REPORT

An investigation of air pollution on the decks of 4 cruise ships

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EXECUTIVE SUMMARY

Particulate matter (PM) pollution consists of small solids or liquid droplets suspended in the air. When inhaled, some PM can damage the heart and lungs. Particles less than 10 micrometers (µm) in diameter are a concern for public health because they can be inhaled deep into the lungs. Very small particles, classified as ultrafine particles or UFPs (100 nanometers or 0.1 µm), and even smaller nanoparticles (less than 100 nanometers) can cause airway inflammation and immunological reactions in the lungs and can travel through the bloodstream to affect other organs. The PM emitted from ship engines burning diesel fuel or heavy fuel oil is primarily composed of particles spanning from a few nanometers to less than one micron (0.001 µm–1.0 µm).

Ship exhaust contains harmful constituents, including metals and polycyclic aromatic hydrocarbons (PAHs), many of which have toxic, mutagenic and/or carcinogenic properties. There is strong evidence that ship engine exhaust impacts air quality in port and coastal cities, but little is known about how ship engine exhaust may impact the air quality on the deck of a ship. This is of concern because tens of millions of passengers take cruises every year, and tens of thousands of people are employed on cruise ships.

Studies have demonstrated UFPs have detrimental effects to the cardiovascular and respiratory systems, including a higher incidence of atherosclerosis and increased disease severity of asthma. Even short-term exposure to UFPs from traffic exhaust is associated with adverse cardiovascular outcomes. Although there are no internationally agreed-upon standards for what is considered safe human health exposure for ultrafine particulates, it is generally accepted that lower counts are better for health.

With those concerns in mind, this study measured the concentration of PM (particles with sizes between 0.02-1.0 μm) on the deck of two Carnival Cruise Line ships in the Caribbean during October 2017 (*Carnival Liberty*) and April–May 2018 (*Carnival Freedom*); on the deck of a Holland America ship (*MS Amsterdam*) that traveled along the west coast of Canada and the U.S. during October 2018, and the deck of a Princess ship (*Emerald*) that traveled along the west coast of the U.S. and Mexico during November 2018. Measurements were taken inconspicuously in the bow area (fore of the smokestacks), as well as in two areas in the stern, aft of the ship's smokestack including areas designated for exercise (running tracks, basketball court).

The average PM readings in the stern areas of each ship were significantly higher than the average readings measured fore of the smokestacks (towards the bow) (paired t-tests, alpha 0.05). The findings of this study demonstrate that a source of PM—likely, in part from the ship's exhaust system—is contributing to poorer air quality in the stern areas of these cruise ships. Concentrations of PM on the decks of these ships are comparable to concentrations measured in polluted cities, including Beijing and Santiago. Despite being on the open water and in open air, vacationers and cruise ship staff may be exposed to elevated concentrations of PM.

THE PROBLEM

The global shipping sector contributes to a range of environmental issues, including poor air quality and climate change.[1, 2] It is speculated that cruise ships burn heavy fuel oil (HFO)[3] wherever they are permitted to do so. HFO is a residual fuel generated during the distillation of crude oil.

Cruise line companies represent a growing segment of the shipping sector. In 2017, a record 26.7 million passengers took a cruise, continuing a growth trend showing a 21% increase in passengers from 2011–2016.[4] Globally, three companies dominate the cruise ship sector with the following market shares: Carnival (42%), Royal Caribbean International (22%) and Norwegian Cruise lines (8%).[5] The number of crew members employed worldwide on cruise ships is estimated to be greater than 223,000.[6]

Shipping exhaust generated from burning HFO contains high levels of sulfur, as well as metals and polycyclic aromatic hydrocarbons (PAHs), many of which have toxic, mutagenic and/or carcinogenic properties.[7] The impacts of cruise ship exhaust on the air quality of port and coastal communities have been documented,[8-9] including the impact of particulate matter (PM).

PM is characterized by the size of particle. The following categories of PM are based on their aerodynamic diameter including coarse particles (PM10—particles ≤ 10 μm), fine particles (PM2.5—particles ≤ 2.5 μm), ultrafine particles or UFP (particles ≤ 0.1 μm or 100 nm), and nanoparticles (particles < 100 nm). Coarse and fine particles have been monitored and reported for decades, and epidemiological studies provide compelling evidence that PM pollution derived from fossil fuel combustion is an important cause of disease and premature death. PM generated from shipping exhaust has been found to show strong biological effects on human lung cells, and public health studies indicate that PM emitted from ship engine exhaust may be to blame for tens of thousands of annual deaths from lung and cardiovascular disease.[7] Documented cellular responses to exposure to particulate matter from diesel exhaust include genotoxicity, oxidative stress and inflammatory signaling.[10]

PM in the ultrafine and nanoparticle size range are relevant to public health because of their increased toxicity. UFP can have thousands of times more surface area than fine particles, which can affect the relative toxicity to the respiratory system, including greater deposition efficiency deep in the lungs.[11] Further, ultrafine and nanoparticles are small enough to experience translocation—meaning that solid ultrafine or nanoparticles can be inhaled into the lungs and move directly into the blood and relocate to other parts of the body.[12] Many in the environmental health research community have suggested that these smallest particles may be the most dangerous to human health.[13-14]

