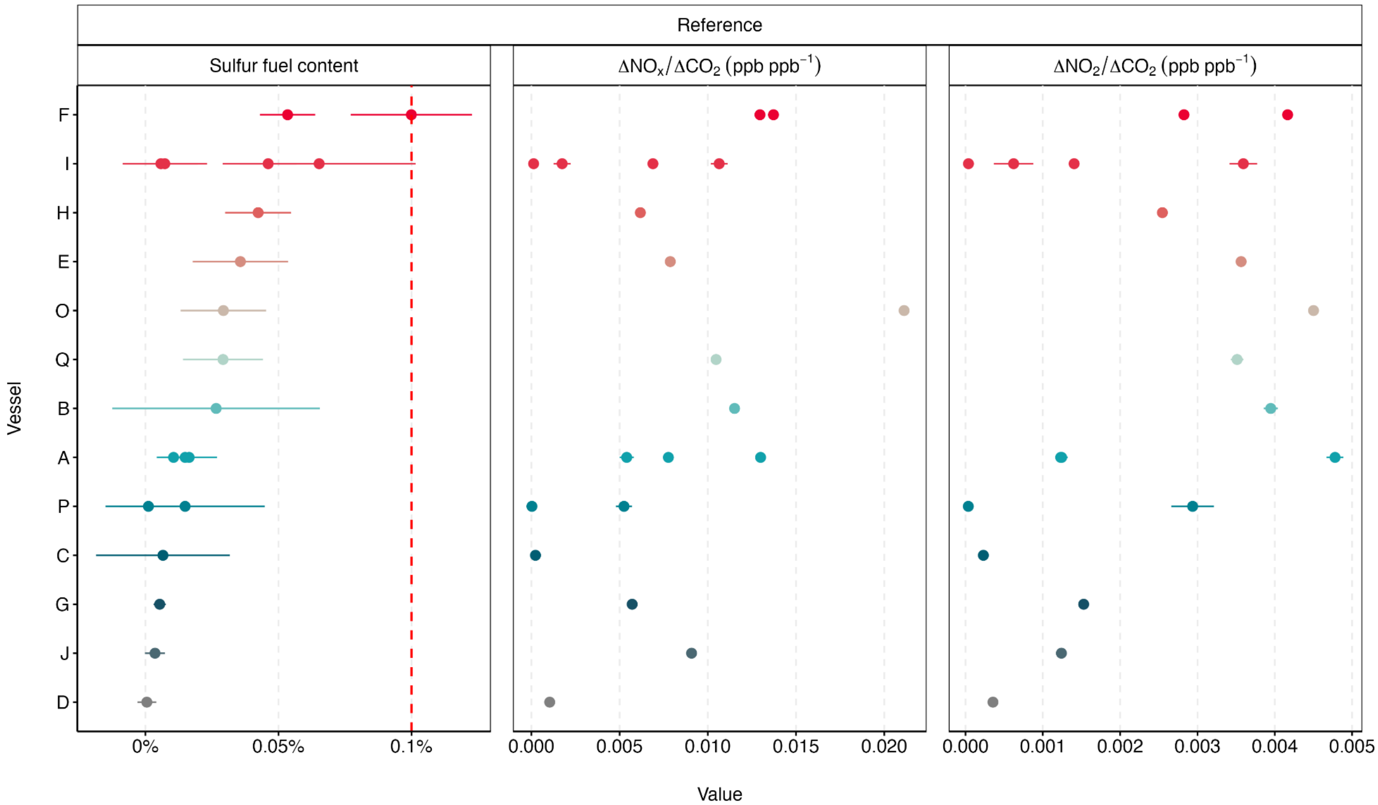

Figure 11: *Sulfur fuel content (SFC) and enhancement ratios of $\Delta NO_2/\Delta CO_2$ and $\Delta NO_x/\Delta CO_2$ for individual ship plumes calculated using data from the reference instruments in Newcastle. The error bars represent the standard error of the model slope. The vertical dashed line represents the maximum amount of sulfur permitted in marine fuels, which is 0.1%.*

