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Using a Network of Low-cost Particle Sensors to Assess the Impact of Ship Emissions on a Residential Community

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ABSTRACT

Shipping emissions are known to affect communities in coastal locations, especially near harbours. This study monitored the air quality near the premier cruise ship terminal in Melbourne over a continuous period of 98 days during the peak cruise ship season in Australia. As shipping emission plumes are intermittent and fluctuate spatially, they cannot be detected accurately by a single fixed monitor. To overcome this limitation, we deployed seven units of the low-cost KOALA air quality monitor, which measures $PM_{2.5}$ and CO concentrations in real time and then transmits the data via 3G to an in-cloud database, in a spatially distributed configuration, four at ground level and three on the upper balconies of two high-rise apartment blocks. The time profile showed numerous spikes in the $PM_{2.5}$ concentration, some of which exceeded 200 µg m^{-3} for periods of 5–10 min, coinciding with ship movements. On average, the spikes were ~4–5 times above the normal background value (~10 µg m^{-3}). Because of their very short duration, these episodes did not significantly raise the 24-h averages at any of the locations; however, they increased the number of days on which these values exceeded the limit specified by the national air quality standard, resulting in more exceedance days for the monitored area than the nearest air quality station. Although the long-term health effects of elevated PM concentrations are known, few studies have been conducted on the risks of short-term exposures to extreme spikes.

Keywords: Low-cost sensor; Particle pollution; $PM_{2.5}$; Ship emissions; Sensor network; Air quality.

INTRODUCTION

Presently, there are over 100,000 transport ships at sea, of which about 6,000 and 300 are large container ships and cruise liners, respectively. Per mass of fuel consumed, ship engines are one of the highest pollution combustion sources worldwide (Corbett and Fischbeck, 1997), and therefore, emissions from ships are a significant contributor to global pollution, accounting for more than 18% of some air pollutants (Schrooten *et al.*, 2009; Dalsoren *et al.*, 2009; Walker *et al.*, 2019). Although land-based transport emissions are closely regulated, ship emissions are not. At present, only oxides of nitrogen and sulphur dioxide are regulated in ship emissions. Despite an estimated annual particulate mass production of over 1.5 million tonnes, there are no standards or guidelines for the emission of particulate matter from ships (Sofiev *et al.*, 2018). Emissions from ships account for up to 50% of the PM-related air pollution in certain coastal areas, rivers and ports (Lu *et al.*, 2006; Ault *et al.*, 2009; Malthias *et al.*, 2010; Poplawski *et al.*, 2011). Although ships entering ports generally use cleaner fuels than they do at sea, emissions produced by ships at ports impact air quality in surrounding regions and have been shown to affect human health (Bailey and Solomon, 2004). Diesel is the preferred fuel used by ships, with heavy fuel oil being the single most widely used type. It is a by-product of the crude oil refining process and is much cheaper than the lighter marine fuels, which is the main reason for its popularity. Diesel engine exhaust has been classified as a Group 1 human lung carcinogen by the International Agency for Research on Cancer (IARC) (Scheepers and Vermeulen, 2012). In 2007 it was estimated that particulate matter emissions from shipping activities were responsible for over 60,000 cardiopulmonary and lung cancer deaths near coastlines annually (Corbett *et al.*, 2007).

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The number of cargo and cruise ships has increased greatly since then and a more recent study has found that marine fuels account for over 250,000 deaths and over 6 million childhood asthma cases each year (Sofiev *et al.*, 2018).

There have been some attempts to model the effects of ship emissions on the air quality in coastal areas (Vutukuru *et al.*, 2008; Jonson *et al.*, 2015). However, assessing the accuracy of these models is made difficult by the nature of the sources. Ships are continuously on the move and, even when they are berthed in port, their emission plumes are intermittent and, therefore, difficult to detect by means of single onshore monitoring stations owing to fluctuating wind directions. Networks of spatially distributed reference instruments are costly and difficult to maintain. In this regard, the emergence of compact low-cost air quality monitors has opened up a viable alternative for this purpose.

In Australia, the peak cruise ship season is from October to April. Station Pier is the premier cruise shipping terminal in the state of Victoria. Opened in 1854, it has historically been Australia's welcoming port for generations of new arrivals. Today, it is also the docking station of the Spirit of Tasmania (SoT), the leading passenger transport between Melbourne and Tasmania (Devonport) also transporting vehicles and freight. It also plays host to a range of passenger ferries, a refuelling vessel and other visiting ships, including Australian and international navy vessels. The SoT makes 1–2 sailings per day throughout the year with a higher frequency of double sailings during the cruise season. In addition to the SoT, over 100 cruise ship dockings take place at Station Pier each year. Regular turn-around cruise ships include the Golden Princess, Queen Elizabeth, Carnival Spirit and Pacific Eden.

Station Pier is located at Beacon Cove, Port Melbourne, where there are a number of residential apartment towers facing the pier. In recent years, there has been much concern from residents in these apartments, as well as in nearby ground level houses, who have officially complained about the effect of fumes from cruise ships burning "highly toxic diesel fuel". Although cruise liners keep their engines running while berthed at terminals, such as Station Pier, that lack an onshore power source, the largest of the emission plumes occur in association with docking and departing. To investigate the spatial and temporal variability of emissions reaching the shore requires monitoring to be carried out over a sufficiently long period over a wide area.

As a consequence of residents' concerns, $PM_{2.5}$ monitoring using a BAM 5014i was conducted for a 26-month period between 2016 and 2018 at the finger pier adjacent to Station Pier (Fig. 1). This showed that the annual average $PM_{2.5}$ values exceeded the Australian air quality $PM_{2.5}$ standard of 8.0 µg m^{-3} in two successive years, with the average for the second year (9.7 µg m^{-3}) being higher than the first (8.5 µg m^{-3}) (Beacon Cove Neighbourhood Association, http://www.beaconcove.org.au/2019/04/update-on-air-quality-monitoring-at.html). It is against this background that the current study was carried out to assess the impact of ship emissions on the immediate residential area around the pier.

