A Review of Research into the Effects of Shipping on Air Quality in Auckland: 2006-2016

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Te Kaunihera o Tāmaki Makaurau

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A review of research into the effects of shipping on air quality in Auckland: 2006-2016

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Auckland Council

Executive summary

The waterfront area of Auckland is a multi-land use area of key importance. Industrial and commercial entities such as the Ports of Auckland and fisheries share space with recreational facilities, tourists, businesses and shoppers in one of the most densely populated areas of New Zealand. The proximity of the port and the associated visiting vessels to this central Auckland location provides easy access to Auckland's commercial centre for industry and tourists alike, but also raises concerns regarding possible impacts on the environment.

Studies carried out world-wide have shown that shipping emissions impact upon the air quality of coastal areas adjacent to shipping routes, to the detriment of human health and the local environment. Shipping vessels have been found to emit a far greater concentration of hazardous air pollutants when compared to land-based transport, which is attributed to their use of poor quality fuel. In light of these concerns, research has been carried out by several groups over the past decade to assess what impacts, if any, shipping vessels have on Auckland's air quality and more particularly, that of the waterfront area.

Results from research with methodology based on measurements of sulphur dioxide (SO_2) concentrations, indicate that SO_2 levels are at their highest close to the waterfront area of Auckland. This is most apparent when winds are from the north-east. Moreover, measurements made over longer periods through the deployment of passive tubes show that concentrations of SO_2 are up to four times higher at the waterfront than at any other site in Auckland.

Passive tube deployments provide a larger spatial resolution of results across Auckland by obtaining multiple simultaneous measurements. The results obtained from these deployments supported data from the long-term monitoring site in Queen Street, showing elevated levels of SO_2 at the lower end of Queen Street. This is despite the Queen Street site being located a significant distance away from the waterfront, along one of the busiest and most populated streets in Auckland's central business district (CBD).

The concentration of SO_2 was found to be highest when the wind comes from the direction of shipping emission sources. However, diesel emissions from heavy goods vehicles and other diesel combustion sources also contribute SO_2 to the atmosphere, while airflows around tall buildings near the waterfront can make the wind direction/SO_2 relationship difficult to interpret conclusively. Therefore, utilising SO_2 and wind direction data in isolation implies, rather than confirms, a shipping emission source.

A more robust, internationally recognised method of detecting shipping sulphate is by identifying the chemical markers vanadium (V) and nickel (Ni) metals along with sulphate. Two reports that utilised this methodology confirm the connection between a predominantly north-east wind flow and elevated concentrations of pollutants from shipping emissions, more particularly towards the waterfront. Moreover, using this identifying technique, evidence of shipping emissions was found at monitoring sites across Auckland.

Overall, $PM_{2.5}$ concentrations decreased across the city during the north-east wind direction, this is likely due to fewer traffic sources to the north-east. However, one site at Albert Park showed an increase in concentrations during the north-east airflow. In the absence of other traffic markers, the result indicates that shipping emissions may also influence $PM_{2.5}$. When the airflow comes from the prevailing south-westerly direction, the shipping plumes appear to have minimal impacts on the waterfront and Auckland's densely populated CBD. However, whether shipping plumes have any impact on areas to the north-east of the city is not known at this stage.

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1.0 Introduction

The Auckland waterfront, in the heart of the central business district, comprises of Auckland's port, Queens Wharf, Viaduct Basin and Wynyard Quarter. The waterfront area is an essential part of the city's identity acting as a gateway for commerce, international tourism, as well as being a venue for many cultural and recreational activities. At the southern end of the waterfront is Auckland's port, New Zealand's second busiest receiving over 1500 ships a year. The visiting fleet includes large vessels conducting international trade and around 100 cruise ships annually. The net worth of cruise ships alone is estimated to be $1.5 million per ship visit (Ports of Auckland Annual Review, 2015).

Research carried out in coastal cities world-wide has revealed that air pollutants emitted from ships can have adverse impacts on human health and coastal ecosystems (Viana et al., 2014). Due to the waterfront and port area being centrally located and densely populated there is a need to investigate how shipping emissions may impact on Auckland's air quality, as well as ensuring Auckland remains in line with current regulatory changes within the international maritime community (MARPOL 2016).

As part of Auckland Council's ongoing remit to maintain and improve air quality, key air pollutants are monitored in various locations throughout the region. The range of contaminants measured at a site is dependent upon the prominent emission source(s) typical in that area. Results from this monitoring programme have indicated higher than expected concentrations of certain pollutants close to the Auckland waterfront. Further subsequent research carried out by other groups supported these results. The types of pollutants measured in elevated levels are commensurate to those typically released from the combustion of poor quality diesel fuel. Shipping vessels often use low-quality fuel due to cost considerations; therefore emissions released by shipping may negatively impact on Auckland's air quality especially when there is onshore (north-east) airflow.

The elevated levels of SO_2 at the Auckland waterfront are most likely caused or exacerbated by the high sulphur content fuels (~2.7%) commonly used to fuel ocean vessels. By contrast, concentrations of sulphur in automotive fuel have decreased markedly over the past few decades leading to a significant reduction in background levels. The decline of sulphur emissions from on-land vehicles also includes POAL's fleet of work vehicles and other heavy-duty diesel vehicles arriving and leaving the port. This is important to consider as multiple emission sources of sulphur and SO_2 in the vicinity of the waterfront can cause uncertainty when trying to identify shipping-only emissions using SO_2 alone.

The identification of the metals vanadium (V) and nickel (Ni) in conjunction with sulphur provides a more reliable marker to identify shipping emissions. These metals are released during the combustion process of heavy diesel typically only used in observable concentrations by shipping fleets. Therefore, if elevated levels of V and Ni are detected along with sulphate, this provides compelling evidence that shipping is the likely source of this emission. Concentrations of chemical species such as V and Ni are measured using elemental analysis from air samples collected on filters. These filters are subjected to further analytical techniques under laboratory conditions through the process detailed in Davy et al. (2014).

Over the past decade, several studies have used SO_2 and/or Ni and V to identify shipping emission sources:

- SO_2 passive monitoring study 2007 (McLeod, 2007).
- Port emissions inventories 2006 and 2010 (Peeters, 2010).
- Ports of Auckland SO_2 monitoring 2011-2014.
- Source apportionment trends report 2006-2014 (Davy et al., 2014).
- Spatially Resolved Techniques for Source Apportionment in New Zealand (SPARTANZ) (Longley et al., 2016).

This report describes the key outcomes from these five investigations, which are then summarised to provide an overview of our current understanding of how shipping emissions impact on Auckland's air quality. By assessing the methodologies used and results obtained this document will serve as a useful reference point to guide future investigations. It is not within the scope of this report to comment on the operation of POAL, nor to advise on possible mitigation strategies.

2.0 Monitoring in Auckland

Air quality monitoring is undertaken by Auckland Council as part of the statutory obligations under the Resource Management Act 1991 (RMA) and the National Environmental Standards for Air Quality 2004 (NESAQ). Air quality monitoring is required to understand the levels of pollutants the population of Auckland are exposed to, inform policy decisions and track their effectiveness, assess compliance with guidelines and standards, monitor air quality trends, and support regulatory functions such as resource consents. A summary of Auckland Council air quality monitoring is available in Auckland Council's State of Auckland report cards (2016).

Auckland Council continuously monitors several air pollutants at sites spread across the Auckland region. In total, there are currently eight permanent sites operational, however, over the past 10 years there has been a maximum of 11 sites operational over the Auckland region (Figure 2.1) ranging from Pukekohe to Warkworth, and Henderson to Botany Downs. These sites were selected to represent a variety of pollutants, their sources, and provide a rough indicator of potential exposure to Auckland's population to potentially hazardous airborne pollutants. Included in the air pollutants monitored are PM_{10} and $PM_{2.5}$ particulates, nitrogen dioxide (NO_2), carbon monoxide (CO), sulphur dioxide (SO_2) and ozone (O_3). Auckland Council also undertakes passive sampling of air pollutants. Passive sampling campaigns involve exposing passive samplers, e.g. an activated filter paper to the air for a period and analysing them to obtain a concentration measurement for the targeted pollutant. Passive sampling campaigns are generally short-term, targeted towards certain pollutants but are a cost effective way to better understand spatial distribution of pollutants.

