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Impact of cruise ship emissions in Victoria, BC, Canada

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ABSTRACT

Characterization of the effects of cruise ship emissions on local air quality is scarce. Our objective was to investigate community level concentrations of fine particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2) and sulphur dioxide (SO_2) associated with cruise ships in James Bay, Victoria, British Columbia (BC), Canada. Data obtained over four years (2005–2008) at the nearest air quality network site located 3.5 km from the study area, a CALPUFF modeling exercise (2007), and continuous measurements taken in the James Bay community over a three-month period during the 2009 cruise ship season were examined. Concentrations of $PM_{2.5}$ and nitrogen oxide (NO) were elevated on weekends with ships present with winds from the direction of the terminal to the monitoring station. SO_2 displayed the greatest impact from the presence of cruise ships in the area. Network data showed peaks in hourly SO_2 when ships were in port during all years. The CALPUFF modeling analysis found predicted 24-hour SO_2 levels to exceed World Health Organization (WHO) guidelines of 20 $\mu g\,m^{-3}$ for approximately 3% of 24-hour periods, with a maximum 24-hour concentration in the community of 41 $\mu g\,m^{-3}$; however, the CALPUFF model underestimated concentrations when predicted and measured concentrations were compared at the network site. Continuous monitoring at the location in the community predicted to experience highest SO_2 concentrations measured a maximum 24-hour concentration of 122 $\mu g\,m^{-3}$ and 16% of 24-hour periods were above the WHO standard. The 10-minute concentrations of SO_2 reached up to 599 $\mu g\,m^{-3}$ and exceeded the WHO 10-minute SO_2 guideline (500 $\mu g\,m^{-3}$) for 0.03% of 10-minute periods. No exceedences of BC Provincial or Canadian guidelines or standards were observed.

1. Introduction

Diesel engines used as the main power supply of most large marine vessels produce a range of emissions, including carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), sulphur oxides (SO_x), hydrocarbons (HC) and particulate matter (PM) (Eyring et al., 2005). Ship engines are one of the highest pollution combustion sources worldwide, per ton of fuel consumed (Corbett and Fischbeck, 1997), and marine transport is recognized to contribute to air pollution in coastal areas (Corbett et al., 2007; Lu et al., 2006). Emissions produced at marine ports can impact air quality in surrounding regions and have an effect on human health (Bailey and Solomon, 2004). Substantial literature exists which report the impacts of diesel exhaust on human health, such as deteriorated lung function (Ruddell et al., 1996), allergies and asthma (Pandya et al., 2002), and increased risk of lung cancer (Bhatia et al., 1998).

Cruise ships are one source of marine emissions whose impact on local air quality has received little attention in the published literature. It is possible cruise ship emissions receive less attention because the cruise industry represents a lower percentage of the world marine vessel fleet, or because cruise vessels generally use fuel with a lower sulphur content than other merchant vessels, such as cargo carrying ships or tankers. However, in areas situated along popular cruise ship routes, such as coastal British Columbia and the Alaskan cruise ship route, cruise ship emissions have the potential to affect local air quality.

We report here on findings of the James Bay Air Quality Study (JBAQS), which was designed to investigate air quality in the James Bay neighbourhood of Victoria, BC, Canada. This study used a combination of air quality monitoring and modeling to investigate the impacts of emissions from cruise ships on local air quality

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during cruise ship seasons over recent years (2005–2009). Unlike other marine ports in BC which serve many types of large vessels, cruise ships are the largest marine emission source operating in James Bay, and have a regular schedule of arrivals and departures.

2. Study area

Cruise ships visiting Victoria make port at the Ogden Point terminal, located at the southwest corner of James Bay, a residential neighbourhood (population of approx. 11,000), situated at the southern tip of Vancouver Island, adjacent to downtown Victoria (Fig. 1). The terminal is within 500 m of the nearest residential dwellings, and although it has four deep sea berths, only three can be used simultaneously, which limits the number of ships at berth to three at any one time. There are no shoreside power capabilities (a.k.a. “cold ironing”), so cruise ships must continue using their engine(s) in port in order to maintain power for basic electrical needs, such as onboard electricity, navigation and communications