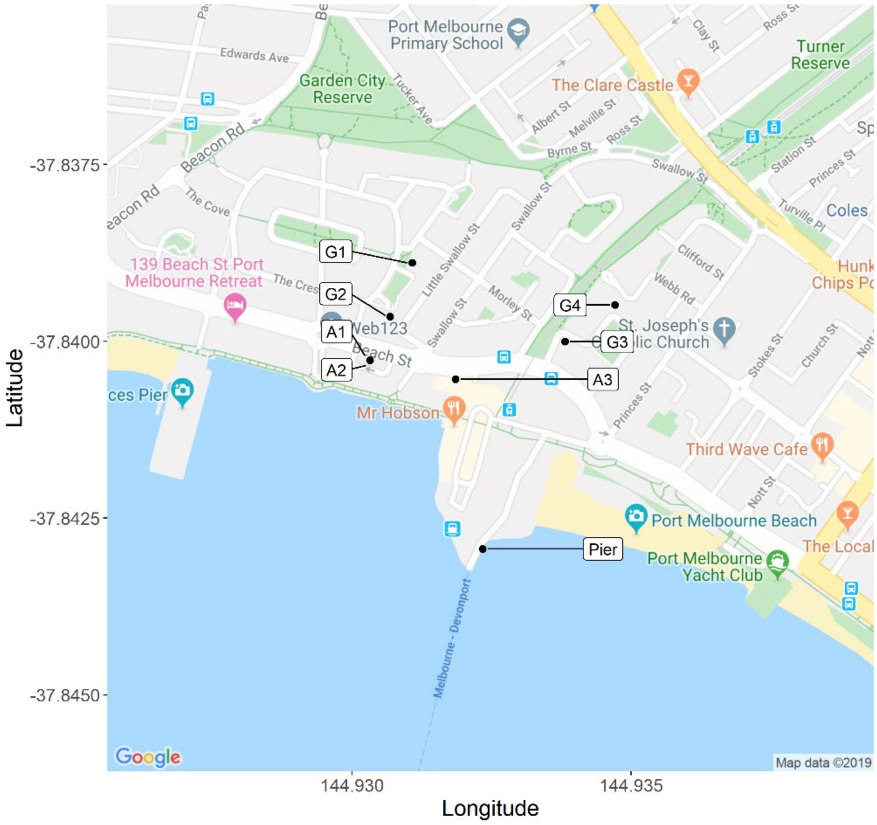

Fig. 1. Map of Beacon Cove, showing the location of the pier and the seven KOALAs. *A* refers to the KOALAs in the apartment blocks and *G* to those at ground level (Google Maps, 2019). The 718-m-long pier is not shown above.

Recently, we designed and tested a compact, stand-alone air quality monitoring device named the *KOALA* (Knowing Our Ambient Local Air Quality) (Fig. S1). The monitor includes two low-cost air quality sensors that measure particle and carbon monoxide (CO) concentrations in the air. Airborne particles and CO are two key products of combustion sources such as motor vehicles, ships and industry. Such a network of nine KOALAs was established and operated successfully during the recently concluded Commonwealth Games at the Gold Coast, Queensland (Kuhn *et al.*, 2020). Currently, there are around 120 KOALA monitors successfully operating in several locations in Australia (Brisbane, Sydney, Adelaide, Perth and the Blue Mountains) and in some overseas countries (China, Vietnam, Sri Lanka, Fiji and the Solomon Islands), and sending data to the program data management centre (DMC) that may be accessed on-line (ILAQH Research. Sensors Project Page, https://research.qut.edu.au/ilaqh/projects/sensors/).

METHODS

Study Design

A network of seven KOALA monitors were installed within 300 m of the 718 m Station Pier cruise ship terminal in Beacon Cove, Port Melbourne, Victoria, and operated over a continuous period of 70–98 days between 24 December 2018 and 31 March 2019 (Table 1). This period overlapped with the peak cruise ship season in Australia, with nearly 1,500 ship traversals of the area near Station Pier. Data from the monitors were transmitted through the mobile phone network to an in-cloud database.

Details of the KOALA monitors used in this project are listed in Table 1, and their locations are shown on the map in Fig. 1. Four of the monitors (G1, G2, G3 and G4) were installed at ground level and powered by solar panels. Three (A1, A2 and A3) were placed on the upper balconies of two high-rise apartment blocks and powered by the mains through a USB cable.

The two high-rise apartment blocks are both at least ten storeys high and are located about 20 m away from the edge of the water and 290–660 m away from the funnels of the ships berthed at the pier (Table 1). A1 and A2 were located in the same apartment block (Tower 2) on Levels 10 and 5, approximately 40 and 20 m above ground level, respectively, almost in the same vertical line. This enabled an estimation of the vertical distribution of pollutants. They were strapped to the walls and railings of the apartment balconies facing the pier. A3 was located on a rooftop balcony at the neighbouring apartment block (Tower 1) at approximately the same height above the ground as A1, thus providing some insight into the horizontal distribution of pollutants. The other four KOALAs were installed in open residential areas, approximately 3–5.5 m above ground level. A3 was the monitoring location that was nearest to the pier.

Instrumentation

The KOALA monitor contains a Plantower PMS1003 low-cost sensor that measures particle concentration in real time. The air sample is drawn into the device and exposed to a fine laser beam. The scattered light is monitored by a photodetector and the signal is converted to a particle number concentration and assigned a size bin. A built-in algorithm is used to estimate, in micrograms per cubic metre, the corresponding particle mass concentration, $PM_{2.5}$, which represents the mass of particles that are larger than 2.5 micrometres. The CO concentration is monitored in real time with an Alphasense CO-B4 sensor. This is a passive device that works on the principle of electrochemical sensing to determine the gas concentration that is expressed in units of parts per million. The KOALA monitors are stand-alone and powered by a solar panel and built-in battery unit (Fig. S1(a)). The sensors and electronics are housed in a weather-proof box. The USB-powered KOALA has been modified to accept a charging current through a USB adapter and cable and removal of the solar panel (Fig. S1(b)). The batteries in the outdoor KOALAs were charged either via the solar panels or by mains power. The minimum requirement was around 5 h of direct sunshine per day. Once fully charged, they could operate continuously for up to 3 days with no further charging. In practice, the battery receives some charge even under cloudy conditions which enabled it to keep operating for longer periods under overcast conditions. Some of the KOALAs were placed within insect netting bags to prevent ants and spiders from entering the monitor enclosures through the two air flow apertures.

Data Transmission and Management

All data were transmitted from the KOALA monitors to a central database, the data management centre (DMC), using the 3G/4G network and data was also stored on an

Table 1. Locations of the KOALAs in Beacon Cove.