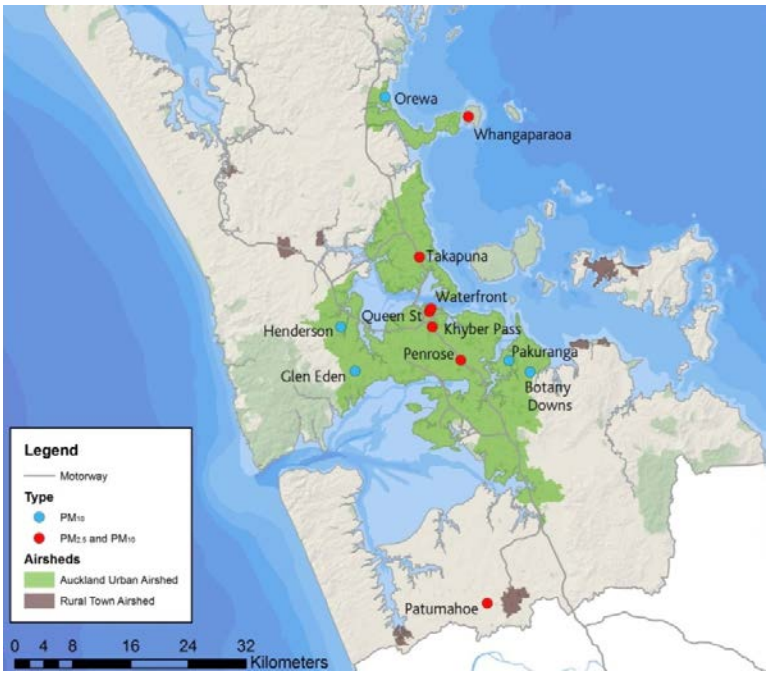

Figure 2-1: A map showing the location of monitoring sites that provided data for this report (Davy et al., 2014).

2.1 National Environmental Standards and regional air quality

The National Environmental Standards for Air Quality (NESAQ) were introduced by the Government in 2004. They contain 14 individual standards or regulations that apply to all of New Zealand. Seven of these regulations ban activities that discharge unacceptable levels of toxic substances into the air and five of the standards impose ambient air quality standards for:

- Carbon monoxide
- PM_{10} particulates
- Nitrogen dioxide
- Sulphur dioxide
- Ozone

The NESAQ ambient standards define the permissible concentrations of contaminants in the air over a specified time. These standards must be complied with throughout New Zealand. For some pollutants the NESAQ standards include a number of permitted exceedances, i.e. a set number of instances where levels in excess of the standard are permitted (Table 2.1).

Table 2-1: National Environmental Standards for Air Quality

Contaminant	Standard	Averaging Time	Number of permitted exceedances per year
Particles (PM_{10})	50 µg/m^3	24 hour	1
Carbon monoxide (CO)	10 mg/m^3	8 hour (running mean)	1
Nitrogen dioxide (NO_2)	200 µg/m^3	1 hour	9
Ozone (O_3)	150 µg/m^3	1 hour	0
Sulphur dioxide (SO_2)	350 µg/m^3	1 hour	9
	570 µg/m^3	1 hour	0

Under the RMA, councils have the ability to further assign additional Air Quality Standards or Targets for pollutants not covered by the NES, or should they wish, to set standards more stringent than those of the NES. Auckland has defined a number of additional targets within its regional plan (Appendix: Table 5-1).

3.0 Monitoring campaigns around Auckland's waterfront

The following sections represent a chronological account of monitoring and research that has been undertaken around Auckland's waterfront and downtown areas over the past decade. These data, combined with existing global scientific evidence, formed the rationale for the council and other stakeholders to develop further monitoring and investigation strategies for emissions arising from shipping.

3.1 SO_2 passive monitoring studies 2007 and 2011

During the New Zealand winter months of 2007, a passive monitoring study of sulphur dioxide (SO_2) was undertaken at 17 locations across the Auckland region (Appendix: Figure 5-2). Historically, SO_2 has been measured in Auckland since the late 1970s at the council's Penrose monitoring station. The 2007 study was commissioned to gain a wider perspective of potential SO_2 concentrations across the region and to understand where SO_2 levels stood in relation to the 2006 revised WHO guidelines for SO_2 (McLeod, 2007).

In this study, monitoring was undertaken over a three month period from June to August. Winter is typically when concentrations of SO_2 in ambient air are higher. This is due to the higher levels of fossil fuels burnt for heating as well as meteorological conditions that are less likely to aid dispersion (ARC, 2010). The wintertime deployment was chosen to provide a 'worst case' scenario for SO_2 concentrations. Verification of the results was achieved by deploying duplicate tubes at each of the peak sites (Appendix: Table 5-2). These tubes were run for the same time period and were analysed at the same time using the same techniques. The results of the duplicates were comparable to volumes of SO_2 in both sample tubes at each location. This demonstrates confidence in volumes and concentrations measured.

Overall, SO_2 concentrations across Auckland are relatively low compared to the NESAQ, with Queen Street and Auckland Port the two exceptions (Figure 3-1 and Table 3-1). Although direct comparisons to national standards cannot be made due to sampling period considerations, concentrations remain low at Queen Street and Auckland Port in relation to the NESAQ.

The concentrations at these two sites are several orders of magnitude higher than any other monitored location in this study. The standard deviation from the average concentrations of all other sites monitored in this survey is low (Table 3-1), which indicates their measured concentrations are largely clustered around the mean, and likely represent background concentrations of SO_2 over the urban Auckland airshed. In contrast, the higher concentrations measured at Queen Street and Auckland Port indicates that these sites have a local source(s).

The method of passive monitoring used in this study cannot determine the source type and pattern of SO_2 emissions (i.e. high volume low-frequency source(s) or low volume high-frequency Source(s)). The fact that both sites with the highest concentrations are located in relative proximity to each other around the downtown and waterfront area does indicate a potential local source(s) of SO_2.

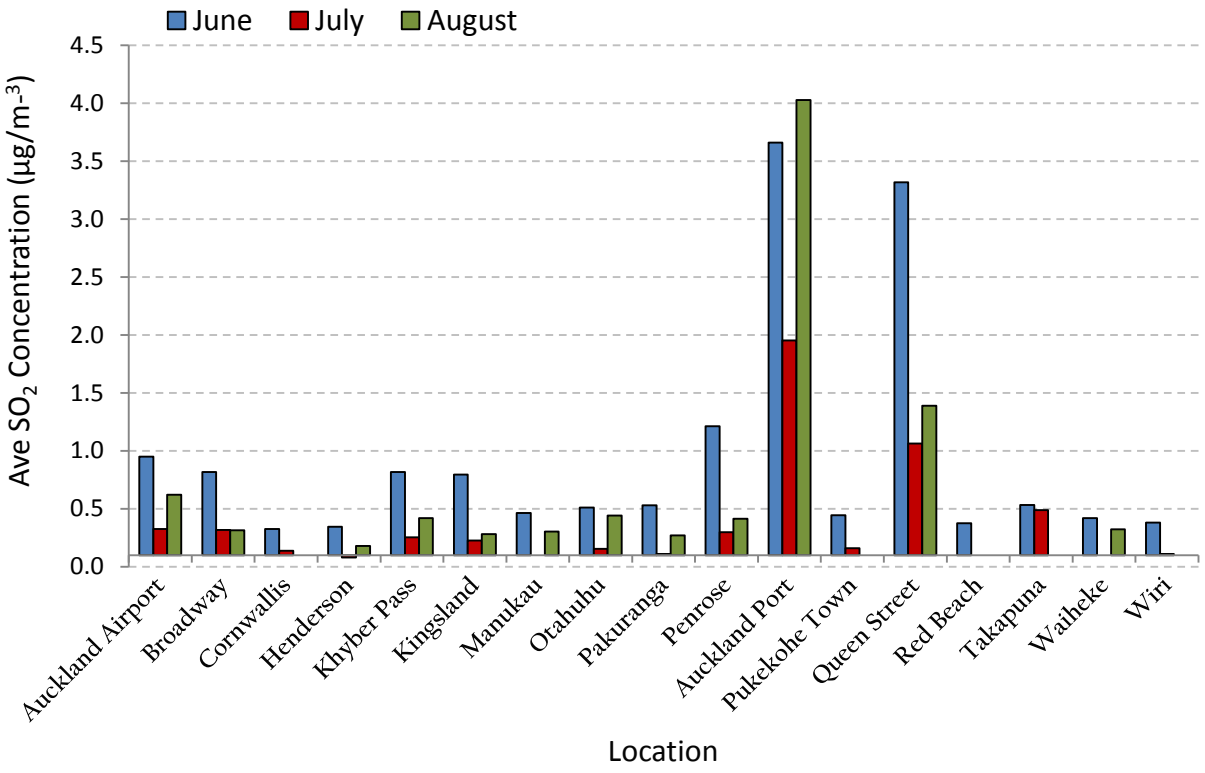

Figure 3-1: SO_2 passive sampling results 2007.

Table 3-1: Summary of monitored results at Queen Street and Auckland Port sites.