The size of particles in ship exhaust spans from a few nanometers to less than one micron (1µm).[15] Little work has been done to quantify the contributions of ship exhaust to air quality on the decks on cruise ships, where guests and cruise ship staff commonly spend time. Journalists in Europe have conducted studies of particulate matter concentrations on passenger decks of a cruise ship using a hand-held PM monitoring device (P-TRAK 8525), which utilizes condensation particle-counting technology. The journalists measured PM concentrations and noted high concentrations of PM—in some cases, particle concentrations were 200 times higher than air measured in a park away from traffic and other sources of air pollution.[16]

CURRENT STUDY

The sampling techniques for this study were designed to inconspicuously measure PM in three environments on each of four cruise ships to understand how each ship's exhaust may impact the air quality on each ship's deck. Measurements were taken while each ship was moving at sea, whereby the forward propulsion of the ship would create spaces on the deck that were upwind and downwind of the ship's smokestacks. The upwind environment was in the bow of the ships; the downwind environments included two areas aft of the smokestacks (see Figures 6–8). Each ship was subject to local winds that further influenced exhaust distribution and PM concentrations present in ambient air. Measurements were also taken in those same three environments while the ship was docked in port and exhaust plumes were subject only to local winds.

The quantity and characterization of shipping exhaust differs based on a variety of factors, including what fuel is being burned and the efficiency of the engine. The

cruise ships observed in this study were continuously emitting exhaust through their smokestacks, because in addition to providing propulsion, the ship generates electricity to power the cabins, air conditioning, and general operation of the ship.

PM measured on the deck of a cruise ship could originate from a variety of possible sources, including exhaust from the ship's engines, the ship's generators, salt and water particles from the sea, wind-borne dust particles from land-based sources, particles emitted from laundry activities, combustion particles from cooking or tobacco products and aerosols from electronic cigarettes/vaporizers. Effort was made to not measure particle concentrations if any passengers of staff were smoking or using vaping products. If a person walked by who was smoking/vaping while a measurement was being taken, the test was not used, and it was re-done when appropriate. Particles generated from cooking or laundry would fluctuate throughout the day depending on the food being prepared and when laundry is dried. In the current study, PM measurements were conducted at different times of day, including early mornings and late evenings when cooking and laundry activities may have been reduced or were not taking place. Salt, water, and dust from the land represent ambient or background levels and likely contribute similar particulate matter concentrations at different locations on the deck of the ship if measured at a similar time. Tests in each of the three environments were always done as close together as possible.

SHIPS STUDIED

Carnival Liberty

Figure 1. Carnival Liberty
Source: James Willamor

Traveled to: Bahamas
Ports visited: Port Canaveral, Freeport, Nassau, Port Canaveral
Sailing date: October, 2017
Guest Capacity: 2,974

Carnival Freedom

Figure 2. Carnival Freedom
Source: Jonathan Palombo

Traveled to: Western Caribbean
Ports visited: Galveston, Montego Bay, Grand Cayman, Cozumel, Galveston
Sailing date: April–May, 2018
Guest Capacity: 2,980

Carnival Liberty, Carnival Freedom, and Emerald Princess have very similar guest capacities. Holland America's Amsterdam is a smaller ship with less than half the guest capacity compared to the Carnival ships.

Holland America MS Amsterdam

Figure 3. Holland America MS Amsterdam
Source: Sabung.hamster

Traveled along North American West Coast
Ports visited: Vancouver, Astoria, San Francisco, Los Angeles
Sailing date: October, 2018
Guest Capacity: 1,380

Emerald Princess

Figure 4. Emerald Princess
Source: Bahnfrend

Traveled to: Mexico
Ports visited: Los Angeles, Santa Barbara, Ensenada, Los Angeles
Sailing date: November, 2018
Guest Capacity: 3,080

EQUIPMENT

The study measured particulate matter concentrations using a P-TRAK Ultrafine Particle Counter 8525 (the same device used in similar work in Europe). This portable instrument detects and counts particles within the size range of 0.02- 1 micrometer (0.02-1 μm or 20–1000 nm).[17] This range of particle size aligns closely with the particle size distribution found in HFO, marine gas oil, and diesel exhaust.[15, 18–19]

Particle concentrations, reported as particles per cubic centimeter (Pt/cc), were recorded at a log interval of one minute. This one-minute concentration was calculated by averaging the PM concentrations measured each second over sixty-seconds. The P-Trak was operated as recommended, using high-purity isopropyl alcohol (99.5% pure) and with zero-check procedures conducted daily. The device used for each study had been factory calibrated within the last 12 months, as recommended by the manufacturer.

Figure 5. P-Trak Ultrafine Particle Counter 8525, TSI Incorporated. (Source: Google Images)

MONITORING

Environmental monitoring does not involve human subjects, and therefore this study was exempt from institutional review. Staff and patrons on the cruise ship were not made aware that measurements of particulate matter were being conducted. No staff or patron asked the researcher anything about the monitoring activities throughout the duration of the cruises. Every effort was made to not impact any guest's experience on the cruise. The P-TRAK was fitted into a cloth bag with an intake tube used to draw air into the machine.