KOALA ID	Location code	Days of data	KOALA power source	Min and max distances from ship funnels (m)	
AQB37	A3	98	USB	290	650
AQB40	A1	97	USB	310	660
AQB41	A2	98	USB	310	660
AQB36	G3	70	Solar	435	785
AQB43	G4	95	USB	510	865
AQB36/35[a]	G2	95	Solar	450	780
AQB39/42[a]	G1	84	Solar	525	860

[a] KOALAs at G1 and G2 were replaced after a Plantower sensor failure (AQB36) and battery problems (AQB39). The Plantower in AQB36 was replaced and the KOALA redeployed to G3.

internal microSD card. The DMC is a cloud-based system built on Amazon Web Services (AWS), which collects, stores and makes available the KOALA data for real-time and delayed examination.

All KOALAs were programmed to measure all parameters at intervals of 5 min and transmit the data to the DMC every 35 min. A visualisation map of the $PM_{2.5}$ concentrations in the area was automatically plotted and made available online to all interested parties right through the monitoring project. An example of this map is shown in Fig. S2.

Data Validation

At the end of the project, two of the KOALAs, AQB35 and AQB36, were placed at the nearest Environment Protection Authority (EPA) of Victoria Air Quality Monitoring Station (AQMS) at Footscray, located about 5 km northwest of Beacon Cove and operated for a period of one month. During this time, the $PM_{2.5}$ concentration data obtained were compared against a Thermo Scientific 5014*i* Beta Attenuation Monitor (BAM), which is the standard PM monitor used by the EPA. This data was used to validate the performance of the KOALAs and to derive any correction factors.

Ship Movement Data

Ship movement notification data at Beacon Cove were purchased from Marine Traffic—a global automatic identification system for ship tracking. The data are based on a circle 500 m in diameter centred on Station Pier. The transmitted time after a vessel crosses the perimeter of this area is reported as an event together with the name of that vessel. This gave a record of the times at which a vessel entered or left the vicinity of Beacon Cove.

Meteorological Data

During the summer months, the wind in Melbourne is mostly from the south so that ship emissions are mostly carried to the shore. Unfortunately, there was no meteorological station located at Beacon Cove. Therefore, we obtained 30-min wind data from the nearest Australian Bureau of Meteorology station, situated about 5 km away at St Kilda.

During the period of the project there were a few controlled hazard burning events around Melbourne and also some bushfires in both Tasmania and Victoria. Satellite images obtained from the Australian Bureau of Meteorology were used to study the movement of smoke and to identify times when the air quality in Melbourne was affected by this smoke.

Data Analysis

For the purposes of this analysis, we assigned the wind directions to four quadrants following the compass as follows: north (315–45°), east (45–135°), south (135–225°) and west (225–315°). For all KOALA locations at Beacon Cove, Station Pier was located in the southern quadrant, and it was expected that ship emissions would be carried to the KOALA locations when the wind was from this quadrant.

In order to assess the impact of ship activity on air quality, we calculated the mean $PM_{2.5}$ concentration during the 30-min interval immediately after a ship entered the Station Pier Marine Traffic notification area and 30-min interval immediately before it left the Marine Traffic notification area. Ship emissions often produced short-term spikes in $PM_{2.5}$ concentration. To analyse these spikes, it was necessary to define a "spike". We defined a spike as a step increase in $PM_{2.5}$ concentration of at least 20 $\mu g\ m^{-3}$ between successive 5-min readings. Controlled burning is regularly undertaken in Australia to remove flammable vegetation to minimise fire hazards. Such hazard reduction fires often envelope the atmosphere with heavy smoke that can last for several days. In order to eliminate such longer-term pollution events, we introduced the additional requirement that the upper bound of the concentration should not last for a total period of more than 30 min.

The data from the KOALAs were recorded in UTC, the meteorological data in AEST (Australian Eastern Standard Time; UTC + 10 h) and the shipping data in AEDT (Australian Eastern Daylight Time; UTC + 11 h). These data were aligned in chronological order before the analysis was carried out. All data from the KOALAs and reference instruments were processed and averaged over the same intervals of time so that the sensor readings could be compared against the reference instruments. Linearity of response was tested using a basic linear regression method, while significant differences in means were tested using a Student's *t*-test at a confidence level of 95%.

RESULTS

All but two of the KOALAs provided a data completeness of over 95% over the entire period of 98 days. The other two experienced some difficulties with low battery power, data communication uploading issues and Plantower failures. The number of days on which data were available for each of the KOALAs is shown in Table 1.

Although the $PM_{2.5}$ concentration spikes produced by ship emissions were significantly higher than the background concentrations and easily identifiable, the corresponding CO concentrations rarely showed any spikes related to ship activity. As such, the CO concentration data were excluded from the analysis as no useful results could be derived from them.

Shipping Details

Over the duration of the monitoring period, there were 2,944 ship arrival/departure events into and out of Beacon Cove. There are two identical SoT vessels in operation, and, throughout the period of the project, these two ships collectively made 1–2 sailings per day (142 in total).

Data Validation

The $PM_{2.5}$ concentrations reported by the two KOALAs, AQB35 and AQB36, stationed at the Footscray EPA AQMS showed good agreement with each other over the 1-month monitoring period. The relationship between the hourly averages was significantly linear with a best slope of 1.03 and an R^2 of 0.98 (Fig. S3).

While the KOALA readings were mostly consistent with the BAM, there were clear discrepancies when the relative humidity exceeded 75%. This is because hygroscopic particles absorb moisture from the air and grow at high humidity (Jayaratne *et al.*, 2018). Locations close to the sea contain more hygroscopic particles due to the influence of marine air. Air quality standards stipulate that particle mass concentrations should be limited to the solid phase excluding the liquid content and, for this reason, standard instruments such as the BAM are fitted with a drying facility at its inlet to remove moisture from the particles that are sampled. The KOALA has no such feature, and so will overestimate the PM concentrations at high humidity. This is illustrated in Fig. S4 which shows the $PM_{2.5}$ concentrations of AQB35 against the relative humidity. Clearly, the KOALA readings increased as the RH increased above 75%.

In Fig. S5, we show the 5-min $PM_{2.5}$ concentrations of AQB35 against the BAM at all values of RH (Fig. S5(a)) and when the RH was less than 75% only (Fig. S5(b)), which resulted in the exclusion of 31% of data. The slope of the best line was 1.65 in Fig. S5(a) and reduced to 1.09 when the data points at RH greater than 75% were removed. This suggests that the KOALAs can be assumed to be accurate at relative humidity up to 75%. In our further analysis (Fig. S6), we consider only time periods when the RH was below 75%. Fig. S6(a) shows the mean hourly values of the two KOALAs against the BAM, showing considerable scatter with an R^2 value of 0.54. Some of the scatter was due to the fact that the averaging times of the KOALA and the BAM were not identical. Fig. S6(b) shows the corresponding graph with the 24-h average values. There was excellent agreement between the readings of the KOALAs and the BAM (slope = 0.99 with $R^2 = 0.83$). As such, no corrections were made to the $PM_{2.5}$ concentration data reported by the KOALAs.