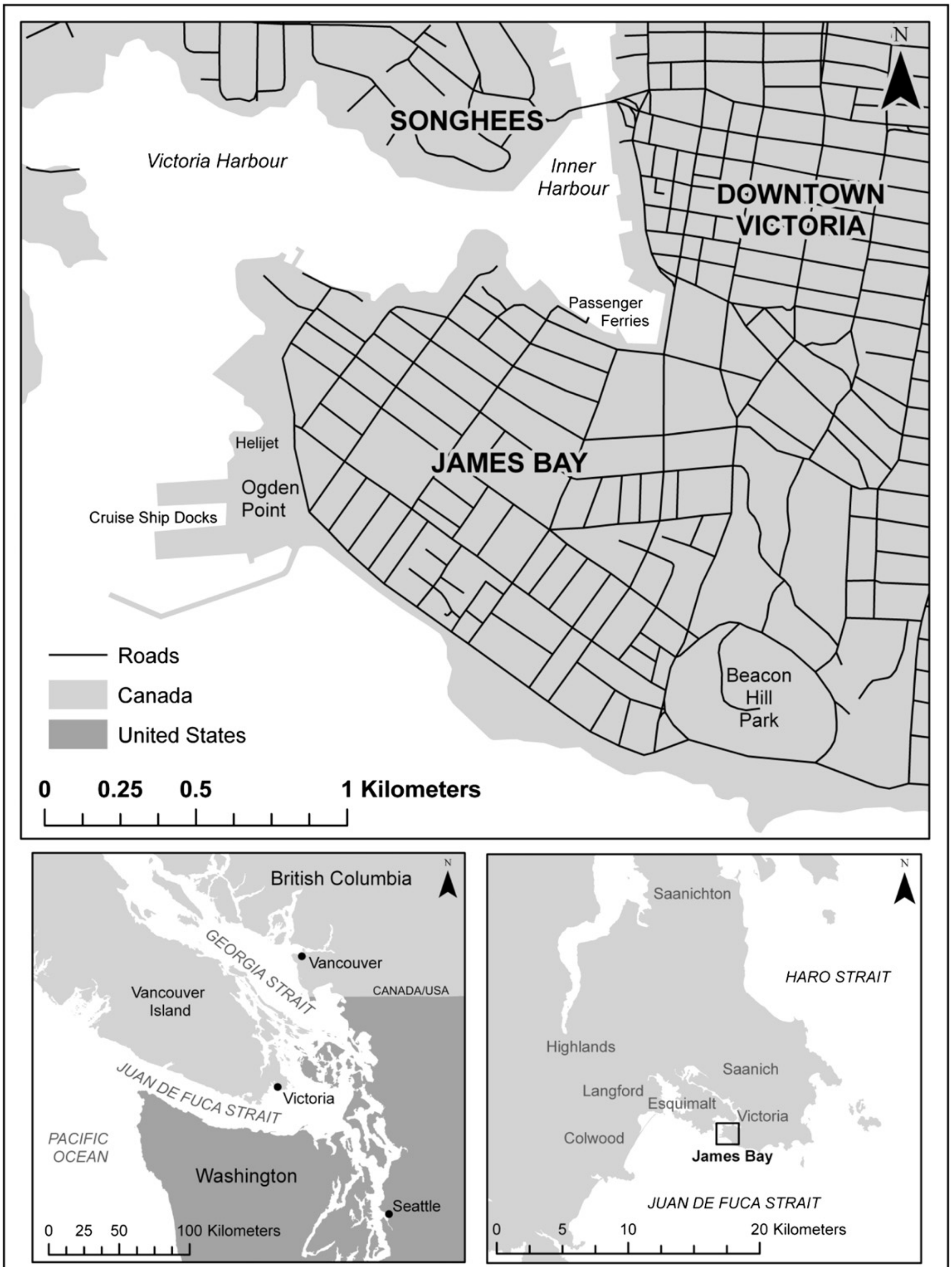

Fig. 1. James Bay, Victoria, British Columbia, Canada.

systems, or air conditioning. Between 2005 and 2009 there has been a >50% increase in the number of cruise ships and passengers visiting Victoria (Table 1). Generally, the cruise ship season extends from April to October. During the season, the majority of cruise ship visits (>80%) occur on Thursdays, Fridays and Saturdays each week. Additionally, on these days most arrivals occur between 06:00–08:00 and 17:00–20:00, and most departures just before midnight. During the 2007 cruise ship season, the average length of time spent in port was 7 h (range 3–16 h).

Other emission sources operating in the area include passenger ferries (4 to 7 sailings per day), and float planes (approximately 70 scheduled flights per weekday and 35 per day on weekends), whose main activities occur within the Victoria Harbour and Inner Harbour, to the north of James Bay. Also, a helijet service operates directly north of the terminal property (11 flights on weekdays and 4 on weekends). Unlike the cruise ships, these sources have relatively stable and continuous daily schedules, which allows for comparing air quality on days with and without cruise ships in port, assuming all other sources remain equal and meteorological conditions are similar. In addition, diesel buses associated with cruise ships transport passengers to and from tourist destinations in the area and follow a designated bus route around the outer perimeter of the community. Military vessels also make infrequent transits through the study area, although their schedules are unknown.

3. Methods

We analyzed existing hourly data (2005–2008) for NO_2, $PM_{2.5}$ and SO_2, collected at a provincial air quality network monitoring site approximately 3.5 km downwind of the port. This site is part of Environment Canada's national air pollution surveillance (NAPS) program (for further details on network sampling and instrumentation, please see: http://www.ec.gc.ca/rnspa-naps/). CALPUFF was used to model the distribution of these pollutants in the residential neighbourhood using data for 2007. Follow-up monitoring of NO_2, $PM_{2.5}$ and SO_2 was conducted for three months in 2009, at a location predicted by the model to have the highest SO_2 concentration.