PM measurements were taken in three open-air areas of the ship (see Figure 7–9). Two of the measurement areas were aft of the smokestacks in the stern. Measurements were also taken in the bow, fore of the smokestacks. Monitoring was done as a series of the three locations, with the order rotated in each series. Measurements in each series were done consecutively, resulting in comparable times for each location data set. Measurements were taken while the ship was in motion traveling at sea and while docked at port. Measurements of PM concentrations were recorded over several minutes in each location (range, 3–38 minutes).

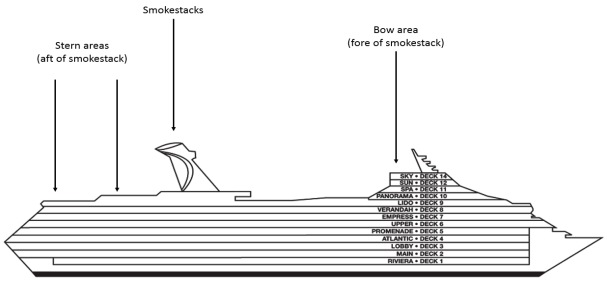

Figure 6. Sampling areas of the Carnival Freedom and Carnival Liberty

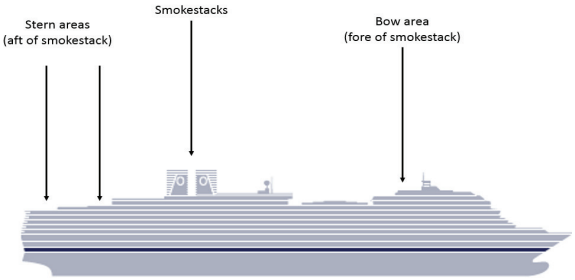

Figure 7. Sampling areas in the Holland America ship MS Amsterdam

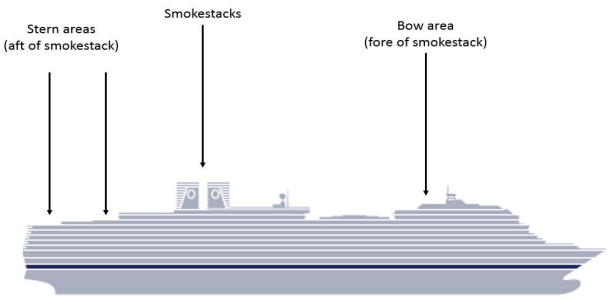

Figure 8. Sampling areas in the Princess ship Emerald

ANALYSIS

Mean particle concentrations (Pt/cc) were calculated based on duration of sampling, by location on ship deck while at sea and while in port. Maximum and minimum one-minute concentrations were identified for each environment under each condition. These are reported for each ship in tables 1–4 below. Further, paired sample t-tests were conducted using an alpha of 0.05 to compare the mean particle concentrations in the bow to those in the stern and the track area or upper stern area.

RESULTS

The average (mean) particles per cubic centimeter (Pt/cc), and maximum 1-minute Pt/cc observed for each location, both in port and at sea, are reported in the Tables 1–4 below.

Table 1. Average and maximum particulate matter concentrations measured in different environments on the deck of the ship **Carnival Liberty**

	IN PORT			AT SEA		
	Average particle count Pt/cc	Minutes of monitoring	Maximum 1-minute concentration Pt/cc	Average particle concentration Pt/cc	Minutes of monitoring	Maximum 1-minute concentration Pt/cc
Stern	25,634	67	85,440	13,364	63	41,560
Track	33,514	31	46,018	13,150	54	45,063
Bow	6,126	27	19,178	4,171	48	9,668

Table 2. Average and maximum particulate matter concentrations measured in different environments on the deck of the ship **Carnival Freedom**

	IN PORT			AT SEA		
	Average particle count Pt/cc	Minutes of monitoring	Maximum 1-minute concentration Pt/cc	Average particle concentration Pt/cc	Minutes of monitoring	Maximum 1-minute concentration Pt/cc
Stern	5,740	89	31,367	9,702	512	47,823
Track	11,880	73	56,091	12,747	512	73,621
Bow	15,604	100	119,983	1,540	523	14,533

Table 3. Average and maximum particulate matter concentrations measured in different environments on the deck of the ship Holland America **MS Amsterdam**

	IN PORT			AT SEA		
	Average particle count Pt/cc	Minutes of monitoring	Maximum 1-minute concentration Pt/cc	Average particle concentration Pt/cc	Minutes of monitoring	Maximum 1-minute concentration Pt/cc
Stern	2,284	89	38,333	16,831	375	76,780
Upper Stern	4,217	88	13,711	14,508	362	43,486
Bow	5,904	95	25,290	2,284	366	12,781

Table 4. Average and maximum particulate matter concentrations measured in different environments on the deck of the ship **Emerald Princess**

	IN PORT			AT SEA		
	Average particle count Pt/cc	Minutes of monitoring	Maximum 1-minute concentration Pt/cc	Average particle concentration Pt/cc	Minutes of monitoring	Maximum 1-minute concentration Pt/cc
Upper Stern	6,502	42	15,416	30,647	269	144,500
Lower Stern	8,234	42	17,140	32,628	268	157,716
Bow	33,408	43	126,786	5,167	257	24,696