Location	June ($\mu g/m^3$)	July ($\mu g/m^3$)	August ($\mu g/m^3$)
Auckland Port[1]	3.99	5.58	4.40
Queen Street	3.62	3.04	1.52
All other sites (Average) (St.Dev)	0.63 (0.27)	0.48 (0.35)	0.26 (0.23)

[1] Note: The use of 'Auckland Port' is a spatial reference to a sampling location near the waterfront/port area, not to Ports of Auckland Limited.

While the significance and source of the higher concentrations measured at Queen Street and Auckland Port cannot be concluded from these data, the evidence indicates that there have been SO_2 concentrations measured at these locations substantially higher than anywhere else in Auckland. It also is worth noting that while these results cannot be directly compared to annual guidelines due to the shorter sampling period, the concentrations indicate that these sites are likely to be well below the World Health Organisation annual SO_2 guideline (Appendix Table 5-1).

A second survey of SO_2 using passive samplers was conducted in 2011. The aim of this study was the ongoing assessment of SO_2 concentrations throughout Auckland, as well as additional follow-up sampling around the waterfront and downtown Auckland based on the evidence of the 2007 passive study.

A total of 36 sites were monitored, of which 17 were placed in the waterfront and downtown areas, a further nine were located around the midtown and uptown areas, with the remaining sites located throughout the wider region. The sampling was conducted over a period similar to that of the 2007 study (Table 3-2).

Table 3-2: Summary of 2011 monitoring at Queen Street and Auckland Port sites compared with all non-waterfront sites.

Average (St.Dev)	June $\mu g/m^3$	July $\mu g/m^3$	August $\mu g/m^3$
All sites	2.49 (4.61)	1.58 (2.91)	2.05 (1.75)
Waterfront sites	3.03 (5.12)	1.70 (3.11)	2.19 (2.19)
Non waterfront sites	1.65 (3.66)	0.82 (0.49)	1.92 (2.14)

The results from this follow up survey were less clear than those presented in the 2007 study, although the results do support the conclusions that indicate higher SO_2 levels and the presence of a local source(s) of this pollutant in Auckland's downtown and waterfront area.

Data collection for this study was slightly problematic due to two reasons:

- A number of passive samplers throughout the study area were lost (likely due to removal by unknown parties).
- A significant number of passive samples had concentrations below their effective detection limits for SO_2 either due to low concentrations.

Due to the lack of data from this diffusion tube deployment the results are not plotted here and the results provided in Table 3-2.

The results summarised above indicate that there are slightly elevated levels of SO_2 present in the waterfront and downtown area when compared to the non-waterfront areas. However, the non-waterfront sites are likely to be less representative of SO_2 concentrations as these sites are where the greatest sample loss occurred.

Within the 2011 investigation higher concentrations of SO_2 were observed at six locations throughout Auckland: Wyndham Street; Princes Wharf; Queen Street; Beach Road; Auckland Hospital, Mt Eden. With the exception of Auckland Hospital and Mt Eden, the remaining sites with higher concentrations of SO_2 are located in the downtown and waterfront area. The significance of raised concentration levels at Auckland Hospital is unclear, although the frequency of buses in the area and emissions from their boiler may contribute to the slightly elevated concentrations noted in this study.

3.2 Port emissions inventories: 2006 and 2010

In 2006 and 2010, studies were undertaken to provide an inventory of emission sources arising specifically from shipping and activities in and around the port and harbour. Prior to 2006, contributions from shipping activities to air pollution concentrations in the Auckland region were estimated in the 2004 Auckland Air Emissions Inventory (ARC, 2006). The Port Related Air Emissions Inventories for 2006 and 2010 provide detailed estimates of emissions (Peeters, 2010).
This study sought to comprehensively account for all sources and provide best practice methodologies to estimate potential emissions from these sources (Table 3.3).

Table 3-3: A summary of all annual emissions (tonnes) (Peeters, 2010)**.**

Year	**2006**	***2010***	**2006**	***2010***	**2006**	**2010**
Source	**Ships - Sea**	***Ships - Sea***	**Ships - Berth**	***Ships - Berth***	**Ferry Boats**	***Ferry Boats***
NO_x	919	*976*	378	*509*	213	*248*
PM_{10}	77.1	*82.6*	45.6	*64.9*	6.9	*4.5*
VOC	34.1	*36.6*	10.9	*14.7*	7.6	*8.8*
CO	75.2	*80.3*	29.1	*39.2*	29.8	*34.9*
SO_2	563.8	*603.5*	421.2	*604.3*	0.5	*0.1*
CO_2	34885	*37115*	28204	*40079*	14968	*17427*
Year	**2006**	***2010***	**2006**	***2010***	**2006**	***2010***
Source	**Fishing Boats**	***Fishing Boats***	**Port Vessels**	***Port Vessels***	**Total**	***Total***
NO_x	108	*93*	24	*25*	1641	*1850*
PM_{10}	6	*4.2*	0.8	*0.5*	136	*157*
VOC	255.2	*247.7*	1	*1*	309	*309*
CO	535.3	*572.9*	3	*3.2*	672	*730*
SO_2	16.3	*5.6*	0.1	*0*	1002	*1214*
CO_2	9147	*8171*	1670	*1743*	88874	*104535*

Overall, this study found there was an increase in shipping emissions between 2006 and 2010. This has been attributed to a large increase in the time vessels spend in port (berthed) to around 56,000 hours in 2006 compared to 63,000 in 2010. All forms of shipping (both cruise and cargo) were estimated to be responsible for emitting around 1200 tonnes of SO_2 and 157 tonnes of PM_{10} during 2010. This study also examined the spatial distribution of SO_2 emissions about the CBD, determining that 50% of SO_2 emissions in the 2010 inventory were released within a 3 km radius of Auckland's CBD. This helps explain the results from the passive tubes deployments in 2007 and 2011. Importantly, this study addresses non-shipping related emission sources in the waterfront area. Of these, the most significant emissions are derived from private vessels with two-stroke engines which emit, primarily, volatile organic compounds (VOC) and carbon monoxide (CO).

Emissions factors from port vessels, ferries and cargo handling and distribution activities were all included in the inventory. Although all these sources contribute to air pollution in the area, none (apart from the aforementioned private vessels) have been considered to be a dominant source, or have the potential to emit significant quantities of pollutants. Research showed that diesel used in ferries and port vehicles was of low sulphur content and unlikely to be contributing in a significant manner to SO_2 levels at the waterfront.

This study took a detailed approach to assessing emissions from shipping, considering the emissions from different activities (at sea vs. in port) and loading (main engines vs auxiliary) to estimate the emissions. Further examination of this data reveals the potential for some classes of ships (and in particular cruise ships), to have a greater contribution to emissions while in port. Unsurprisingly, container shipping activities account for the most significant volume of air pollutants, simply because they have the highest numbers of visitations which account for around 30% in 2006 and 37% in 2010 of the total time in port. However, when the ratio of time in port was compared to the estimated emissions for each class of ship, both cruise ships and container ships (in general) appear to be the worst polluters. For their 37% proportion of time in port, container ships accounted for an average of 53% of the emissions (across all pollutants) in 2010. Cruise ships spent approximately 3% of the total time in port for 2010, yet contributed on average to around 18% of the total emissions estimated for that year (Peeters. 2010).

It is important to note that results of this study are based on external emission factors, not actual operational data from emission sources and shipping in Auckland. Therefore the author cites some uncertainties around operational data for which assumptions were made. Despite these uncertainties, this report provided a detailed apportioning of emissions sources and their effect on air pollution concentrations in the Waitemata Harbour.
An updated port related emissions inventory has been commissioned and is due for release late 2017.

3.3 Ports of Auckland SO_2 monitoring 2011-2014

From 2011 until 2014 Ports of Auckland Limited placed an air quality monitoring trailer within the boundary of the port to monitor SO_2 and meteorological conditions over a period of three years providing a semi-permanent monitoring site and continuous monitoring data. The data recorded was useful for establishing links between shipping emissions and SO_2 concentrations. The timing of the monitoring campaign was also to investigate possible impacts from the 2011 Rugby World Cup, hosted by New Zealand, due to a higher than average number of visiting sea vessels, including large cruise ships.