Figure 12 shows a comparison between $\Delta NO_2/\Delta CO_2$, $\Delta NO_x/\Delta CO_2$ and $\Delta SO_2/\Delta CO_2$ enhancement ratios for the LCS compared to the WASP reference instruments. For NO_2, a good correlation between the reference and LCS data was seen (R^2 = 0.57) and encouragingly the points lay close to the 1:1 line (slope = 0.84). For $\Delta NO_x/\Delta CO_2$, the correlation was reasonably strong (R^2 = 0.63) but the LCS values were significantly lower (slope = 0.29). This is likely due to a negative interference in high NO_2, low O_3 plumes on the NO sensor. Finally, for $\Delta SO_2/\Delta CO_2$ the LCS produced values which were higher than the reference measurements by approximately a factor of 5 (slope = 3.2), suggesting that the SO_2 sensor measurement is not sensitive enough for this calculation. However, it is worth noting that the reference instrument was not able to detect all plumes of SO_2 due to the fact that most ships are now meeting the new stricter SO_2 limit. For plumes that were detected, the uncertainty in the slope of $\Delta SO_2/\Delta CO_2$ was generally larger than those for $\Delta NO_2/\Delta CO_2$, $\Delta NO_x/\Delta CO_2$ due to the comparatively small enhancements in SO_2.

Figure 12 illustrates that despite the difference in the absolute values of concentrations obtained from the LCS and the reference instrumentation, for NO_2 at least, representative values for emission factors from ships can be obtained from LCS alone. This is an important result since one of the key difficulties associated with

LCS is the challenge associated with calibration to obtain an accurate measure of absolute concentrations. However, we show that the relative response to the enhancements can be sufficient to provide a decent measure of NO_2 emission factors.