Time Series

Fig. 2 shows the time series of the $PM_{2.5}$ concentrations measured by the seven KOALAs over the entire measurement project. These plots include all 5-min data points.

High $PM_{2.5}$ concentrations were observed on a few days coinciding with entrainment of smoke from fire events around Melbourne as well as from further afield in Tasmania. This was assisted by winds from the directions of the fires. This resulted in elevated $PM_{2.5}$ concentrations of the order of 20–50 µg m^{-3} that lasted from a few hours up to 3–4 days at a time. Such a prolonged event is observable in Fig. 2 around 1–4 February when satellite images clearly showed smoke from fires in Tasmania being carried towards Melbourne. Elevated $PM_{2.5}$ concentrations due to smoke from these events were observed by all seven KOALAs at Station Pier as well as by the BAM at the EPA AQMS at Footscray.

At all other times, the mean $PM_{2.5}$ concentration remained below 20 µg m^{-3}. A striking feature of the time profiles shown in Fig. 2 are the large numbers of very high spikes, some of them exceeding 200 µg m^{-3} for short periods of 5–15 min. Many of these spikes occurred close to the arrival and departure times of ships at Station Pier whenever a KOALA intercepted the pollution plume from a ship. The height of a spike depended on the emission rate and the dilution factor in the atmosphere, which is generally determined by wind speed and direction. Most of the spikes occurred when the wind was blowing from the south. To illustrate this clearly, we present the $PM_{2.5}$ concentration time series reported by AQB37 located on the roof of Tower 1 (A3), over the 3 days—25, 26 and 27 December 2018—together with the arrival

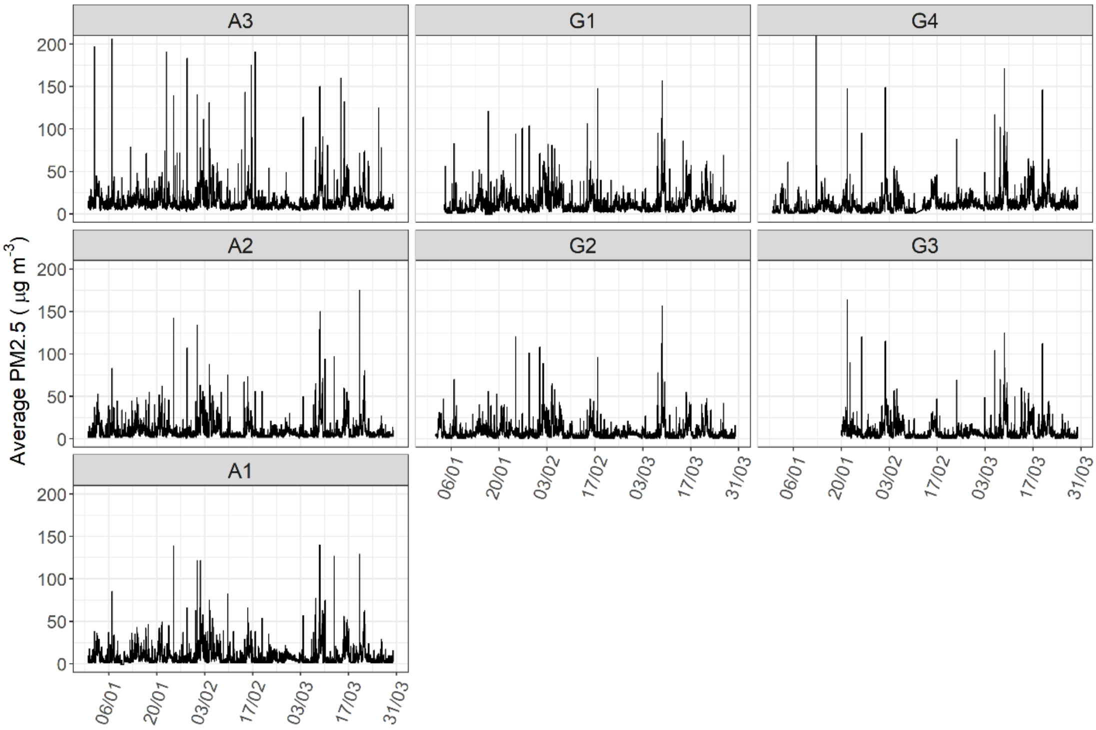

Fig. 2. Time series of the 5-min $PM_{2.5}$ concentrations measured by the KOALAs at the seven locations over the entire project.

and departure times of the SoT and the general wind direction at the times (Fig. 3). In this period, there were five visits of the SoT to Station Pier. While none of the arrivals resulted in pollution spikes, four out of the five departures that took place when the wind was from the south or south-west clearly produced high spikes. The only exception was on the 25th, when the wind was from the north (land side). The other small spike on 27 December pertains to the departure of another cruise ship.

Daily Averages

Clearly, the emissions from ships, especially the SoT, produced short-term $PM_{2.5}$ concentration spikes in the area around Station Pier. In order to assess the longer-term impacts on the general pollution levels, we first investigate the daily average values. Fig. 4 shows the mean 24-h average $PM_{2.5}$ concentrations over the project for each of the seven locations.

The daily averages at each location varied considerably, from about 2 to 53 µg m^{-3}. The mean daily averages over the entire period of monitoring at the seven locations ranged from about 7 to about 13 µg m^{-3}. The standard deviations of the mean daily values over this period at each site, shown by the error bars in the graph, were about 6 µg m^{-3}.

It should be noted that the mean 24-h average $PM_{2.5}$ concentrations over the project for each of the seven locations were well below the WHO guideline and Australian air quality standard of 25 µg m^{-3}, shown by the broken red horizontal line in Fig. 4. Most of the high values occurred on days affected by smoke from fires burning around Melbourne and Tasmania. The highest concentration was on the roof of Tower 1. This was also the KOALA situated closest to the cruise terminal and the mean concentration was significantly higher than that measured by the KOALA at the same height in Tower 2 (A2). In turn, the concentration measured at Level 10 of Tower 2 (A2) was higher than that measured at Level 5 of Tower 2 (A1), indicating that the pollution was higher at roof level than at lower levels. This was not surprising as the height of the funnel of most ships docking at Station Pier ranged between 37 and 57 m above water level, whereas the heights of Levels 5 and 10 in Tower 2 were approximately 20 and 40 m, respectively. Exhaust plumes from ships are hotter than the surrounding environment and generally rise in the atmosphere or disperse horizontally with the wind. Vertical movement downwards may occur under turbulent conditions. There was only one day (9 March) when the 24-h average exceeded 25 µg m^{-3} at all seven locations. The mean 24-h average $PM_{2.5}$ concentration measured at the Footscray AQMS by the BAM over the entire project was 8.5 µg m^{-3} with a standard deviation of 4.0 µg m^{-3}. This value was exceeded by the corresponding measurements by only three of the KOALAs (A3, G2 and G4).