3.1. Air quality network data

The BC Ministry of Environment operates a continuous air quality monitoring station on Topaz Avenue, approximately 3.5 kilometres northeast of the Ogden Point cruise ship terminal. This station measures a variety of common air contaminants and meteorological variables. The Topaz station is generally downwind of the port during the cruise ship season (Fig. 2). Hourly data for NO_2, $PM_{2.5}$, SO_2, wind speed (WS) and wind direction (WD) were obtained from the Topaz Station for the years 2005 to 2008 (January 1–December 31), as well as for the 3 month period where continuous monitoring was conducted with the BC Ministry of Environment's Mobile Air Monitoring Lab (MAML) in James Bay in 2009 (see Section 3.3). Data were divided into three categories for analysis: (1) "Off Season" (all days between November and March, typically); (2) "Non-Cruise" days during the summer cruise ship season but without cruise ships in port (Sundays through Tuesdays most often), and; (3) "Cruise" days during the cruise ship season with ships scheduled in port (Wednesdays through Saturdays). Hourly averages from the Topaz station were further summarised to provide average hourly diurnal patterns for each category, and 24-hour averages (midnight to midnight) were calculated for each day in each category. Data from the MAML were also aggregated to 10 min averages, 1 h averages, and 24 h averages, and average hourly levels for each category were calculated to provide diurnal patterns.

3.2. CALPUFF air quality model

The California Puff Modeling System (CALPUFF Version 6.112) was used to simulate the dispersion of NO_x, $PM_{2.5}$ and SO_x from cruise ship and passenger ferry emissions in the James Bay community and surrounding region during the 2007 cruise ship season (April 24–November 3 inclusive). CALPUFF (Earth Tech, Concord, MA) is a multi-layer, multi-species, non-steady state Lagrangian Gaussian puff dispersion model which can simulate the effects of temporally and spatially variable meteorological conditions from point, line, area or volume sources (Scire et al., 2000). It is available free of charge and can be downloaded from the Atmospheric Studies Group website (http://www.src.com/calpuff/calpuff1.htm).

The CALPUFF model was configured for an analysis of a 20 km^2 study domain centered on the Ogden Point terminal, subdivided into 100×100 m grid cells. Modeled winds and estimated concentrations are averaged quantities relating to each grid cell. Vertically, the modeling domain is resolved into 12 layers up to 3000 m height. Terrain and land use data from DMTI Spatial (Markham, Ontario) were used to characterize terrain heights at the horizontal scale of 100 m, and the characterize surface friction and thermodynamic properties for each grid cell. A meteorological simulation was completed with CALPUFF's meteorological processor (CALMET) following best practice guidelines for the province (MoE, 2008). The model uses an internal blending process to combine upper air flow data from the ETA mesoscale model at 12 km resolution with surface data from four stations (Ogden Point, Topaz, Victoria International Airport and NOAA Hein Bank Buoy Station 46088).

Cruise ships and passenger ferries were characterized as point sources while at berth, and as line sources while manoeuvring and transiting near berth, according to detailed ship schedules for the 2007 season. Ship emission factors for 4-stroke marine diesel engines were used to characterize cruise ship emissions during at berth, manoeuvring and transit activity, using estimates of average power (kW) developed by ship engines in each mode of activity considered appropriate in recent Canadian marine emissions analyses. The energy based emissions factors used were 14.00, 4.20 and 0.91 g kWh^{-1} for NO_x, SO_x and PM_2 respectively. In addition, an average boiler rate of 0.345 tonnes/hour was established for cruise ships during all modes of activity. Gas factors were obtained from

Table 1
Summary of Ogden Point cruise ship activity (2005–2009).

Year	Cruise Ship Season	# Ships	Number of Days			Frequency of days with # of ships in port (%)				
			Cruise	Non-Cruise	Off Season	1	2	3	4	5
2005	April 23–October 14	148	77	98	190	45	27	23	4	1
2006	April 29–October 14	182	88	77	201	33	38	21	7	1
2007	April 24–November 3	163	88	105	172	49	23	25	1	2
2008	April 3–October 14	211	105	90	170	38	30	26	4	2
2009	April 23–October 14	228	106	69	190	31	27	34	8	0