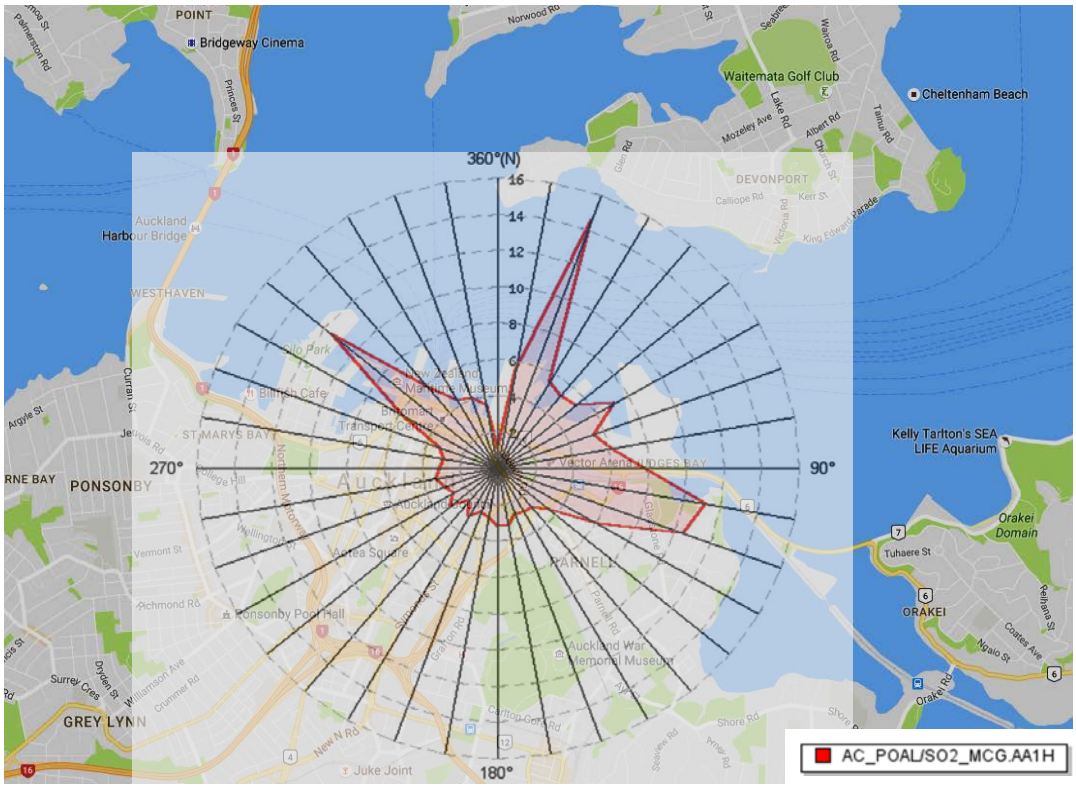

Figure 3-2: Hour averaged data covering the entire monitoring period 2011-2014 on Quay Street, Auckland waterfront.

Figure 3-2 shows that the primary contribution source of SO_2 for this monitoring station appeared to be from the shipping wharves to the north-west of the monitoring station. The north/north-east concentration peak source would also seem to come from the shipping vessels within the harbour or Ferry and shipping lanes. It is likely that the concentration increase to the east-south-east is also recirculation of shipping emission SO_2; however, the wider directional peak may be due to recirculation via the tall buildings on the southern side of Quay Street. It is also possible that some of the SO_2 concentrations from the south-east/north-west direction might emanate from heavy goods vehicle traffic travelling on Quay Street. Although levels from this source are likely to be low when compared to shipping and there is no indication of a traffic source from central Auckland (this would be represented by a concentration peak from Auckland's CBD to the south). Auckland Transport shows that

about 7% of the total fleet of vehicles travelling on Quay Street are heavy goods vehicles and 3% are the largest, type 2 heavy good vehicles (“Traffic counts,” 2017).

Over the same period, SO_2 concentrations were also being monitored by Auckland Council in Penrose, 5 km south-east of the CBD. The results from Penrose are displayed in Figure 3.3 and show that most of the SO_2 come from the south. Although there is a small SO_2 peak directed north, the most noticeable concentration spike emanates to the south-east of the measurement point. The direction of the peak is in line with the Southern Motorway (State Highway 1) and Ellerslie-Panmure Highway indicating the key source here is related to local transport sources. This result implies that SO_2 emitted from shipping, either does not permeate 7 km inland or shipping emissions cannot readily be identified through SO_2 due to dilution of concentrations with distance.

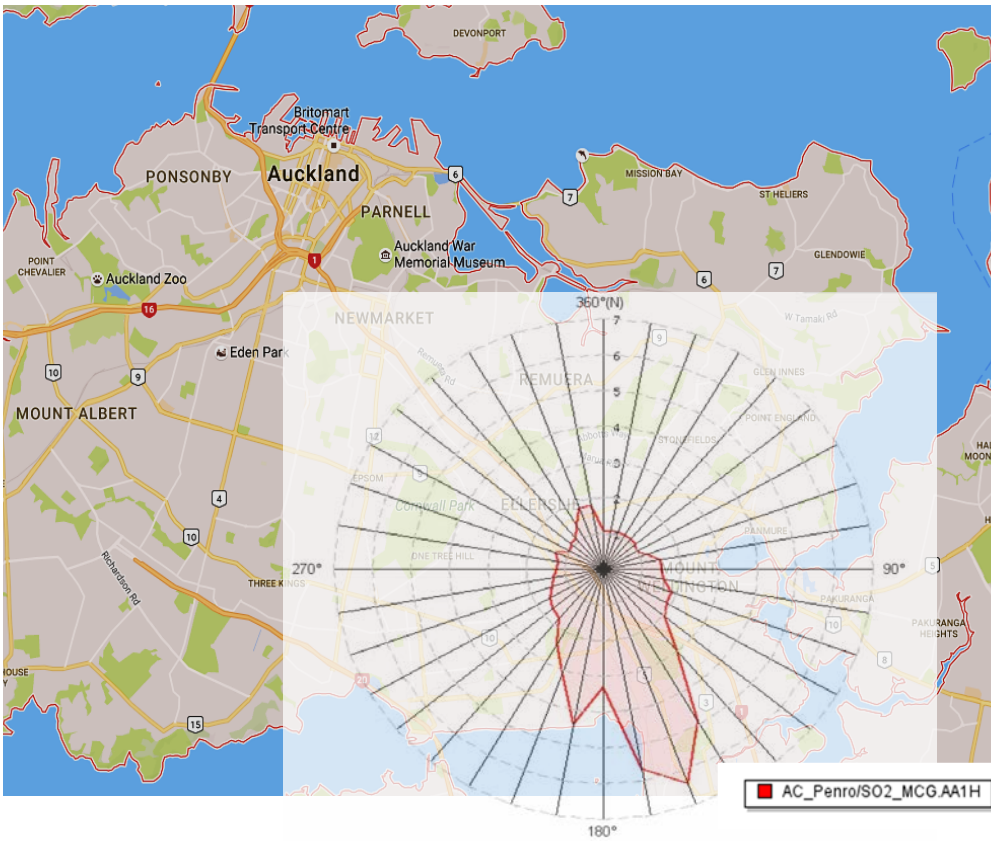

Figure 3-3: Concentration Rose for SO_2 from Penrose monitoring station from 2011-2014.

3.3.1 SO_2 exceedances during the Rugby World Cup, October 2011

Several exceedances were recorded at the Quay Street monitoring site during the 2011 Rugby World Cup, hosted by New Zealand. Maximum 1-hour concentrations were found to reach or exceed 450µg/m^3 on the 13th and 14th October 2011 (Figure 3-4). During this period the city of Auckland was visited by an increased number of sea vessels including several cruise ships ‘hotelling’ at berth (Appendix: Figure 5-4).

Taking the time period for the 13th until the 17th October in isolation, the concentration rose presented in Figure 3-5 shows that the highest concentrations were when the airflow was coming directly from the wharves which were home to the largest visiting cruise ships. It is notable that the highest concentrations were recorded in the evening. This may be a result of the extra power needed to start the propulsion of large cruise ships or, if they were hoteling, the emission may have been generated by the extra power needed to accommodate on-board evening activities.