Fig. 5 shows the number of days vs. the 24-h average $PM_{2.5}$ concentrations measured at each of the seven locations. We see that the Australian air quality standard, shown by the red broken line, was exceeded on 2–8 days, depending on the location. Most of these high pollution days were due to the entrainment of bushfire smoke. It is instructive to compare these values with the corresponding value obtained over the same period by the BAM at the Footscray AQMS, where the standard was exceeded on just one day (9 March). This is an interesting observation as it indicates that, although the mean $PM_{2.5}$ concentrations measured were approximately the same, the number of days on which the concentration exceeded the standard value at all seven locations in Beacon Cove were higher than at Footscray. As the two locations were only about 5 km apart, this observation cannot be explained in terms of bushfire smoke alone, and it is suggestive that it was a consequence of the additional pollution provided by ship emissions.

Relationship to Wind Direction

In order to assess if the wind direction made a significant difference to the measured $PM_{2.5}$ concentrations, we calculated

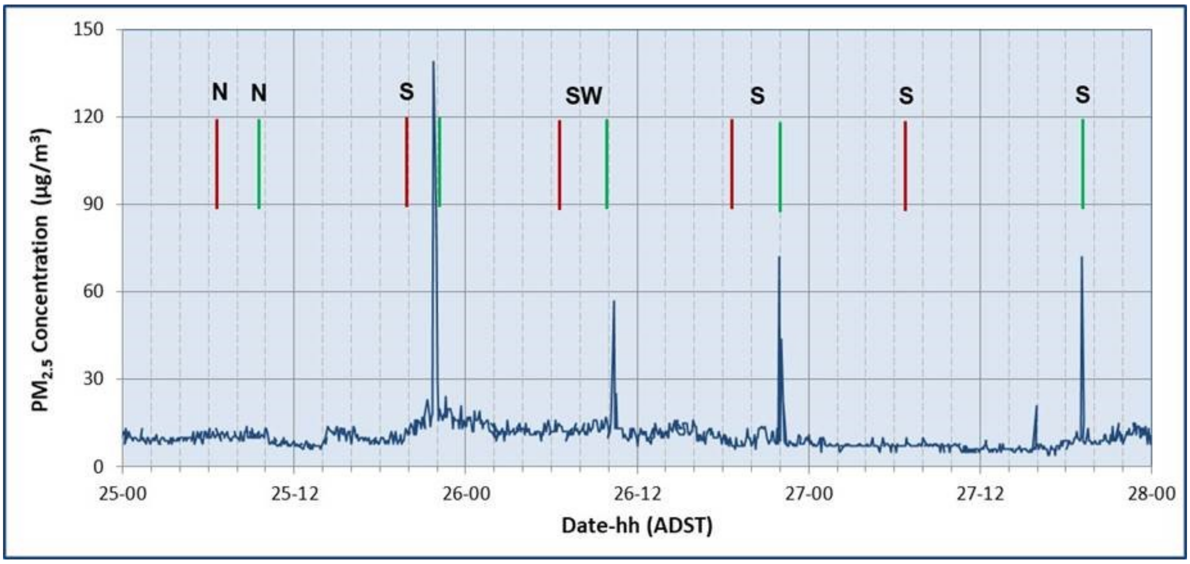

Fig. 3. $PM_{2.5}$ concentration time series at A3 over a typical 3-day period, together with the arrival (red line) and departure (green line) times of the SoT and the general wind direction at the times.

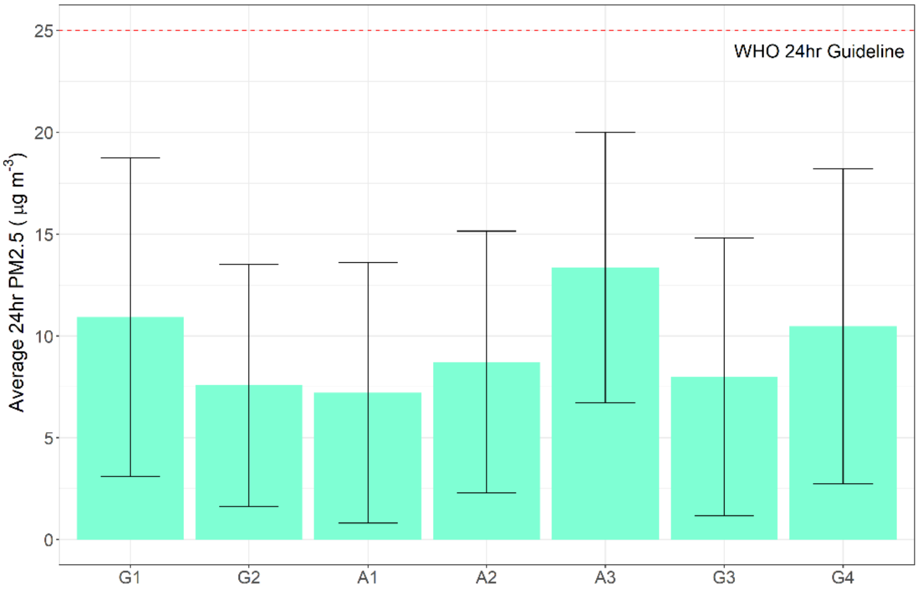

Fig. 4. Histogram showing the mean 24-h average $PM_{2.5}$ concentrations over the project for each of the seven locations. The error bars indicate the standard deviations.