While all four ships were traveling at sea, average particle counts (Pt/cc) were significantly higher in the areas aft of the smokestacks towards the stern, compared to areas towards the bow (forward of the smokestacks) ($p<0.05$). On the Carnival Liberty, particle counts in the stern or running track area were approximately three times higher than the bow. On the Carnival Freedom, particle counts measured on the stern were approximately six times higher, and those on the running track were eight times higher, than concentrations measured near the bow. On the Holland America MS Amsterdam, average particle counts were approximately eight times higher in the stern areas compared to the concentrations measured near the bow. On the Princess ship Emerald, particle counts in the stern area were approximately 6 times higher in the stern areas compared to the bow. For detailed findings from each test conducted on each ship, refer to the tables presented in Appendix A–D. Using paired t-tests (compare means), it was found that the difference in means between stern areas and the bow areas were found to be statistically significant (alpha 0.05). See Appendix E for each paired t-test result.

While in port, particle counts on the Carnival Liberty were generally higher than at sea, with average particle counts four to five times higher aft of the smokestacks than in the bow. On the Carnival Freedom, particle counts were lowest on the stern, but on the bow still measured approximately four times higher than particle counts while at sea. The Holland America ship, the MS Amsterdam, had much lower particle counts in the stern in port as compared to when the ship was at sea. On the Princess' ship Emerald, port readings in the bow were comparable to readings observed in the stern while the ship was moving.

Test-by-test readings, including maximum and minimum one-minute particle counts measured on each ship, are detailed at the end of the report in the appendices.

DISCUSSION

The results of this study demonstrate that while each cruise ship was at sea, concentrations of particulate matter were significantly higher in the areas aft of the smokestacks compared to the bow area. This suggests that a source between the bow and the aft of the ship contributed particulate matter. The size of particulate matter measured in this study aligns closely with the size of particles known to be generated by ship engines, and the ship's exhaust system is located between the environments with disparate PM measurements, suggesting the source of the particulate matter is likely, in part, the ships' engine exhaust.

There is not universal agreement on how to measure or report particulate matter from the UFP or nanoparticle size range. However, by reviewing studies that have similarly measured outdoor particulate matter with a P-TRAK device, it is possible to compare the findings of this study to other environments. While at sea, average particulate matter concentrations in the areas aft of the smokestacks of the ships ranged between 9,702–32,628 Pt/cc, with a maximum one-minute particulate matter concentration of 157,716 Pt/cc.

Differences in particulate matter concentrations observed in port and at sea may be explained by local winds distributing ship exhaust differently, and therefore contributing to higher concentrations in the bow area, compared to when the ship is moving (see appendices).

There remain some unknowns with this study, including which fuel types were being used by the ships throughout the voyage and how efficiently the engines were operating.

"Ship engine emissions are important with regard to lung and cardiovascular diseases especially in coastal regions worldwide … Epidemiological studies attribute up to 60,000 annual deaths from lung and cardiovascular disease to ship engine [particulate matter]."

Oeder S, Kanashova T, Sippula O,Sapcariu SC, Streibel T, Arteaga-Salas JM, et al. (2015) Particulate Matter from Both Heavy Fuel Oil and Diesel Fuel Shipping Emissions Show Strong Biological Effects on Human Lung Cells at Realistic and Comparable In Vitro Exposure Conditions. PLoS ONE 10(6): e0126536. doi:10.1371/journal. pone.0126536

Other studies from around the world measuring particulate matter in outdoor settings with a P-Trak are presented here:

- UFP levels in train stations in Taipei, measured using a P-Trak in 2009, averaged 15,500 Pt/cc.[20]
- An air quality study measured UFP with a P-Trak in different locations in Beijing, China in 2009. Average UFP concentration was 30,000 Pt/cc on a busy street.[21]
- A study in industrialized southeast China measured concentrations of ultrafine particles in a high-traffic area using a P-TRAK; median value was 45,805.[22]
- UFP concentrations measured with a P-Trak in Santiago, Chile found ranges of 8,000–30,100 Pt/cc.[23]
- Outdoor median concentrations of UFPs were measured with a P-Trak in Antwerp, Belgium 15,600 Pt/cc.[24]

Based on the findings of these other studies, particulate matter concentrations observed in different parts of the cruise ships' decks were comparable to some polluted environments, including urban settings in Asia, South America, and Europe.

The results of this study suggest that patrons and staff who are in the aft areas of cruise ships, like those in this study, are likely exposed to elevated levels of particulate matter, and that some of the particulate matter observed in this study was likely generated by shipping exhaust. This raises health concerns, given that ship exhaust is known to contain such dangerous constituents as metals and PAHs.[7]

Exposure to UFP is not advisable to any population; however, the US EPA and the World Health Organization warn that specific groups within the general population, including children, the elderly and people with respiratory and cardiovascular disease,[25-26] may have a greater risk of pollution effects.