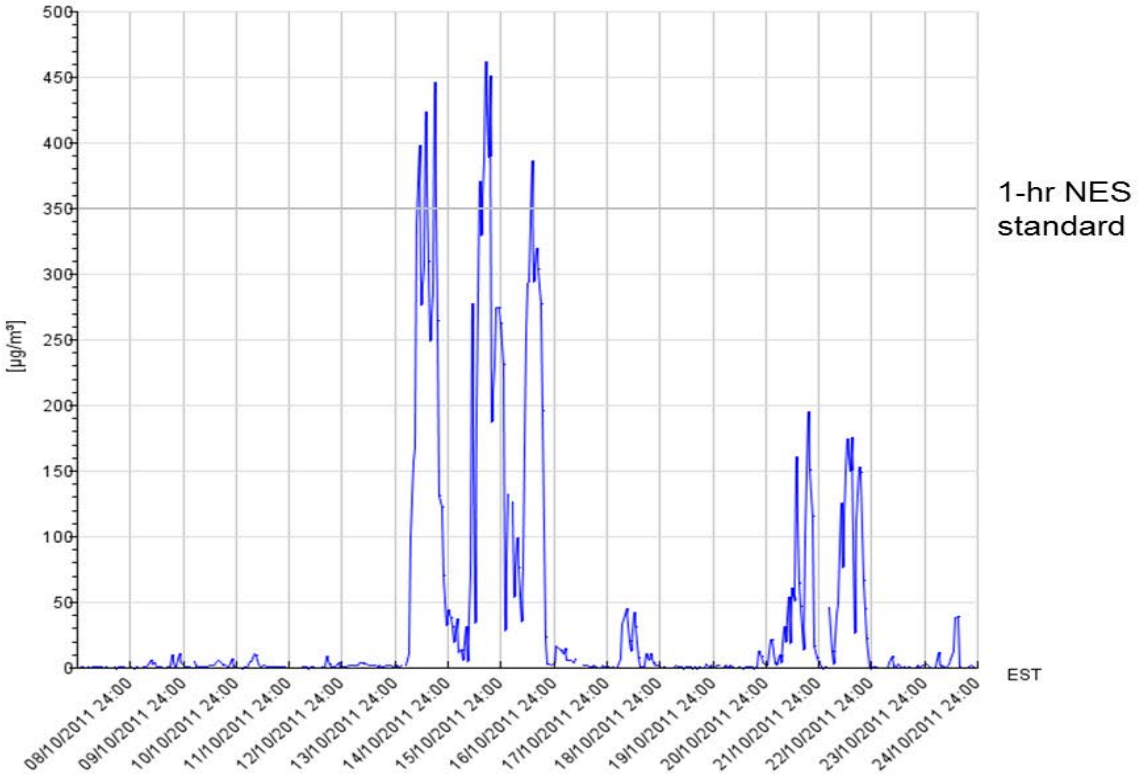

Figure 3-4: Exceedances in SO_2 concentration measured on Quay Street during the Rugby World Cup, October 2011.

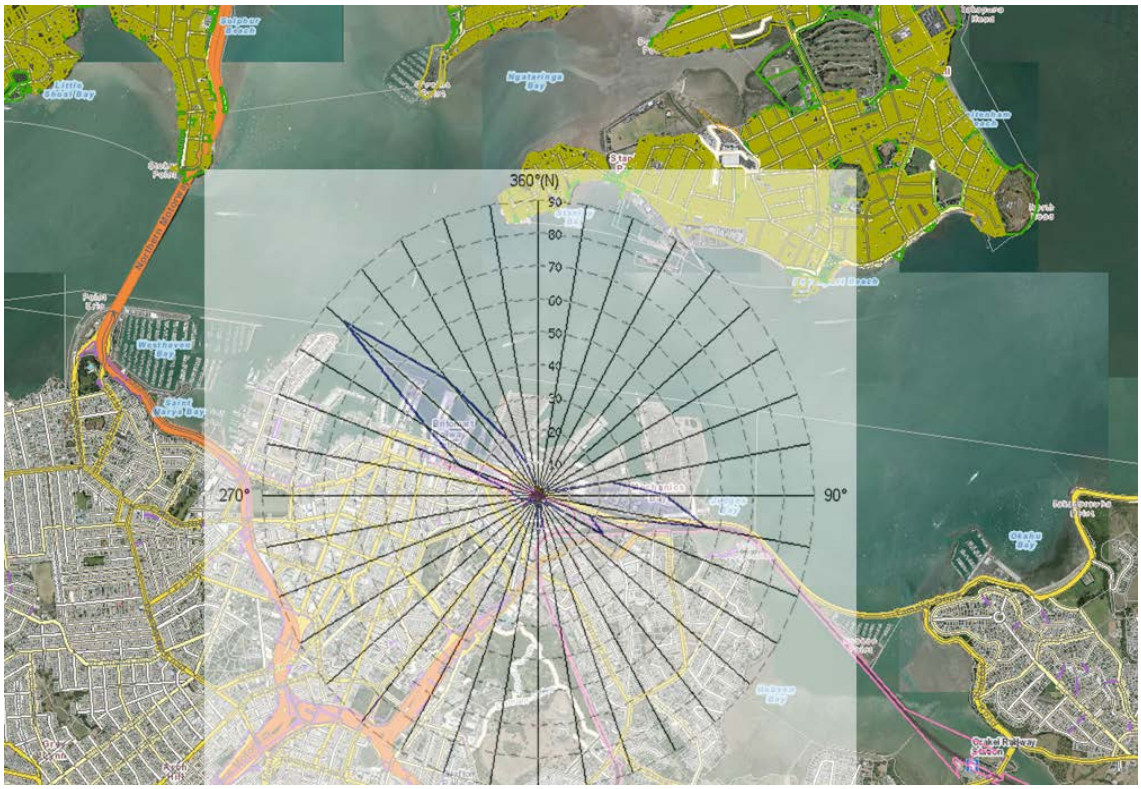

Figure 3-5: Concentration rose for the 13th until the 17th October, 2011 showing the origin of the highest concentrations of SO_2 emanating from Princes Wharf, used to dock some of the largest cruise ships.

3.4 Source apportionment trends report 2006-2014

This report presents an analysis of airborne particle samples collected at five ambient air quality monitoring sites across the Auckland region from 2006 to 2014. Understanding the composition and identifying the sources of air pollution is vital for effective air quality management and policy implementation. Airborne particles are composed of many elements and compounds from different sources and, by analysing these components using techniques detailed in Davy et al., (2014), the sources and their relative contributions to air pollution can be identified.

Source apportionment results from the Queen Street site shows a range of PM_{10} and $PM_{2.5}$ sources consistent with our current understanding of pollutant sources in Auckland. These include vehicles, domestic heating (biomass burning) and natural sources. Analysis of both particle fraction sizes also shows the presence of two different types of sulphate within the particulate. Primary sulphate particles are emitted directly from the source such as from a ship's stack. Secondary sulphate particulate is produced from sulphur containing precursor gases by atmospheric gas-to-particle reaction pathways. The sulphur containing precursor gases can be produced by the combustion of fuels (SO_2), emitted by marine biota (dimethyl sulphide or DMS) or from volcanic emissions (SO_2 and H_2S). From the varied sources of

sulphate it is possible to distinguish a shipping source by the presence of vanadium (V) and nickel (Ni), which are commonly associated with the combustion of poor quality fuels. Source apportionment results for Queen Street (Figure 3-6) show shipping contributed on average 7% to the total $PM_{2.5}$ fraction and 2% to the PM_{10} fraction at Queen Street between 2006 and 2013 (Davy et al., 2014). The toxicity of constituent elements to both ecosystems and people make these contributions notable (Wan et al., 2016).

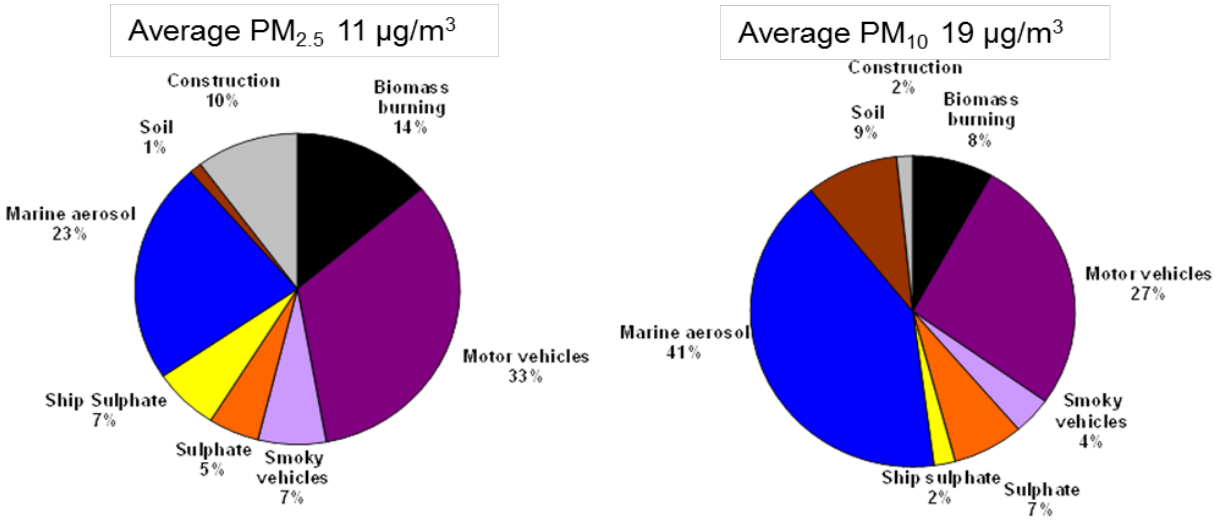

Figure 3-6: Average annual $PM_{2.5}$ and PM_{10} mass concentrations recorded at Queen Street for the period 2006-2009 (Davy et al., 2009).