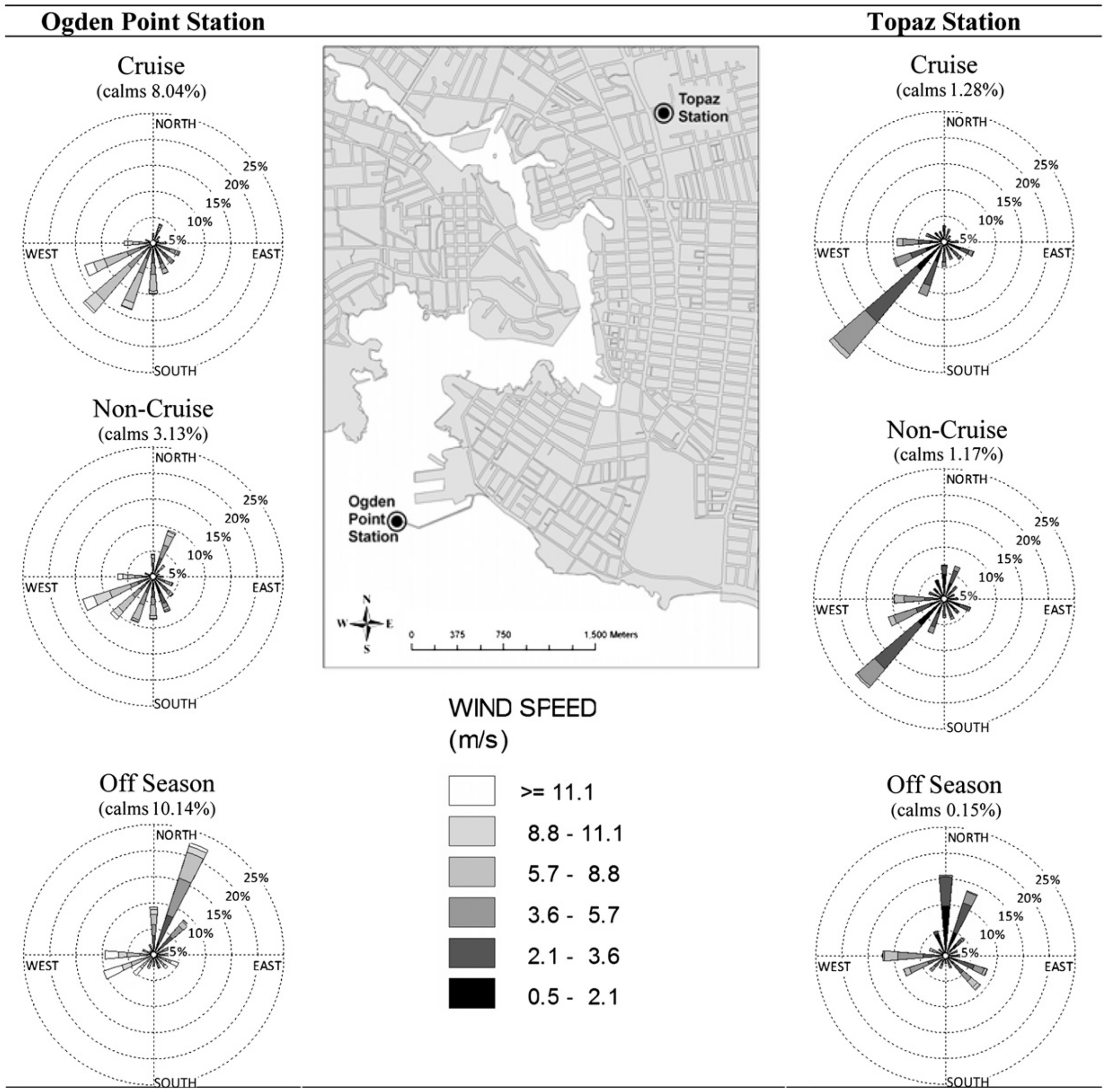

Fig. 2. Wind speed and wind direction measured at Ogden Point and Topaz meteorological stations (2008) during Cruise, Non-Cruise and Off Season periods.

the BC Chamber of Shipping 2005/2006 Marine Emissions Inventory (COSBC, 2007) and PM factors from the EPA 'AP-42' compilation of emission factors for boilers consuming no.5 fuel oil, or boiler emission rates of 12.30, 20.00 and 0.60 kg $tonne^{-1}$ for NO_x, SO_x and $PM_{2.5}$ respectively. In all cases, cruise ships were assumed to be using intermediate fuel oil (IFO) with a sulphur content of 1.6%.

Specific information to characterize the variation in energy demand of individual cruise vessels engines while at berth could not be obtained. A simplistic linear equation was developed to estimate cruise vessel power based on vessel passenger capacity (P) (which was available for each cruise ship):

$$\mathrm{AveragePower(kw)} = (1 - \mathrm{monthvar})(5143 + (P - 1250)2.857)$$

This equation was validated with actual ship engine and fuel usage for two cruise vessels while stopped at Ogden Point. The '*monthvar*' parameter was included to account for variability in energy consumption (Hart and de Dear, 2004) and the expected reduction in dockside engine load during cooler months when air conditioning demands would be low (this assumption could not be tested during the project). This equation implies the total engine power developed at berth ranged from 3.6 to 10.3 MW, for the vessels that visited during the year. Transit and manoeuvring were characterized on a vessel by vessel basis with the following:

- Transit time/distance of 0.18 h/2 km with engine power twice that used while at berth;
- Manoeuvring time near berth of 0.17 h with engine power 1.25 times that used while at berth.

The times noted above were based on suggestions from the local harbour authority and not on actual observations. The CALPUFF model timestep was 1-h, as is typically used for dispersion studies. This necessitated averaging (lowering) of the estimated emissions to represent 1-h average values, as emissions for a full hour would have resulted in gross over-estimates. Although a shorter 10-minute modeling time period was considered for manoeuvring, supporting data was lacking and computational time would have been prohibitive.