APPENDIX A

Particulate matter concentrations (Pt/cc) measured on the **Carnival Liberty** (Pilot study)

Test	Date	Start time	Location 1 Stern 2 Track 3 Bow	Particle concentration (Pt/cc)			# of data points (# of minutes)	1 At sea 2 In port
				Average	1-minute Max	1-minute Min		
1	Oct 22	22:04	3	464	476	456	4	1
1	Oct 22	22:13	2	6,334	7,662	4,666	4	1
1	Oct 22	22:25	1	7,420	10,063	6,115	4	1
2	Oct 23	6:49	1	50,323	64,935	42,467	7	2
2	Oct 23	7:00	3	19,178	24,240	13,265	4	2
2	Oct 23	7:08	1	28,744	41,662	22,494	4	2
2	Oct 23	14:51	1	14,104	30,695	6,985	13	2
3	Oct 23	15:06	2	4,837	7,184	3,602	7	2
3	Oct 23	15:19	3	2,816	6,048	692	8	2
4	Oct 23	16:39	1	28,608	32,351	22,578	3	1
4	Oct 23	16:43	2	19,023	45,063	4,687	18	1
4	Oct 23	17:07	3	911	1,131	561	5	1
5	Oct 24	7:10	3	6,686	14,744	2,509	8	2
5	Oct 24	7:21	1	20,001	37,365	6,474	38	2
6	Oct 24	14:34	1	61,366	85,440	34,891	5	2
6	Oct 24	15:04	2	43,018	62,650	23,383	7	2
6	Oct 24	15:17	3	1,812	5,040	542	7	2
6	Oct 24	15:33	2	41,408	67,163	16,740	17	2
7	Oct 24	21:50	1	22,456	41,560	502	10	1
7	Oct 24	22:05	3	9,668	18,371	3,441	8	1
7	Oct 24	22:16	2	8,884	15,450	4,132	6	1
8	Oct 25	13:40	1	13,942	17,013	10,444	13	1
8	Oct 25	13:56	2	9,551	11,288	8,710	6	1
8	Oct 25	14:17	3	2,978	3,597	2,303	10	1
9	Oct 25	18:34	1	12,744	16,382	10,632	17	1
9	Oct 25	18:52	2	16,440	34,361	6,673	9	1
9	Oct 25	19:04	3	3,970	4,114	3,843	12	1
10	Oct 25	22:04	1	8,046	9,487	6,525	5	1
10	Oct 25	22:10	2	8,052	14,543	5,871	8	1
10	Oct 25	22:21	3	4,185	4,839	3,547	4	1
11	Oct 26	5:43	3	4,456	7,079	3,769	5	1
11	Oct 26	5:51	2	6,389	8,087	3,374	7	1
11	Oct 26	5:59	1	5,483	9,995	4,277	7	1

APPENDIX B

Particulate matter concentrations (Pt/cc) measured on the **Carnival Freedom**

Test group	Date	Start time	Location 1 Stern 2 Track 3 Bow	Particle concentration (Pt/cc)			# of data points (# of minutes)	1 At sea 2 In port
				Average	1-minute Max	1-minute Min		
1	April 28	16:06	2	13,762	53,539	1982	14	1
1	April 28	16:23	1	6,933	10,069	4,522	11	1
1	April 28	16:38	3	1,871	2,101	1,681	7	1
2	April 28	18:30	1	8,701	11,414	6,596	12	1
2	April 28	18:44	2	8,734	9,955	3,769	11	1
2	April 28	18:58	3	1,810	1,922	1,690	16	1
3	April 28	21:35	2	6,230	9,898	1,644	16	1
3	April 28	2153	1	2,901	3,944	1,653	9	1
3	April 28	2207	3	1,173	1,290	1,047	17	1
4	April 29	9:12	3	783	840	748	10	1
4	April 29	9:25	2	8,582	34,779	2,811	12	1
4	April 29	9:41	1	4,925	7,044	2,809	11	1
5	April 29	12:55	1	9,756	11,896	7,507	13	1
5	April 29	13:10	2	6,197	15,456	1,549	11	1
5	April 29	13:25	3	1,257	1,373	1,075	14	1
6	April 29	16:55	2	12,581	43,750	1,039	14	1
6	April 29	17:12	1	3,095	4,121	2,629	9	1
6	April 29	17:25	1	3,689	5,048	2,759	12	1
6	April 29	17:40	3	918	985	828	13	1
7	April 29	21:20	1	6,304	7,114	4,988	17	1
7	April 29	21:39	2	6,667	14,445	686	11	1
7	April 29	21:54	3	737	796	701	16	1
8	April 30	5:22	3	361	501	291	13	1
8	April 30	5:38	2	1,535	3,670	292	11	1
8	April 30	5:50	1	3,226	4,308	540	12	1
9	April 30	8:40	1	9,177	12,290	3,983	20	1
9	April 30	9:02	2	19,583	32,155	7,032	30	1
9	April 30	9:36	3	1,158	1,286	1,080	23	1
10	April 30	12:44	2	12,481	22,670	1,277	12	1
10	April 30	12:57	1	12,501	15,699	11,082	11	1
10	April 30	13:12	3	758	830	716	20	1
11	April 30	16:23	1	10,685	12,916	8,915	17	1
11	April 30	16:42	2	16,661	21,756	12,137	17	1
11	April 30	17:02	3	450	504	414	22	1
12	April 30	19:30	1	5,310	7,199	3,632	21	1
12	April 30	19:53	2	12,149	17,125	7,153	34	1
12	April 30	20:30	3	415	442	396	13	1
13	May 1	4:55	3	499	599	383	30	1
13	May 1	5:29	2	12,210	16,963	5,896	24	1
13	May 1	5:55	1	4,416	6,550	2,960	29	1