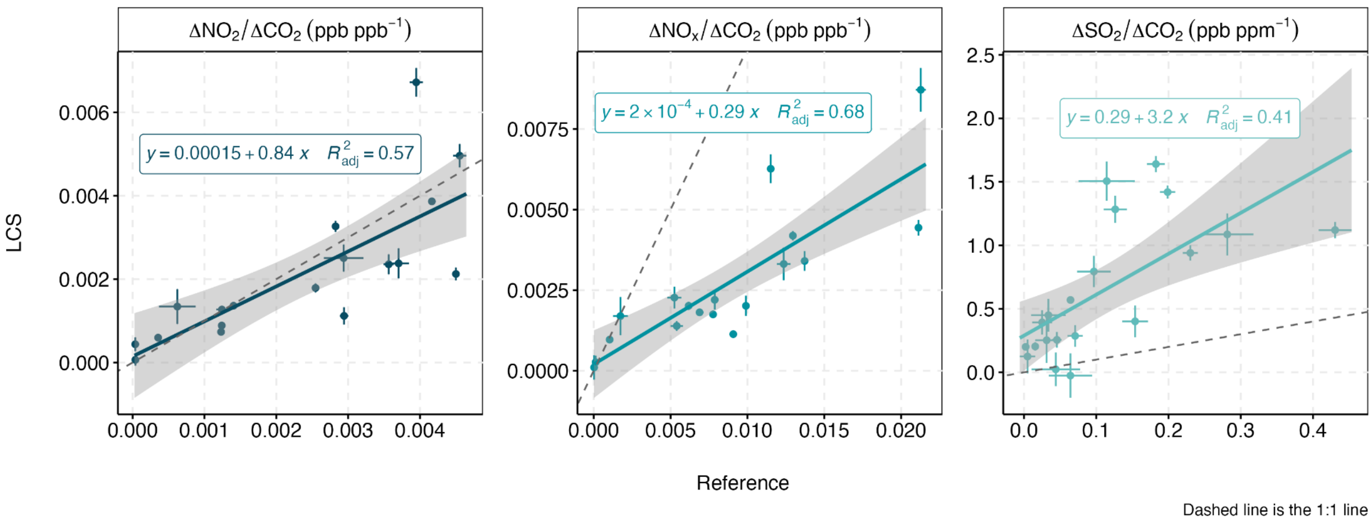

Figure 12: *Comparison between LCS and* reference *data for calculating enhancement ratios of* $\Delta NO_2/\Delta CO_2$*,* $\Delta NO_x/\Delta CO_2$ *and* $\Delta SO_2/\Delta CO_2$ *for individual ship plumes. The error bars represent the standard error of the model slope for each ratio. The solid line represents the line of best fit from a linear regression and the shading shows the standard error of the fit. The dashed line represents the 1:1 line.*

In summary, the LCS show great promise for measuring NO_x/CO_2 emission ratios from ships, something that is likely to become increasingly important as more stringent regulations on NO_x emissions from ships are introduced. The interference on the NO sensor would need investigating and correcting for but we believe this is something that could be done for future sensor measurements.

WP4/WP5

After the assessment of the gas sensors in the early stages of the project, effort on the project was redirected towards improving the sensitivity of the sensor package, as this is a prerequisite for making useful measurements once the instrument is deployed in ports. As a result of this, we did not have the resources to progress beyond early-stage discussions of sensor ruggedisation within this project.

<u>Sensor Deployment on Buoy Platforms</u>

JET manufactures a 1750 mm diameter buoy platform, capable of hosting small sensor packages and powering them continuously with off-grid power sources.

Investigation into using multiple ruggedization designs to the sensors have been considered, with consideration and efforts made to ensure that this ruggedization does not compromise the overall performance.

From the preliminary work undertaken, it is understood to be highly feasible to have the sensor pack permanently deployed at sea on a JET Connected Buoy.