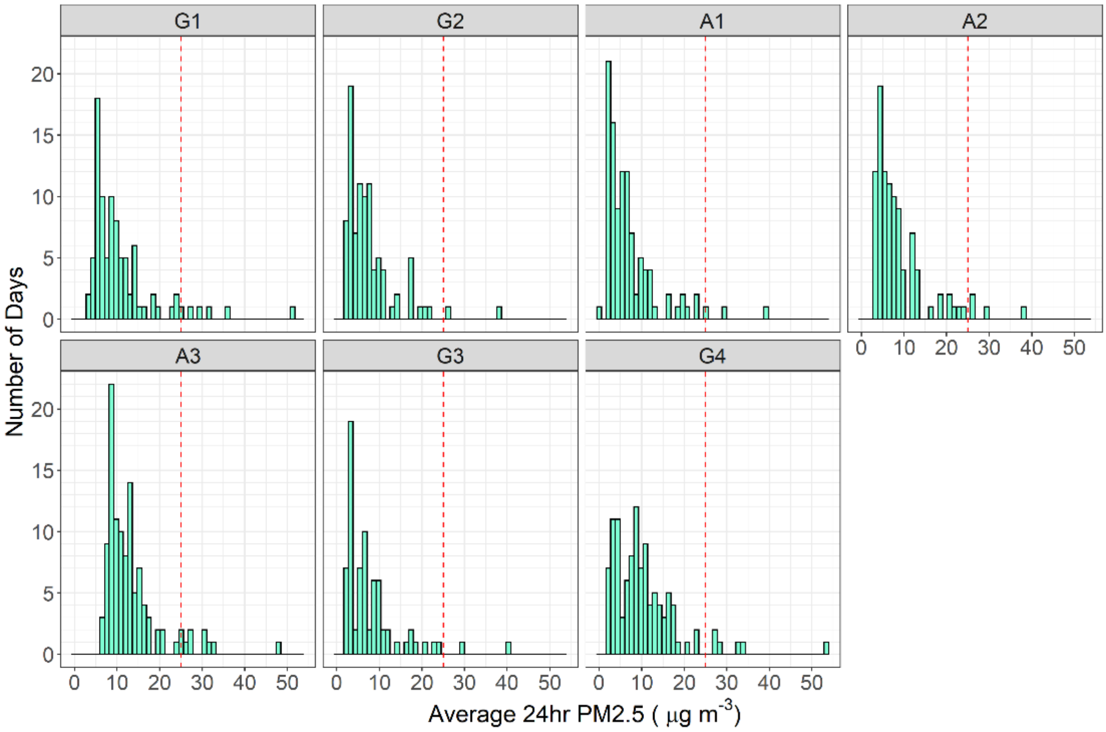

Fig. 5. Histogram of number of days vs. the 24-h average $PM_{2.5}$ concentrations measured at each of the seven locations.

the mean 5-min average concentrations for each of the KOALAs when the wind was from the southern quadrant and when it was from all other directions (Fig. S7). The wind direction had an insignificant impact on the mean $PM_{2.5}$ concentrations at all locations. High $PM_{2.5}$ concentrations were observed on days when there was smoke carried by northerly winds from fire events inland, and also on days when satellite images showed smoke from fires in Tasmania being carried in southerly winds. On other days, winds from the sea were generally "clean" as, except for ship emissions, there are no pollution sources in the open ocean. However, the result indicated that the $PM_{2.5}$ concentrations in the northerly and southerly winds balanced each other.

Relationship between $PM_{2.5}$ Concentrations and Ship Activity

In order to assess if there was an impact during ship activity, we studied the mean $PM_{2.5}$ concentrations during the 30-min intervals immediately after a ship entered Beacon Cove and the 30-min intervals immediately before it departed from the cove. Then, we calculated the percentage number of such time slots when the $PM_{2.5}$ concentration exceeded a given value. The results are shown for all locations in Fig. 6. Clearly, there were some instances where the mean $PM_{2.5}$ concentration during the 30-min periods coinciding with ship movements extended well above the typical background values. $PM_{2.5}$ concentration spikes of up to 200 µg m^{-3} were observed during some such times.

$PM_{2.5}$ Concentration Spikes

During the 98 days of observation, a total of 435 $PM_{2.5}$ concentration spikes were observed across the seven locations. Fig. 7 shows the number of $PM_{2.5}$ concentration spikes observed per day at each of the seven locations, together with the height of the spikes. The totals have been converted to spikes per day to enable comparison between locations. Note that the largest numbers of spikes were observed at the three apartment locations, with A3, the location closest to the pier, showing the highest number of spikes (98). As in the 24-h average $PM_{2.5}$ concentrations, the number of spikes observed at roof level on Tower 1 (A3) was higher than that at the same level on Tower 2 (A2), which was further away from the pier. Similarly, the number of spikes observed at Level 10 of Tower 2 (A2) was higher than that observed at Level 5 (A1). This again suggests that, at roof level, the pollution decreased with distance from the pier, while it increased with height above the ground. This is again explicable in terms of the height of the funnels of the ships above the water. The mean number of spikes per day at the three apartment locations was 0.86, while that at the four ground level locations was 0.54, an increase of 60%, although it should be noted that the highest levels at one of the furthest ground locations (G1) were very similar to that at A1. Furthermore, this location was the more inland of the G1 and G2 locations but was further from Tower 2 that was between G1 and G2 and the ships. It is possible that the buildings' topography may have influenced where the emissions were deposited at lower levels.

The frequency and intensity of the spikes depended on the wind direction. Fig. 8 shows the percentage of $PM_{2.5}$ spikes > x against spike height x, separated into when the wind was from the northern and southern quadrants. A larger number of high spikes were observed when the wind was from the southern quadrant. No spikes larger than 150 µg m^{-3} were observed when the wind was from outside this quadrant.

At most times, the observation of spikes at a location was closely dependent on the wind direction. Referring to the map in Fig. 1, the seven locations could be classified into two clusters—NW of the pier (A1, A2, A3, G1 and G2) and NE of the pier (G3 and G4). While most of the spikes at the western group of sites occurred when the wind was from between S and SE, most of the spikes at the eastern group of sites were observed when the wind was from between S