14	May 1	8:05	3	5,668	6,513	4,934	11	1
14	May 1	8:20	1	9,762	18,563	4,248	11	1
14	May 1	8:32	2	12,066	37,621	6,704	15	1
15	May 1	15:38	1	3,652	6,147	2,086	9	2
15	May 1	15:49	2	2,886	4,506	2,225	12	2
15	May 1	16:05	3	781	962	580	13	2
16	May 1	18:02	2	2,967	3,650	2,361	11	1
16	May 1	18:15	1	4,035	5,895	2,665	10	1
16	May 1	18:29	3	645	1,057	356	15	1
17	May 1	20:48	2	5,579	9,187	1,001	24	1
17	May 1	21:14	1	4,118	6,693	2,561	23	1
17	May 1	21:44	3	436	527	382	27	1
18	May 2	6:23	1	8,326	17,038	4,671	10	1
18	May 2	6:35	2	8,913	15,035	2,167	11	1
18	May 2	6:49	3	554	630	494	12	1
19	May 2	14:29	1	1,251	4,492	525	11	2
19	May 2	14:42	2	1,357	2,454	568	9	2
19	May 2	14:55	3	21,246	44,513	1,057	35	2
20	May 2	15:52	3	1,700	2,678	1,367	11	2
20	May 2	16:08	1	18,151	31,367	10,820	16	2
20	May 2	16:25	2	24,607	56,091	2,460	25	2
21	May 2	19:41	1	16,428	18,819	14,749	13	1
21	May 2	20:12	2	7,292	9,617	5,963	15	1
21	May 2	20:31	3	1,601	1,735	1,516	15	1
22	May 2	21:49	3	1,844	2,315	1,323	20	1
22	May 2	22:13	2	6,008	10,796	2,262	21	1
22	May 2	22:40	1	11,756	14,306	7,776	21	1
23	May 3	4:46	1	20,785	40,308	6,558	20	1
23	May 3	5:09	2	25,007	36,790	2,942	30	1
23	May 3	5:46	3	3,114	3,260	2,911	29	1
24	May 3	8:42	1	10,745	20,665	5,442	21	1
24	May 3	9:05	2	40,756	73,621	8,795	21	1
24	May 3	9:33	3	18,590	119,983	3,567	25	2
25	May 3	11:45	1	1,950	3,247	1,627	30	2
25	May 3	12:17	2	5,855	12,523	3,455	21	2
25	May 3	12:43	3	18,479	52,921	4,187	30	2
26	May 3	16:40	1	2,402	3,741	1,835	15	2
26	May 3	17:00	3	18,856	56,108	4,218	17	2
26	May 3	17:28	3	18,008	40,956	2,512	19	2
27	May 3	18:09	1	13,716	47,823	2,733	30	1
27	May 3	18:42	3	1,200	1,349	744	25	1
28	May 3	22:00	1	15,330	17,932	12,847	13	1
28	May 3	22:12	2	15,561	18,918	13,859	6	1
28	May 3	22:24	3	1,547	1,813	1,329	14	1
29	May 4	6:03	1	8,517	21,555	3,432	31	1
29	May 4	6:40	3	2,862	10,680	824	31	1

29	May 4	7:18	2	18,950	42,420	7,379	33	1
30	May 4	10:00	1	13,476	24,430	7,218	33	1
30	May 4	10:49	2	17,167	29,186	10,851	31	1
30	May 4	11:26	3	1,828	2,325	1,646	33	1
31	May 4	15:13	1	18,788	40,646	2,473	27	1
31	May 4	15:51	2	5,672	12,558	1,423	26	1
31	May 4	16:40	3	1,286	1,707	1,159	30	1
32	May 4	19:12	1	9,854	13,274	8,267	17	1
32	May 4	19:33	2	6,917	14,429	4,098	20	1
32	May 4	19:56	3	1,480	1,641	1,376	19	1
33	May 4	22:05	1	11,554	15,084	7,703	13	1
33	May 4	22:20	2	6,415	14,308	5,109	14	1
33	May 4	22:37	3	1,824	1,948	1,721	14	1
34	May 5	5:09	1	3,167	5,055	2,323	15	1
34	May 5	5:26	2	2,541	5,773	1,968	15	1
34	May 5	5:46	3	5,925	14,533	3,114	14	1
35	May 5	7:43	2	13,707	27,677	8,608	6	2
35	May 5	7:50	1	9,915	17,476	5,558	8	2
35	May 5	8:04	3	2,972	3,303	2,630	9	2

APPENDIX C

Particulate matter concentrations (Pt/cc) measured on the **Holland America MS Amsterdam**