When the data collected from the Queen Street site is compared with the corresponding wind direction data, a pattern can be seen that indicates the highest recorded levels of sulphate coincide with winds from the north-east, the direction of the waterfront area (Figure 3-7). This result corresponds well with the concentrations rose for SO_2 shown in Figure 3-2. The directional analysis of both SO_2 and sulphate indicates that during periods when the measuring site recorded the highest concentrations (upper quartile) the wind direction was predominantly from the north-east, i.e. the direction of the waterfront and the port. This is notable due to the fact that as this is the direction away from the main urban centre of Auckland intuitively, this direction should provide some of the lower concentrations. The fact that this direction records some of the highest concentrations provides compelling evidence that a proportion of sulphate recorded at the Queens Street site comes from shipping.

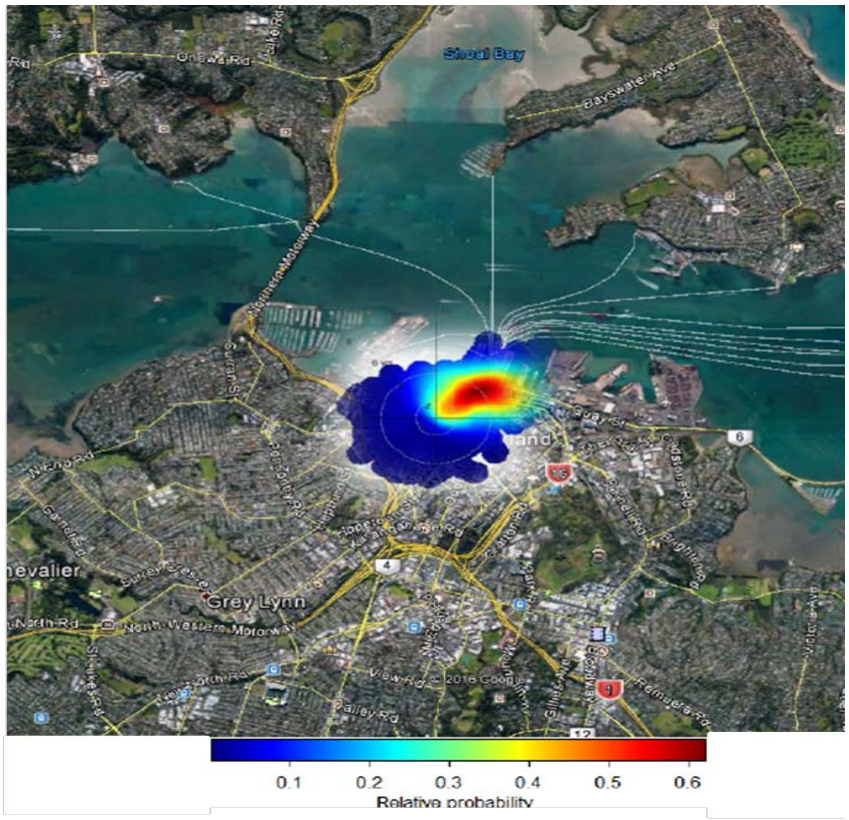

Figure 3-7: The influence of non-sea salt (nss) secondary sulphate (sulphate not originating from oceanic sources) over central Auckland taken from the Queen St site. The colours represent the probability of the source coming from a certain direction in relation to wind speed (Davy et al. 2014). Only the upper quartile of data was considered in the probability function.

The secondary sulphate particulate detected at Queen Street was also detected at the four other sampling sites considered in the source apportionment study (Figure 3-8). Directional 'bulges' of the highest concentrations of non-sea salt sulphate can be seen at all sites, with the exception of Penrose, pointing towards the waterfront or the shipping route through the Hauraki Gulf. The Queen Street and Khyber Pass sites indicate a sulphate source from the waterfront/downtown area, as does Henderson. Directional data from the Takapuna site suggests that emissions from the shipping channels are also likely to be a contributing source. This indicates that occasional peaks in secondary sulphate values can be attributed toward the waterfront area of Auckland. The comparison between the measurements of total sulphate (Figure 3-2) and the upper quartile of secondary sulphate (Figures 3-7 and 3-8) highlights the usefulness of receptor modelling for increased accuracy on apportioning pollutant concentration to source (Hopke, 2016).

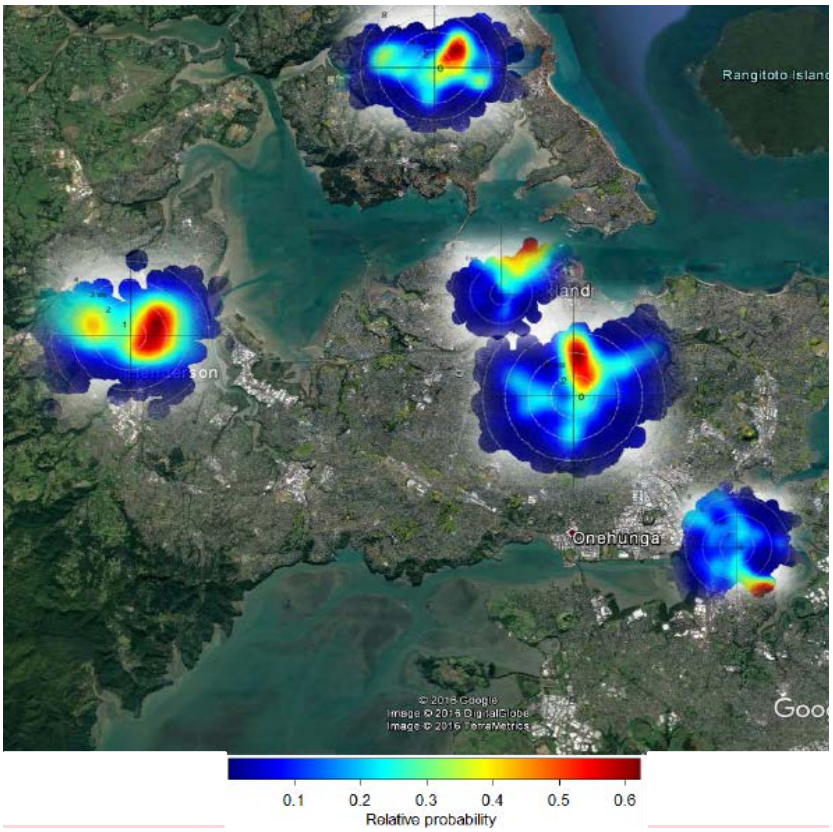

Figure 3-8: Analysis showing the upper quartile of secondary (nss) sulphate concentrations combined with wind speed and direction at all five considered Auckland monitoring sites (Davy et al., 2014).

3.5 SPARTANZ Pilot Study 2014

Spatially Resolved Techniques for Source Apportionment in New Zealand (SPARTANZ) was an observationally based pilot study carried out by NIWA and the University of Pittsburgh. This research involved the deployment a dense network of sensors over 12 specific locations across urban Auckland during April 2014 to investigate certain chemical markers. The samplers were hung from lampposts three metres above the street and sampled ambient air between 07:00 and 19:00 Monday-Friday. This period of time was employed to allow sampling during periods described as business hours within Auckland city. Background concentrations were now measured as part of the scope of this project. The sensors sampled fine ($PM_{2.5}$) particulate which was then able to be further analysed to identify and apportion organic and elemental composition, linked to certain key sources prevalent in the urban air. Previous studies had taken place in New York and Pittsburgh in the United States (Longley et al., 2016).

Over the four weeks the research was carried out, the overall $PM_{2.5}$ concentration was 7.2 $\mu g/m^3$. This is a slightly lower concentration than the long-term trend average for Queen Street noted by Davy et al., (2010) in Figure 3-4. The concentrations showed a three-fold variability over the four weeks and were highly dependent on the site traffic volume (Longley et al., 2016).

For brief scoping projects such as SPARTANZ, climatic conditions are crucial to explaining many of the results obtained.