For ferries, specific vessel and fuel characteristics were obtained. Unlike cruise ships, ferries do not use auxiliary engines during all periods at berth, as shore power is used. This was accounted for in the emissions inputs.

3.3. MAML continuous monitoring in James Bay

The BC Ministry of Environment's Mobile Air Monitoring Laboratory was used during the 2009 cruise ship season to continuously monitor NO_2, SO_2 and $PM_{2.5}$. The monitor was placed at a location in James Bay downwind of the Ogden Point terminal, in the area predicted to experience the highest hourly SO_2 concentration levels by the CALPUFF model based on 2007 data (Fig. 3). This particular site was selected because it provided enough space to safely park the mobile monitoring vehicle off-road, and had access to continuous power. Although the 2009 MAML data cannot be used to directly validate short-term estimates from the 2007 CALPUFF modeling analysis, MAML provides data on actual levels and frequencies of short-term pollution peaks. Hourly concentrations of all pollutants (as well as 10-minute SO_2 levels) were examined over 87 days (2072 h), from 1:00 May 30 to 8:00 August 24, 2009. Hourly values were used to calculate 24-hour averages (midnight to midnight). All instruments were calibrated and maintained by the BC Ministry of Environment staff.

4. Results

Measured and predicted concentrations of pollutants are compared to air quality objectives, standards and guidelines established by different agencies or regulatory bodies which are applicable to this study (Table 2). The guidelines established by the Capital Regional District (CRD) in 2004 are intended to be used only for reporting purposes (CRD, 2007). These should not be considered regulatory standards such as those established by Canada (Health Canada, 2006) and BC (Government of British Columbia, 2009) in the 1970's which were reviewed in 1996 or 1998. Notably, the 24-hour SO_2 level set by the World Health Organization (WHO, 2006) is more stringent than regulatory objectives and standards

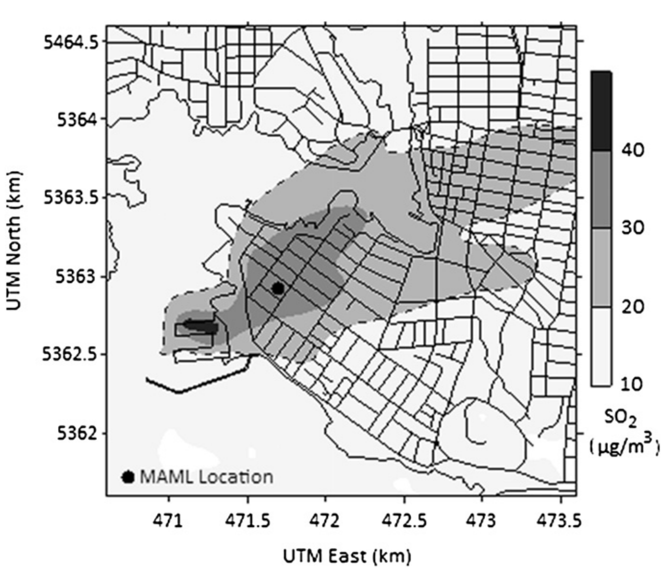

Fig. 3. Placement of MAML monitor in the James Bay community, in area with expected maximum SO_2 concentrations as predicted by the CALPUFF model (2007).

Table 2
Summary of air quality objectives, standards and guidelines ($\mu g\ m^{-3}$) relevant to the study area.

Agency	Period	NO_2	$PM_{2.5}$	SO_2
CRD	1-hour	200	–	–
	24-hour	–	25	125
BC Level A	1-hour	–	–	450
	24-hour	–	25	160
Canada Maximum Desirable	1-hour	–	–	450
	24-hour	–	25[a]	150
Canada Maximum Acceptable	1-hour	400	–	–
	24-hour	200	–	–
World Health Organization	10-minute	–	–	500
	1-hour	200	–	–
	24-hour	–	30	20
US EPA	1-hour	190[b]	–	200
	24-hour	–	–	–

[a] The Canada Wide Standard for $PM_{2.5}$ is considered to be exceeded when the average of the 98th percentile for each of three consecutive years is above 30 $\mu g\ m^{-3}$.
[b] 99th percentile averaged over three consecutive years.

adopted by most countries in the world, yet is set as the goal for countries to strive towards improving air quality and health of citizens. The United States Environmental Protection Agency has also proposed 1-hour average SO_2 and NO_2 concentrations lower than those currently applicable in Canada (USEPA, 2010).

4.1. Air quality network data

Concentrations of all pollutants measured at the Topaz Station (3.5 km downwind of the terminal) were found to be below established BC and Canadian regulatory standards (Table 3). In general, pollutants follow similar diurnal patterns from year to year, with some variations reflecting differences in the schedules of emission sources and intensities, as well as varying atmospheric and meteorological conditions between years.