Test	Test group	Date	Start time	Location 1 Stern 2 Track 3 Bow	Particle concentration (Pt/cc)			# of data points (# of minutes)	1 At sea 2 In port
					Average	1-minute Max	1-minute Min		
3	1	Sep 25	15:39	2	7,213	13,711	3,529	22	2
4	1	Sep 25	16:04	3	16,056	25,290	7,489	20	2
5	1	Sep 25	16:28	1	15,321	38,333	8,284	25	2
6	2	Sep 25	18:38	1	21,251	45,561	4,387	25	1
8	2	Sep 25	19:39	2	4,589	19,116	218	21	1
9	2	Sep 25	20:05	3	1,498	2,415	1,002	24	1
11	3	Sep 25	23:04	3	4,003	7,385	2,221	22	1
12	3	Sep 25	23:29	2	8,057	32,770	3,106	23	1
13	3	Sep 25	23:52	1	46,106	76,780	18,930	26	1
14	4	Sep 26	8:23	1	30,303	41,820	20,385	25	1
15	4	Sep 26	8:48	2	29,879	37,486	22,845	23	1
16	4	Sep 26	9:15	3	2,580	3,086	23,318	23	1
20	5	Sep 26	17:32	3	2,661	3,198	2,502	27	2
22	5	Sep 26	18:12	1	3,230	4,067	2,774	21	2
23	5	Sep 26	18:34	2	2,539	2,663	2,256	21	2
24	6	Sep 26	21:07	3	2,621	11,046	1,786	20	1
25	6	Sep 26	21:30	2	2,062	2,852	1,845	20	1
26	6	Sep 26	21:51	1	1,906	1,991	1,862	21	1
27	7	Sep 27	7:00	2	3,276	5,843	2,707	24	1
28	7	Sep 27	7:25	1	3,209	3,910	2,665	24	1
29	7	Sep 27	7:52	3	8,311	12,781	2,461	23	1
30	8	Sep 27	10:05	1	14,614	21,695	7,095	23	1
31	8	Sep 27	10:29	2	3,195	5,159	2,346	22	1
32	8	Sep 27	10:55	3	2,140	2,334	2,038	23	1
33	9	Sep 27	12:39	3	1,615	2,229	1,243	20	1
34	9	Sep 27	13:02	2	1,825	2,481	1,582	26	1
35	9	Sep 27	13:28	1	16,506	33,618	8,663	22	1
36	10	Sep 27	16:54	3	1,073	1,166	1,020	22	1
37	10	Sep 27	17:19	1	23,106	27,425	17,951	23	1
38	10	Sep 27	17:43	2	28,600	32,081	20,255	22	1
39	11	Sep 27	21:41	3	896	829	755	23	1
40	11	Sep 27	22:06	2	33,633	43,486	23,172	21	1
41	11	Sep 27	22:49	1	27,108	34,246	18,237	21	1
42	12	Sep 28	4:45	2	16,347	25,160	5,454	21	1
43	12	Sep 28	5:07	3	1,009	1,063	957	21	1
44	12	Sep 28	5:33	1	10,720	20,021	6,796	23	1
45	13	Sep 28	9:23	1	2,439	6,216	1,639	21	2
46	13	Sep 28	9:44	2	2,250	3,925	1,481	22	2
47	13	Sep 28	10:08	3	2,877	5,188	1,339	22	2
48	14	Sep 28	21:03	1	4,298	4,876	3,533	22	2

49	14	Sep 28	21:29	2	4,763	5,835	3,510	23	2
50	14	Sep 28	21:48	3	4,024	4,694	3,100	26	2
51	15	Sep 29	6:20	2	23,795	25,968	20,206	23	1
52	15	Sep 29	6:44	1	15,284	16,392	12,883	21	1
53	15	Sep 29	7:10	3	691	772	620	22	1
54	16	Sep 29	10:55	3	775	2,307	597	26	1
55	16	Sep 29	11:24	2	12,639	19,150	12,639	26	1
56	16	Sep 29	11:50	1	7,973	14,511	2,778	30	1
57	17	Sep 29	14:17	2	11,877	14,858	7,464	25	1
58	17	Sep 29	14:43	1	12,521	15,505	1,325	24	1
59	17	Sep 29	15:08	3	598	686	500	27	1
60	18	Sep 29	18:27	3	945	1,756	407	26	1
61	18	Sep 29	18:58	2	17,587	22,216	12,844	23	1
62	18	Sep 29	19:23	1	12,206	16,771	6,358	22	1
63	19	Sep 29	22:06	3	419	479	368	21	1
64	19	Sep 29	22:29	2	10,087	19,311	2,750	21	1
65	19	Sep 29	22:53	1	2,271	8,089	1,166	22	1
66	20	Sep 30	5:13	1	20,924	27,980	13,195	23	1
67	20	Sep 30	5:35	2	27,491	30,623	21,533	21	1
68	20	Sep 30	5:59	3	7,706	9,607	5,602	23	1