During the four-week periods, three of the weeks were dominated by prevailing south-westerly winds, typical for Auckland (Weeks 1, 3 and 4). However, on the second week the winds came from a north-easterly direction. The wind direction was found to be important when identifying the source of air pollutants over the city (Figure 3-9). This was due to the different source impacts from the different prevailing wind directions. For example, the majority of concentrations in the CBD area of Auckland were from traffic or traffic related emissions. However, when using markers Ni, V and sulphur, as with the research of Davy et al., (2014), heavy oil combustion, typical of shipping emissions were detected in north-easterly winds, especially closer to the port or harbour front, along with significant levels of sodium, which decreased with distance from the harbour front in NE winds (Longley et al., 2016). The concentrations and spatial patterns reported in this study are indicative, rather than definitive, but do offer useful information on the spatial distribution of key air pollutants through central Auckland.

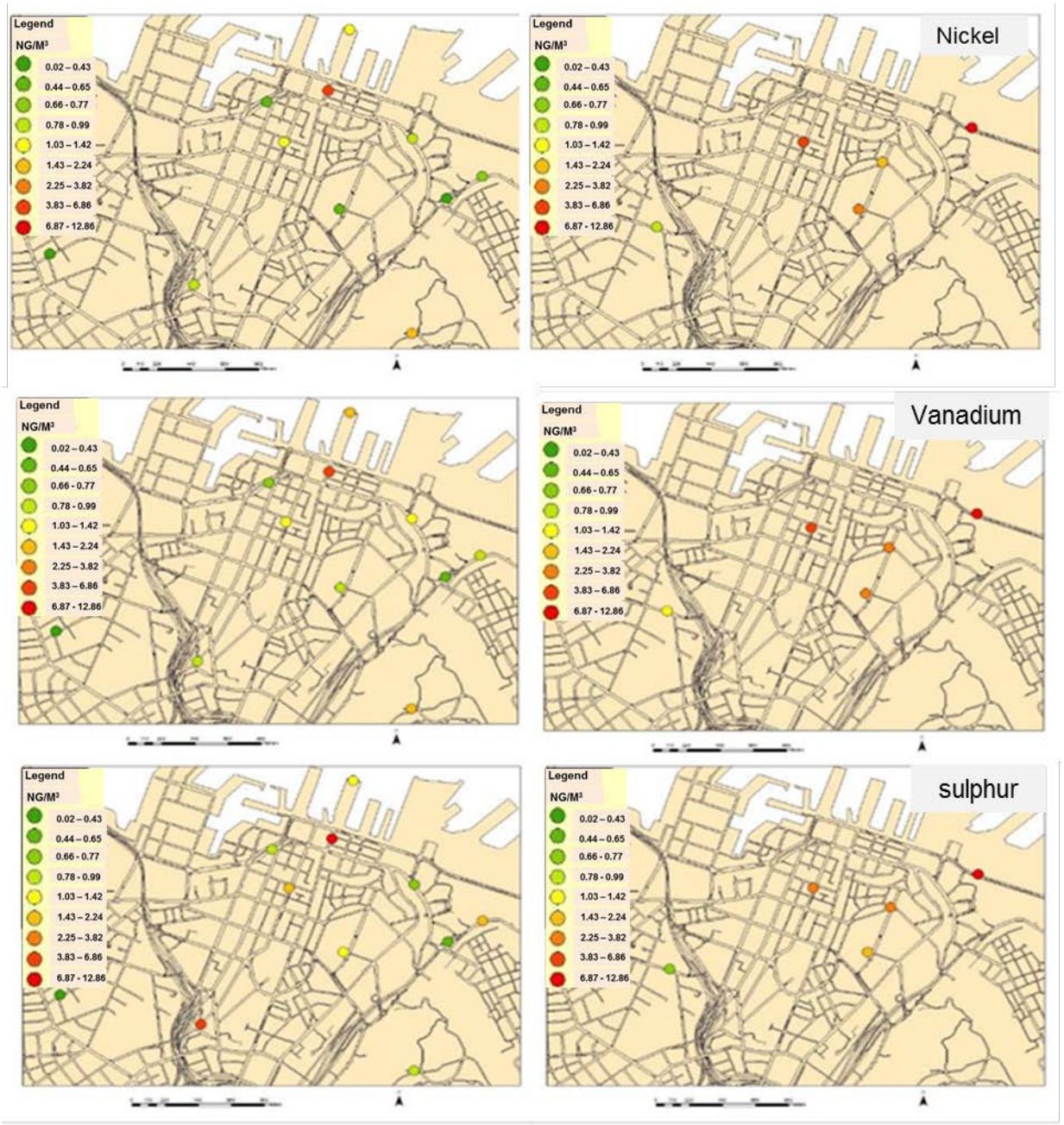

Figure 3-9: Concentrations of nickel (top), vanadium (middle) and sulphur (bottom). Left: results when the prevailing wind was from the south-west; and right: when the prevailing winds were from the north-east; Note logarithmic scales (Longley et al., 2016).

4.0 Conclusions

Results show concentrations of SO_2 are higher close to the waterfront area of Auckland, most notably when the airflow was from a north-east direction. Multiple passive tube deployments have revealed concentrations of SO_2 that are four times higher at the waterfront than at other sites across Auckland. Moreover, the passive tube campaigns of 2007 and 2011 also indicated elevated levels of SO_2 at the Queen Street site, several hundred metres away from the waterfront area along one of Auckland's busiest streets.

Measurements from Quay Street, collected over three years, support the passive tube results in revealing elevated levels of SO_2 to the north-east (dock), the east-south-east and north-west of the monitoring site. These plumes in SO_2 concentration were most likely a result of emissions from shipping vessels docked either in the container port or the cruise ship berthing wharves. The exact source was again dependent on wind direction. The SO_2 plumes also run roughly linear with Quay Street, a major transportation route for port vehicles and large transport trucks that use diesel fuel. Despite significant reductions in sulphur content for road transport Quay Street may still be considered an emission source of SO_2. The lack of precise source emission identification highlights the problematic nature of just using SO_2 in isolation as an indicator of shipping-related air pollutant.

GNS Science has conducted source apportionment investigations based on the elemental analysis in 2007, 2009, 2011 and a full trends report covering the period 2006-2014 (Davy et al., 2014). Their results use internationally recognised receptor modelling techniques from elemental signatures including metals vanadium (V) and nickel (Ni) as well as from sulphur and its derivatives. This method allowed for the identification of sulphur from shipping emissions to be separated from other prominent sulphur/sulphate sources, such as secondary sulphate derived from dimethyl sulphate from marine emissions or primary sulphur emissions from volcanoes.

Results from elemental analysis detected a shipping sulphate signature at many of the measured sites throughout Auckland. Concentrations were once again highest at the waterfront and Queen Street locations. Moreover, there was also evidence that shipping emissions interact with and contribute to Auckland's air pollution while the ships are under propulsion in the shipping lanes approaching or leaving port (Davy et al., 2014). This result was most notable from the Takapuna air quality station located on Auckland's North Shore.

The SPARTANZ pilot study also utilised elemental analysis techniques and agreed with the GNS Science work in showing elevated V and Ni levels throughout the central Auckland area. A concentration gradient that increased towards the waterfront was noted when there was north-east airflow. This study also suggests that there may also be a corresponding increase in $PM_{2.5}$ concentrations in areas of proximity to the waterfront. The brevity of this pilot study means further investigations are required to support this result.

The evidence presented from the five summarised reports delivers compelling evidence that shipping emissions from near-port and docked vessels do impact and degrade the air quality of Auckland, with the waterfront area and the CBD the most affected by shipping emissions,

presumably due to proximity. The highest shipping emissions-related pollutant measurements at the Auckland waterfront were when the winds were from the north-east. When the winds emanated from the prevailing direction (for Auckland this is from the south-west), there appeared to be considerably less impact from shipping at Auckland's waterfront area. To date, it is not known what shipping influences, if any, the south-westerly airflow would have on populated areas to the north-east of Auckland's CBD, such as Devonport. Any future studies should consider this knowledge gap when planning their monitoring strategy.

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5.0 References

Auckland Regional Council, ARC, 2010. State of the Auckland Region 2009.

Auckland Council, 2016. State of Auckland Report Card: Air Quality, Urban Area report card. Retrieved from: http://stateofauckland.aucklandcouncil.govt.nz/air-quality-report-card/urban-auckland-reporting-area-2017

Davy, P., Ancelet,, T., Markwitz,, A., Trompetter, W., 2014. Source apportionment and trend analysis of air particulate matter in the Auckland Region (Consultancy Report No. 2014/194). GNS Science.

Davy, P., Trompetter, B., Markwitz, A., 2010. Source apportionment of airborne particles in the Auckland region: 2010 Analysis . GNS Sci. Consult. Rep. 2010262.

Hopke, P.K., 2016. Review of receptor modeling methods for source apportionment. J. Air Waste Manag. Assoc. 66, 237–259. doi:10.1080/10962247.2016.1140693

Longley, I., Tunno, B., Clougherty, J., 2016. 2016, Spatially Resolved Technique for Source Apportionment in New Zealand: A pilot study. NIWA Rep. Auckl. Counc. Auckl. N. Z.