Hourly average concentrations of NO_2 and $PM_{2.5}$ peak in the morning between 6–9 am from increased vehicle traffic, with a secondary peak present in the evening hours associated with residential heating. In 2006, the evening peak in NO_2 concentrations was almost 10 $\mu g\ m^{-3}$ higher during Cruise periods. However, in 2007 evening concentrations were highest in the Off Season, although concentrations in were 1–3 $\mu g\ m^{-3}$ higher in Cruise versus Non-Cruise periods of that same year. Levels of $PM_{2.5}$ are always highest during evening hours in the Off Season period, due to the use of wood-burning appliances for residential heating

Table 3
Maximum 1-hour and 24-hour concentrations ($\mu g\ m^{-3}$) measured at Topaz (2005–2008).

Year	Time Period	NO_2		$PM_{2.5}$		SO_2	
		1 h	24 h	1 h	24 h	1 h	24 h
2005	Cruise	101	40	43	10	83	12
	Non-Cruise	80	37	43	9	16	5
	Off Season	78	41	78	20	29	11
2006	Cruise	98	50	32	15	77	15
	Non-Cruise	86	46	35	16	48	15
	Off Season	90	43	74	23	19	9
2007	Cruise	77	48	35	9	88	23
	Non-Cruise	73	42	69	19	29	5
	Off Season	79	43	58	22	24	7
2008	Cruise	84	44	28	14	146	24
	Non-Cruise	84	44	58	15	31	9
	Off Season	91	44	72	18	20	7

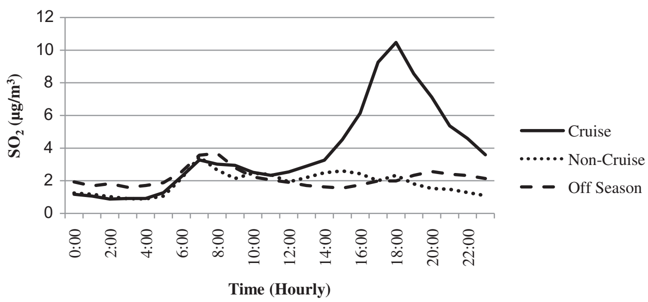

Fig. 4. Hourly average SO_2 concentrations measured at Topaz during Cruise, Non-Cruise and Off Season periods (2007).

during cooler months. The diurnal pattern of hourly SO_2 levels indicates cruise ships as the dominant source (Fig. 4), although elevated morning concentrations from vehicle traffic are still observable. Elevated SO_2 concentrations on Cruise days during evening hours (when the bulk of cruise ship activity occurs) are common across all 4 years of network monitoring data. Hourly SO_2 concentrations during Cruise periods are 1.6–5.2 times higher than Non-Cruise and 2.9–7.3 times higher than Off Season periods over all years (2005–2008) (See supplementary tables for observed data from individual years.).

The highest maximum 1-hour (146 $\mu g\,m^{-3}$) and 24-hour (24 $\mu g\,m^{-3}$) SO_2 concentrations occurred in 2008, which had the longest cruise ship season (195 days) and greatest number of ship visits. SO_2 concentrations were always highest during Cruise periods for both 1-hour and 24-hour periods, with the exception of 2006 where the maximum 24-hour SO_2 concentration was equal in both Cruise and Non-Cruise periods. Expected ship schedules were used for this analysis, so it is possible an unscheduled sailing may have occurred on a Non-Cruise day. In addition, other vessels for which schedules could not be obtained may have visited the study area (Coast Guard, Navy or research vessels).

To further assess whether short-term spikes in SO_2 levels experienced at the Topaz site are attributable to cruise ship emissions, data for each year and time period were graphed by wind direction. Fig. 5 displays data from 2008, although the same pattern was also observed in 2005–2007. The cruise terminal is almost exactly southwest of the Topaz Station, at approximately 225 degrees, and examining SO_2 concentrations by wind direction highlights that elevated levels during the cruise ship season occur almost exclusively when the wind direction is from the southwest quadrant.

Concentrations of $PM_{2.5}$ were always highest during the Off Season, indicating local winter-time sources of $PM_{2.5}$. NO_2 levels were variable, with higher concentrations during the cruise ship

Table 4
CALPUFF model results ($\mu g\,m^{-3}$) for 2007 cruise ship season scenario.

Time Period	Background (BG)	Entire Study Domain		James Bay Neighbourhood	
		Modeled Sources	Modeled Sources + BG	Modeled Sources	Modeled Sources + BG
NO_2					
1-hour	51	153	204	85	136
24-hour	36	17	53	17	53
Average	21	1	22	1	22
$PM_{2.5}$					
1-hour	16	30	46	16	32
24-hour	12	4	16	4	16
Average	5	0	5	0	5
SO_2					
1-hour	13	257	270	151	164
24-hour	7	39	46	33	40
Average	2	2	4	2	4

season in some years and not in others. Although concentrations of these pollutants did not display as great an influence from cruise emissions as SO_2, activity of ships could be detected in measured levels when data were analyzed by wind direction and divided by weekday versus weekend. Analyses conducted on hourly data measured at Topaz during the 2008 year found average $PM_{2.5}$ levels on weekend days to be up to 5 $\mu g\,m^{-3}$ higher when cruise ships were in port and winds were from the southwest. Maximum NO concentrations were up to 75 $\mu g\,m^{-3}$ higher when ships were in port on weekend days and winds were from the southwest, than when ships were absent from Ogden Point. NO_2 was generally higher on cruise weekend days with southwest winds, but the magnitude was not as great as for NO. NO_2 levels are lower than NO and only a portion of emissions emitted from ships would have been converted to NO_2 by the time the plume reaches Topaz. The relationship between these pollutants and the presence of cruise ships is more evident on weekend days when contributions from other background sources are lower, such as high levels of weekday traffic near the Topaz Station.