APPENDIX D

Particulate matter concentrations (Pt/cc) measured on the **Emerald Princess**

Test	Test group	Date	Start time	Location 1 U. Stern 2 L. Stern 3 Bow	Particle concentration (Pt/cc)			# of data points (# of minutes)	1 At sea 2 In port
					Average	1-minute Max	1-minute Min		
2	1	Nov 25	16:34	1	11,808	29,615	5,163	24	1
4	1	Nov 25	17:04	2	31,783	113,630	11,869	22	1
5	1	Nov 25	17:31	3	4,130	5,032	3,891	22	1
6	2	Nov 25	19:59	3	7,703	16,136	5,254	22	1
7	2	Nov 25	20:24	1	31,981	124,738	4,906	22	1
8	2	Nov 25	20:51	2	44,139	100,058	25,138	24	1
9	3	Nov 26	5:18	1	29,491	41,910	20,835	24	1
10	3	Nov 26	5:50	2	29,123	52,801	4,377	25	1
11	3	Nov 26	6:18	3	6,084	9,082	4,479	23	1
12	4	Nov 26	11:00	3	3,822	8,999	3,027	22	2
13	4	Nov 26	11:25	1	7,309	15,416	4,012	21	2
14	4	Nov 26	11:51	2	12,582	17,140	8,191	22	2
16	5	Nov 26	18:56	2	7,612	12,188	4,262	24	1
17	5	Nov 26	19:24	1	37,754	144,500	3,575	22	1
18	5	Nov 26	19:54	3	5,634	6,815	4,645	21	1
19	6	Nov 27	1:30	1	25,152	45,386	5,896	22	1
20	6	Nov 27	1:54	2	50,900	71,786	30,195	21	1
21	6	Nov 27	2:19	3	12,773	17,026	10,022	21	1
22	7	Nov 27	6:59	3	4,845	5,167	4,680	21	1
23	7	Nov 27	7:24	2	26,113	34,800	17,743	21	1
24	7	Nov 27	7:47	1	27,467	36,850	8,174	23	1
26	8	Nov 27	12:45	3	1,592	1,606	1,569	21	1
28	8	Nov 27	13:39	2	23,940	64,180	6,048	21	1
29	8	Nov 27	14:12	1	58,186	96,820	8,786	21	1
30	9	Nov 27	18:20	2	14,786	72,905	1,323	21	1
31	9	Nov 27	18:54	3	6,097	24,696	994	22	1
32	9	Nov 27	19:22	1	28,568	59,026	8,527	24	1
33	10	Nov 27	21:43	3	1,651	3,444	1,294	21	1
34	10	Nov 27	22:08	1	32,837	51,721	9,913	21	1
35	10	Nov 27	22:34	2	15,439	24,670	7,297	21	1
36	11	Nov 28	6:04	3	5,595	6,587	4,306	21	1
37	11	Nov 28	6:31	2	96,289	157,716	38,018	21	1
38	11	Nov 28	6:54	1	33,579	78,796	6,670	21	1
39	12	Nov 28	15:28	2	3,679	6,960	1,630	21	2
40	12	Nov 28	15:53	1	5,695	12,642	982	21	2
41	12	Nov 28	16:30	3	64,402	126,786	13,864	21	2
42	13	Nov 28	18:45	3	1,245	3,859	312	21	1
43	13	Nov 28	19:10	1	30,717	70,995	8,228	21	1
44	13	Nov 28	19:36	2	48,878	98,371	22,686	21	1
45	14	Nov 29	4:49	2	10,452	56,766	1,797	26	1

46	14	Nov 29	5:17	1	24,429	52,210	6,434	24	1
47	14	Nov 29	5:47	3	4,446	13,833	1,214	21	1

APPENDIX E – PAIRED T-TESTS

Liberty	**t**	**n**	**p**	**Sd**
Bow vs. stern	3.1444	7	0.019956	8663
Bow vs. track area	2.436422	7	0.030849	6465
Stern vs. track area	-0.879629	7	0.4129	6665

The difference between the average of the **stern minus bow** and μ0 is big enough to be statistically significant.
The difference between the average of the **track minus bow** and μ0 is big enough to be statistically significant.
The difference between the average of the **track minus stern** and μ0 is not big enough to be statistically significant.

Freedom	**t**	**n**	**p**	**Sd**
Bow vs. stern	7.932814	27	2.07E-08	4891
Bow vs. track area	7.818732	27	2.71118e-8	5800
Stern vs. track area	1.14615	27	0.262173	5710

The difference between the average of the **stern minus bow** and μ0 is big enough to be statistically significant.
The difference between the average of the **track minus bow** and μ0 is big enough to be statistically significant.
The difference between the average of the **track minus stern** and μ0 is not big enough to be statistically significant.

Amsterdam	**t**	**n**	**p**	**Sd**
Bow vs. stern	4.315514	16	0.00061	11474
Bow vs. upper stern	4.920617	16	0.00018	11641
Stern vs. upper stern	-0.62143	16	0.54365	12499

The difference between the average of the **stern minus bow** and μ0 is big enough to be statistically significant.
The difference between the average of the **upper stern minus bow** and μ0 is big enough to be statistically significant.
The difference between the average of the **stern minus upper stern** and μ0 is not big enough to be statistically significant.

Emerald	**t**	**n**	**p**	**Sd**
Bow vs. upper stern	4.064211	12	0.00186975	23983
Bow vs. lower stern	7.407945	12	0.0000134638	12087
Lower stern vs. upper stern	-0.290946	12	0.776505	27270

The difference between the average of the **lower stern minus bow** and μ0 is big enough to be statistically significant.
The difference between the average of the **upper stern minus bow** and μ0 is big enough to be statistically significant.
The difference between the average of the **lower stern minus upper stern** and μ0 is not big enough to be statistically significant.

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