MARPOL, 2014, Annex VI – an update of international regulatory developments for the prevention of air pollution and the energy efficiency of ships [WWW document]. URL https://www.gov.im/lib/docs/ded/shipregistry/legislation/regs/sd20140223mspreventionofairpoll.pdf (accessed 2.18.17).

McLeod, K., 2007. Ambient Sulphur Dioxide Monitoring Winter 2007 (No. AQ7109-09).

Metcalfe, J., Wickham, L., Sridhar, S., 2014. Guidelines 201401 Use of background air quality data in resource consent applications [WWW Document]. URL http://www.aucklandcouncil.govt.nz/EN/planspoliciesprojects/reports/technicalpublications/Documents/gd201401useofbackgroundairqualitydatainresourceconsentapp.pdf (accessed 2.21.17).

Peeters,, S., 2010. Port-Related Air Emissions for the Auckland Region 2006 and 2010. MP Consult. Ltd. Auckl. Reg. Counci.

Petersen, J and Gillies, M (2014). The ambient air quality monitoring network in the Auckland region 2013. Auckland Council technical report, TR2014/035

Ports of Auckland Annual Review [WWW Document], 2015. URL http://www.poal.co.nz/media-publications/resultsandreviews/Annual%20Review%202015.pdf (accessed 11.30.16).

Traffic counts [WWW Document], 2017. URL https://at.govt.nz/about-us/reports-publications/traffic-counts/ (accessed 2.23.17).

Viana, M., Hammingh,, P., Colette,, A., Querol,, X., Degraeuwe, B., Vlieger, I., Aardenne,, J., 2014. Impact of maritime transport emissions on coastal air quality in Europe. Atmos. Environ. Volume 90, Pages 96–105.

Wan, Z., Zhu, M., Chen, S., Sperling, D., 2016. Pollution: Three steps to a green shipping industry. Nat. News 530, 275. doi:10.1038/530275a

Appendix

Table A1: Air quality criteria Air quality criteria for Auckland. They combine the most recent of the national environmental standard for air quality, the Auckland Ambient Air Quality Standards, and the World Health Organisation global guidelines. (The allowable number of exceedances per year of the standards is noted where relevant) Taken from Metcalfe et al., 2014.

Contaminant	Standard	Averaging Time	Number of permissible exceedances per year
Particles less than 10 microns (PM_{10})	50 µg/m^3	24 hour	1
	20 µg/m^3	Annual	0
Particles less than 2.5 microns ($PM_{2.5}$)	25 µg/m^3	24 hour	0
	10 µg/m^3	Annual	0
Nitrogen dioxide (NO_2)	200 µg/m^3	1 hour	9
	100 µg/m^3	24 hour	0
	40 µ/m^3	Annual	0
Carbon monoxide (CO)	10 mg/m^3	8 hours*	one 8-hour period
	30 mg/m^3	1 hour	0
Sulphur dioxide (SO_2)	350 µg/m^3	1 hour	9
	570 µg/m^3	1 hour	0
	20 µg/m^3	24 hour	0
Ozone (O_3)	150 µg/m^3	1 hour	0
	100 µg/m^3	8 hour	0
Lead	0.2 µg/m^3	3 months**	0
Benzene	3.6 µg/m^3	Annual	0
Benzo[a]pyrene	0.0003 µg/m^3	Annual	0
1,3-Butadiene	2.4 µg/m^3	Annual	0
Formaldehyde	100 µg/m^3	30 minutes	0
Acetaldehyde	30 µg/m^3	Annual	0
Mercury (inorganic)	0.33 µg/m^3	Annual	0
Mercury (organic)	0.13 µg/m^3	Annual	0
Chromium VI	0.0011 µg/m^3	Annual	0
Chromium metal and Chromium III	0.11 µg/m^3	Annual	0
Arsenic (inorganic)	0.0055 µg/m^3	Annual	0
Arsine	0.055 µg/m^3	Annual	0

Figure A-1: Location of the 2007 passive tube deployment around the Auckland region.

Table A-2: Passive SO_2 Results-Winter 2007. Note the similarity between the values of sample A and B denoted in the duplicate column.

Site	Duplicate	June Concentrations ($\mu g/m^3$)	July Concentrations ($\mu g/m^3$)	August Concentrations ($\mu g/m^3$)
Auckland Airport	A	1.04	0.93	0.68
Auckland Airport	B	0.93	0.96	0.75
Broadway	A	0.89	0.90	0.34
Broadway	B	0.83	0.69	0.35
Cornwallis	A	0.36	0.40	–[1]
Cornwallis	B	0.34	0.48	–[1]
Henderson	A	0.38	0.23	0.20
Henderson	B	0.38	0.32	0.14
Khyber Pass	A	0.89	0.73	0.46
Khyber Pass	B	0.94	0.76	0.46
Kingsland	A	0.87	0.65	0.31
Kingsland	B	0.75	0.68	0.53
Manukau	A	0.51	–[1]	0.33
Manukau	B	0.40	–[1]	0.33
Otahuhu	A	0.56	0.44	0.48
Otahuhu	B	0.58	0.58	0.50
Pakuranga	A	0.58	0.32	0.29
Pakuranga	B	0.50	0.32	0.28
Penrose	A	1.32	0.85	0.45
Penrose	B	1.16	0.86	0.44
Port of Auckland	A	3.99	5.58	4.40
Port of Auckland	B	3.32	5.84	4.32
Pukekohe Town	A	0.49	0.46	–[1]
Pukekohe Town	B	0.44	0.37	–[1]
Queen Street	A	3.62	3.04	1.52
Queen Street	B	3.65	3.11	1.45
Red Beach	A	0.41	–[1]	–[1]
Red Beach	B	0.45	–[1]	–[1]
Takapuna	A	0.58	1.40[2]	–[1]
Takapuna	B	0.51	0.53	–[1]
Waiheke	A	0.46	–[1]	0.35
Waiheke	B	0.44	–[1]	0.25
Wiri	A	0.42	0.32	–[1]
Wiri	B	0.39	0.22	–[1]

Figure A-2: Several cruise ships docked during the 2011 Rugby World Cup (October 2011).

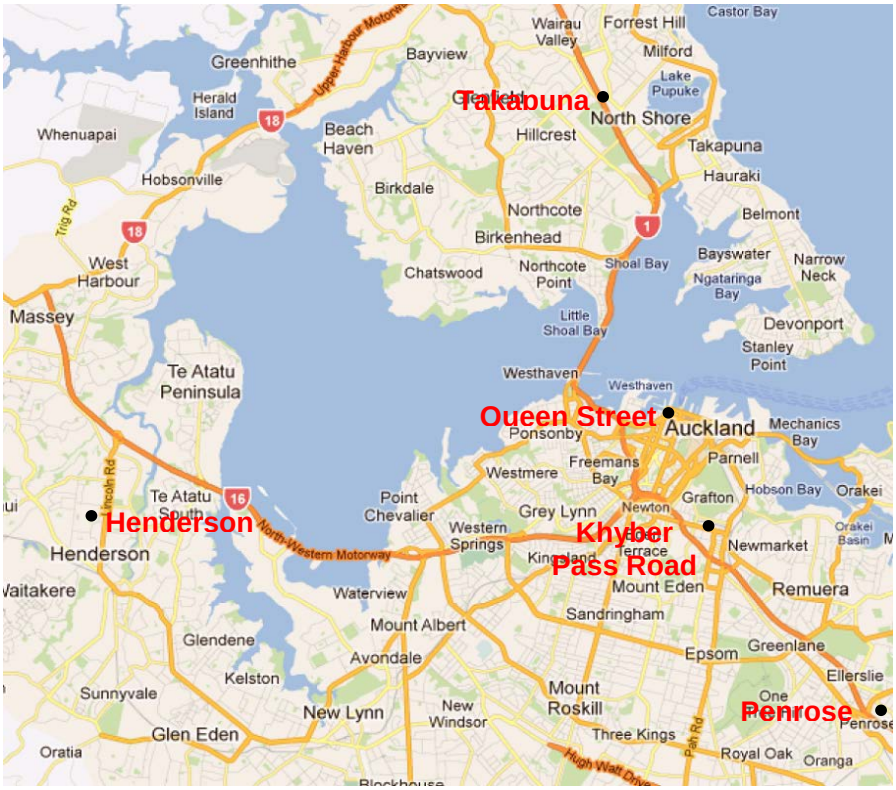

Figure A-3: Location of the five monitoring sites (●) included in the Auckland receptor modelling study (Davy et al., 2014).

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