4.2. CALPUFF model

The CALPUFF air quality modeling analysis for the 2007 cruise ship season provided estimated $PM_{2.5}$, NO_x and SO_x concentrations in and near James Bay. No chemical transformations (e.g., secondary PM) were simulated in the model. NO_x predictions were converted to NO_2 (external from the model) using the Ambient Ratio Method recommended by the BC Ministry of Environment (MoE, 2008). Concentrations of SO_x were conservatively assumed to

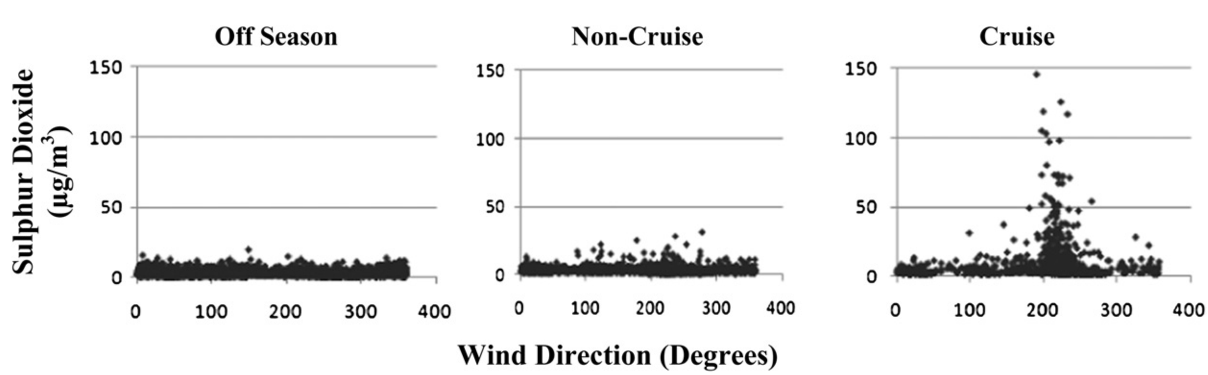

Fig. 5. 1-hour SO_2 concentrations measured at Topaz (2008) by wind direction and season.

Table 5
Comparison of maximum predicted to maximum measured concentrations of SO_2, NO_2 and $PM_{2.5}$ at Topaz Station (April 24–November 3, 2007).

	SO_2 ($\mu g\,m^{-3}$)		FAC	NO_2 ($\mu g\,m^{-3}$)		FAC	PM_{25} ($\mu g\,m^{-3}$)		FAC
	Model	Meas.	(P/O)	Model	Meas.	(P/O)	Model	Meas.	P/O
1-Hour									
No Background	48		0.5	60		0.8	5		0.1
With Background	61	88	0.7	111	77	1.4	21	69	0.3
24-Hour									
No Background	4		0.2	5		0.1	1		0.1
With Background	11	23	0.5	41	48	0.9	12	19	0.6

equal SO_2, as near source SO_2 levels in the community were of greatest interest.

Ship emissions were considered in addition to background concentration levels established as the 98th percentile measured at Topaz Station for 1-hour and 24-hour levels (2007 data). This station is influenced by traffic emissions and there is clear evidence that SO_2 from cruise ships reaches this location, therefore the 98th percentile was selected rather than the 100th or 99th percentile in order to minimize the influence of observed short-term peaks in concentrations due to cruise or other activities.

Background concentrations, maximum concentrations from modeled sources, and their combination were summarised for the entire study domain and within the James Bay community (Table 4). Predicted maximum 24-hour SO_2 in the entire domain (46 $\mu g\,m^{-3}$) and in James Bay (41 $\mu g\,m^{-3}$) exceed the WHO guideline of 20 $\mu g\,m^{-3}$ for 24-hour SO_2 concentrations. In the case of 24-hour SO_2, concentrations above 20 $\mu g\,m^{-3}$ were predicted to occur in approximately 3% of 24-hour periods in the modeling time period, which equates to 5 days out of 194 modeled. The maximum 24-hour SO_2 concentration in James Bay was predicted to occur on May 11th, one of two days with the maximum number of ships in port over a 24-hour period (5 ships). The other day with 5 ships in port was September 22nd, and this day experienced the second highest predicted 24-hour SO_2 concentrations in James Bay (40 $\mu g\,m^{-3}$). Modeled values suggested that passenger ferries in transit and at berth contribute <.1%, while cruise ships in transit and at berth contribute 16% and 84% respectively to these maximums. Predicted maximum 1-hour NO_2 in the domain (204 $\mu g\,m^{-3}$) slightly exceeded the CRD and WHO guidelines of 200 $\mu g\,m^{-3}$ for 1-hour NO_2, and occurred on only 1 out of the 4656 h in the modeling period (less than .001% of the time), following the departure of two cruise ships at 23:59 on June 30. Ferries in transit and at berth contributed 1% and 3%, while cruise ships in transit and in berth contributed 39% and 57% to the maximum predicted 1-hour NO_2. The exceedance of NO_2 is considered to have lower significance than exceedances of SO_2 due to the appreciable uncertainty of the NO to NO_2 conversion method used.