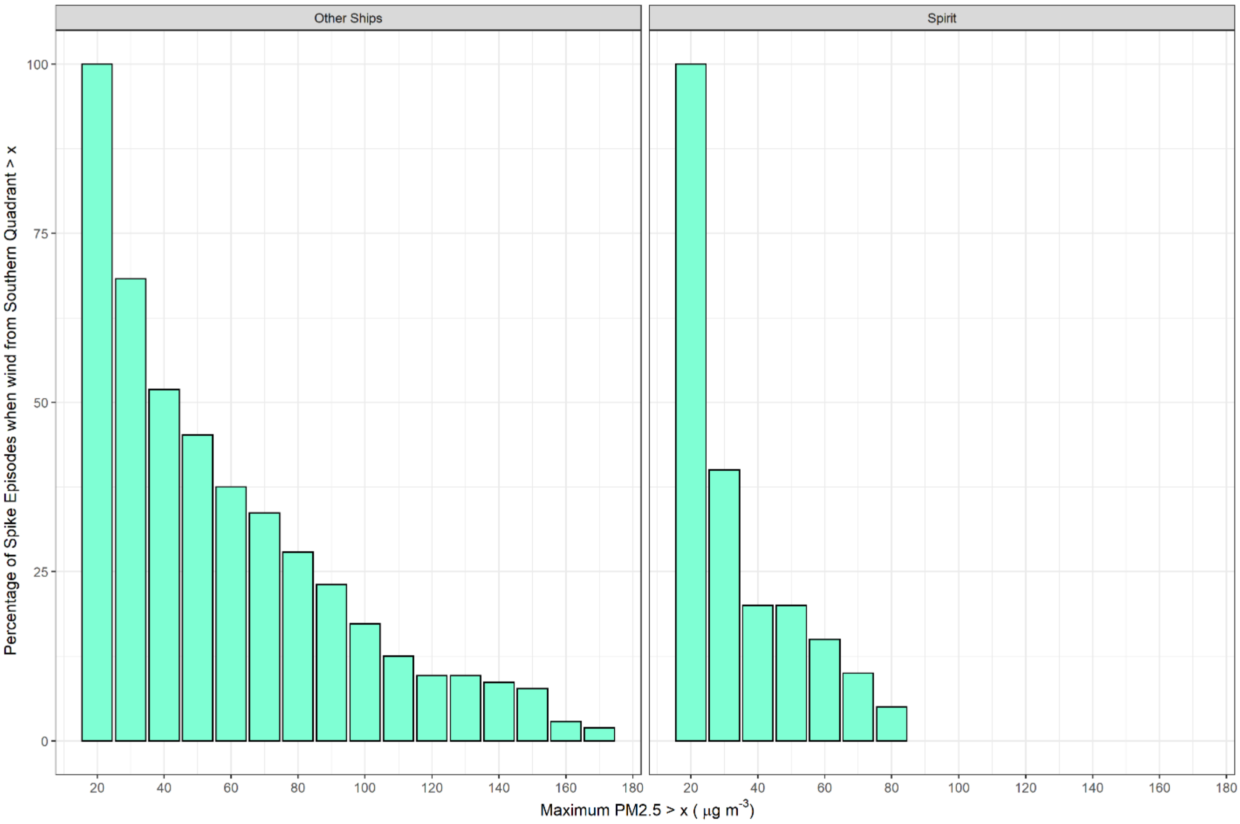

Fig. 6. Histograms showing the percentages of 30-min intervals with mean $PM_{2.5}$ concentration > x as a function of x, for all seven locations.

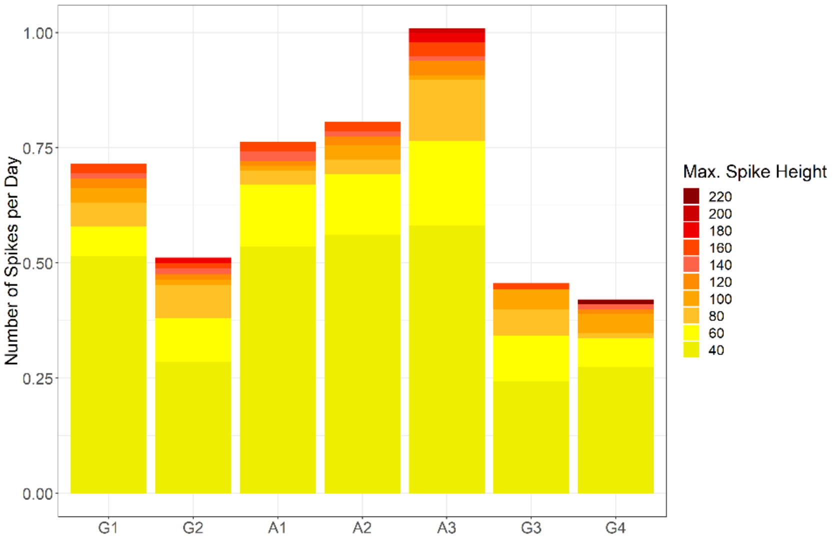

Fig. 7. Mean number of 5-min data spikes per day for each of the seven locations, with the vertical bars divided according to spike height bins in µg m^{-3}.

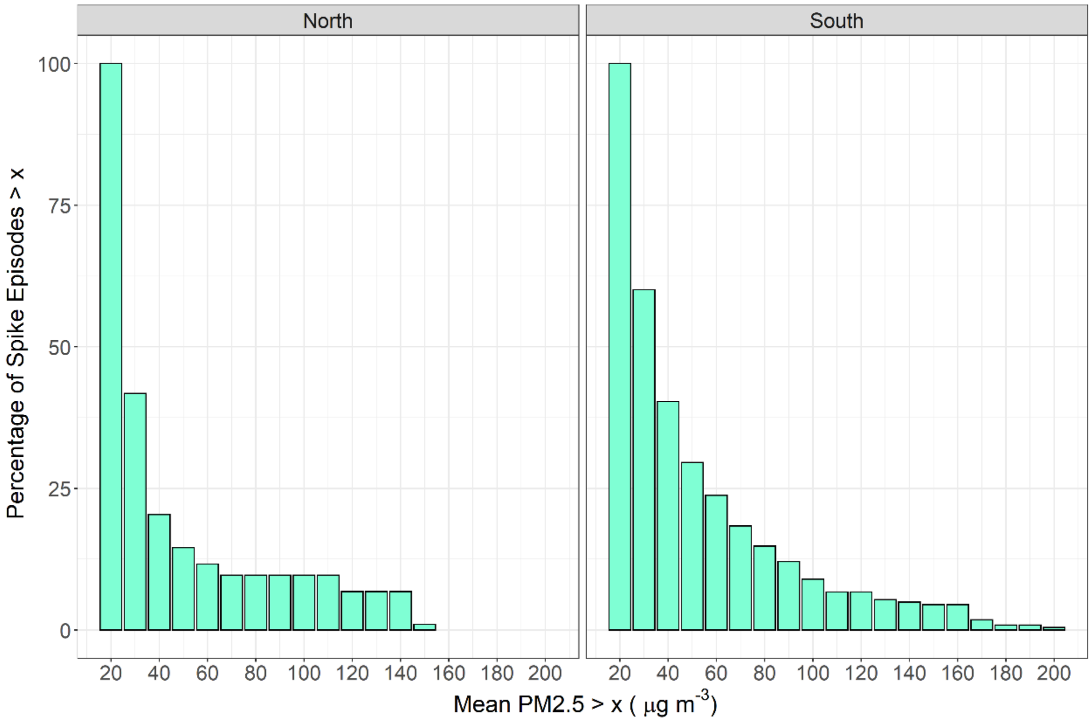

Fig. 8. Histogram showing the percentage of PM$_{2.5}$ spikes > x against spike height x, when the wind was from the northern and southern quadrants.