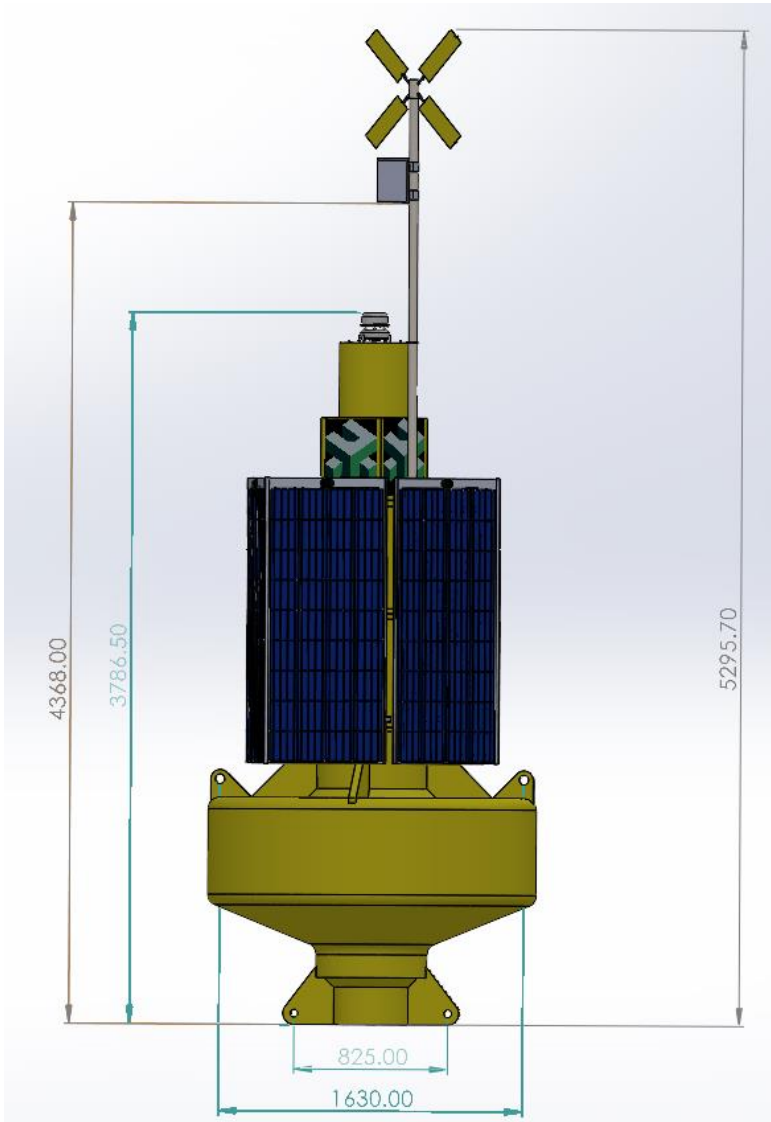

Figure 13. JET Buoy with mounting position of an example box highlighted.

What are the next steps for this research? Will you be applying for further funding? What will you need to continue researching this topic?

The van and reference instrumentation will continue to be used to measure emission ratios from ships and other transport sources. A Horizon 2020 EU project has recently been submitted to do this in 8 cities around Europe.

We will also continue to assess the SO2 measurement in order to provide a minimum detectable SFC level. We can then examine how close the measurements need to be to the ship in order to make the measurement, something that could be possible with the buoy or UAV deployment.

Additional next steps will include the integration of the sensor package onto JETs floating 5G buoy infrastructure. There is potential to utilize JETs newly established 5G test-bed at the Port of Grimsby, where the initial trials of sensor integration and performance at sea can be reviewed. Alternatively, follow on work could also include the deployment and integration of an entirely new buoy platform in a different port location. The scale of opportunity for follow on R&D will be determined by the overall funding available, as well as end-user or stakeholder engagement. One possible fund opportunity would be UKRI's Industry Impact Fund (here), of which themes include health and Net Zero.

Another potential application is the use of the LCS instrument on an Unmanned Aerial Vehicle (UAV) to measure the ship plumes. This would provide a more detailed map of the gases and PM's in the plume with both horizontal and vertical resolution. This has already been proven to be a valuable application in similar projects (the Scipper project), and would complement the measurements made by the buoy in the water and the van on the land. RAL Space have expertise in the use of UAVs with custom instrumentation.

Please outline the role of STFC in this project
The low-cost sensor package tested in the project was developed and built by STFC.
Please list a brief list of all outputs and impacts below. These may include papers, articles or blogs, presentations at events or conferences, meetings about future plans for the research. Please include links wherever possible
Data from the project was presented at the EGU conference in April 2023 (https://doi.org/10.5194/egusphere-egu23-7986) Clean air networks conference invited talk and poster (Shona Wilde) https://www.ukcleanair.org/2023/06/01/clean-air-networks-conference-university-of-birmingham-5-6-july-2023/

Were there any unexpected outcomes as part of the project?

The project allowed the team at STFC to better understand the benefits and challenges associated with using the LCS in the field.

What are your plans to share the outcomes of this research with others? (Give details of any future meetings, conferences, papers or other dissemination planned)

A paper on SFC and NO_x / CO_2 from ships will be submitted by the end of August 2023. This will also include data from the NERC ACRUISE project, taken from the FAAM aircraft in the English channel and wider Atlantic Ocean (outside the sulfur control zone). York to lead.

A Paper on sensor and reference measurement comparisons will be written. More calibration work is required for this. STFC will work in collaboration with York to achieve this. STFC will lead the paper.

Project Impact: What is the most significant output/impact from this project?

Demonstration of the validity of point measurements from publicly accessible spaces to calculate emission ratios from shipping.

Sensors show great promise for emission ratio calculation, especially NO_2.

Collaboration between York, STFC and JET. This new collaboration should lead to future work in this and potentially other areas.

This project has facilitated a strong collaborative relationship for JET with key academic specialists, delivering a new data-stream and potential revenue opportunities for the company. The project builds on JETs existing real-time data collection and transmission opportunities, facilitating increasingly sustainable, cleaner and efficient port operations through 5G at sea.