and SW. This is illustrated in Table 2, using ten SoT departure events that produced at least one spike larger than 100 µg m^{-3} over the approximate 1-month period from 2 January to 2 February 2019. In this sample, there is no exception to this rule, with the occurrence of peaks in the two location clusters correlating with the wind directions. An interesting observation was made on the evening of 2 February. On this day, the SoT arrived just after 19:00 with the wind blowing from 170° (SSE). All five KOALAs in the western cluster of locations showed high peaks, while the two in the eastern cluster did not. Later the same day, the SoT departed at 21:41, when the wind direction had changed to 190° (SSW). Now, the two KOALAs in the eastern cluster showed high peaks while the five in the western cluster did not. This illustrates the sensitivity of detection of the pollution spikes from individual ship emission events to wind direction. It also explains why so few, just 15%, of the ship arrival/departure times resulted in a detectable spike in PM$_{2.5}$.

Table 2. Spike heights (rounded to the nearest 5 µg m^{-3}) observed at each of the seven locations, together with the prevalent wind directions at that time. The first five locations are to the NW of the pier. G3 and G4 are to the NE of the pier. A dash indicates that no spike was observed at that location.

Date	SoT (AEDT)	A3	A1	A2	G1	G2	G4	G3	Wind Directions
02 Jan	19:12	190	30	30	80	–	–	–	SSE
07 Jan	21:53	205	75	75	70	75	–	–	SSE
17 Jan	21:51	65	30	30	55	120	–	–	SSE
22 Jan	19:51	–	–	–	–	–	145	160	SSW
25 Jan	21:55	140	145	140	130	90	–	–	SE
26 Jan	23:05	–	–	–	–	–	95	120	SSW
29 Jan	20:21	180	60	100	100	100	–	–	SSE
01 Feb	21:20	140	120	130	105	65	–	–	SE
02 Feb	19:08	70	120	90	50	50	–	–	SSE
02 Feb	21:41	–	–	–	–	–	145	110	SSW

Relationship between PM$_{2.5}$ Spikes and Ship Activity

While most spikes were associated with reported ship movements, there were a large number of spikes that were not. Fig. S8 shows the spikes higher than 20 µg m^{-3} that were observed within 30 min after the arrival of a ship and up to 30 min before its departure, together with all spikes observed. To enable easy comparison, the totals observed at each location have been converted to spikes per day. This figure gives an indication of the relative impact of ship-related spikes upon arrival and departure, on all spikes.

Fig. S8 demonstrates that 65–75% of the spikes observed at each of the seven locations were a result of ship arrival and departure activity. The highest percentage (75%) was observed by the KOALA on the Tower 1 rooftop (A3), which was the closest location to the pier. The origin of the other spikes is unknown, although it was noted that the cruise ships did “fire up” their engines when hotelling whilst they were docked. Also, there was a high-emitting refuelling ship that spent a significant amount of time within the area when the ships were berthed.

The mean PM$_{2.5}$ concentrations during the entire monitoring period are compared with those of the various spike episodes in Fig. S9. A spike episode may last from 5 to 30 min and, therefore, the values shown in this figure are the mean values during the spikes and not the mean values of the peak heights of the spikes.

The highest concentrations were observed during the spike episodes related to ships other than the SoT. The mean PM$_{2.5}$ concentration during a spike episode of the SoT was about 4 times higher than at other times. During events from other ships, it was over 5 times higher. Although the average PM$_{2.5}$ concentrations of the spike episodes from the SoT are high, they are not as high compared to the mean of the spikes from the other ships. Spikes generally lasted for less than 30 min, so they did not contribute significantly to the 24-h averages, stipulated by the Australian air quality standards and WHO guidelines. Given the monitoring period was only for 98 days, their contribution to annual average PM$_{2.5}$ values is unknown.

SUMMARY AND CONCLUSIONS

Our analysis of PM$_{2.5}$ concentrations in Beacon Cove, which we monitored for 98 consecutive days, identified several of the factors affecting air quality but also highlighted gaps in knowledge. The 24-h average values ranged from 7 to 13 µg m^{-3} at the seven monitoring locations, indicating that the air quality was almost twice as poor in certain areas. Also, 2–8 days of exceeding the PM$_{2.5}$ limit specified by the Australian air quality standard were observed at each location.

During the measurement period, we detected 2,944 ship arrivals/departures at/from Beacon Cove and 435 PM$_{2.5}$ spikes producing concentrations above 20 µg m^{-3} (and occasionally reaching even 200 µg m^{-3}) across all the monitoring locations. Although 307 of these spikes, or 71%, occurred within 30 min of an arrival/departure, only 15% of them coincided with the arrival/departure times. Both the 24-h average concentrations and the number of spikes observed at the elevated monitoring sites increased with the altitude. Lower concentrations were found at the locations on the ground, which were farther inland; however, the levels of PM$_{2.5}$ and the distance from the harbour displayed a complicated relationship: The average values of the former increased with the latter, but the magnitude of the spikes varied.

On average, the spikes were ~4–5 times above the normal background value (~10 µg m^{-3}). Because of their very short duration, these episodes did not significantly raise the 24-h averages at any of the locations. The share formed by the more constant ship hotelling emissions remains unknown. Although the mean PM$_{2.5}$ concentrations measured by the KOALAs did not significantly differ from those reported by the nearest AQMS, all seven monitoring locations recorded a higher number of days on which the 24-h average exceeded the standard limit. These results cannot be explained solely by the influence of bushfire smoke; hence, we attribute them to the combination of ship emissions, including the potential contribution of hotelling, especially when they spiked in concentration, and clean air from the sea during periods without maritime activity at the pier.

Although the long-term health effects of elevated PM concentrations are known, few studies have been conducted on the risks of short-term exposures to extreme spikes—a topic that, based on our data, merits additional research. Furthermore, if we assume that maritime traffic will only increase, ports will not be in compliance with future pollution standards unless measures to reduce ship emissions are implemented. Finally, our study demonstrates the usefulness of deploying multiple low-cost sensors in investigating emissions in such situations.

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SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at https://doi.org/10.4209/aaqr.2020.06.0280

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