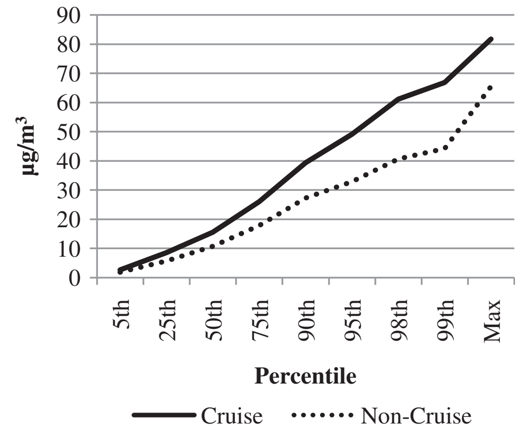

Fig. 6. Frequency distribution of 1-hour NO_2 measured by MAML (2009).

The Topaz Station was included as a discrete receptor point within the modeling analysis to compare modeled to measured concentration levels (Table 5). Comparing maximum measured to maximum predicted concentrations *without* the addition of background assumes that peak concentrations at the Topaz site are attributable to only cruise and ferry sources. This assumption may be applicable for 1-hour SO_2, since marine sources are the only major source in the region; however, for other pollutants such as $PM_{2.5}$ and NO_2 which are largely produced by vehicular traffic, it may be more appropriate to compare peak concentrations taking background into account. Also, for longer time periods SO_2 sources such as diesel buses operating in the vicinity of Topaz may also contribute and should not be overlooked.

The CALPUFF model underestimated maximum 1-hour and 24-hour concentrations for all pollutants at Topaz when the addition of background was not taken into consideration. When background is considered, the model then overestimates maximum 1-hour NO_2. Unlike SO_2 and $PM_{2.5}$ estimates, there is greater uncertainty associated with NO_2 concentrations, as NO_x must be converted to NO_2 using an external conversion method, as previously noted.

The FAC statistic reported in Table 5 is the ratio of predicted to observed (P/O) concentrations, calculated by dividing the predicted by the observed (the agreement of modeled to measured concentrations of air quality models is often compared by assessing if the agreement is within a factor of 2, or FAC 0.5–2.0, depending on whether the model under or over-predicts concentrations, respectively). This statistic can be calculated for individual predicted/observed pairs, or for the percentage of the entire dataset. In the case of maximum 1-hour concentrations, the model is predicting within a factor of 2 for SO_2 and NO_2 with and without the addition of background, but not for $PM_{2.5}$ in either case. For maximum 24-hour concentrations, when background is taken into

Table 6
Comparison of 1-hour and 24-hour concentrations of NO_2, $PM_{2.5}$ and SO_2 measured at MAML and Topaz Station (May 30–August 24, 2009).

Pollutant	1-hour ($\mu g\,m^{-3}$)						24-hour ($\mu g\,m^3$)					
	Range	99th	95th	90th	Avg.	SD	Range	99th	95th	90th	Avg.	SD
MAML Monitor (James Bay)												
NO_2	0–79	63	43	34	17	13	3–40	34	29	27	17	8
$PM_{2.5}$	1–32	20	16	14	8	4	2–17	17	15	13	8	4
SO_2	0–448	248	49	14	12	41	1–122	103	55	34	12	22
Topaz Station												
NO_2	0–100	65	46	36	19	14	5–42	41	36	31	19	9
$PM_{2.5}$	0–30	21	15	12	6	5	1–17	16	12	10	6	3
SO_2	1–170	61	24	12	6	12	1–28	25	18	12	6	5

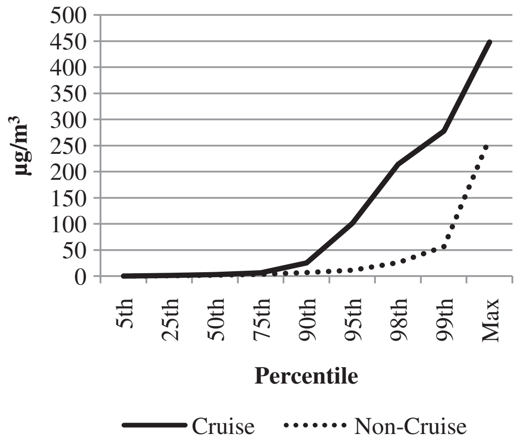

Fig. 7. Frequency distribution of 1-hour SO_2 measured by MAML (2009).

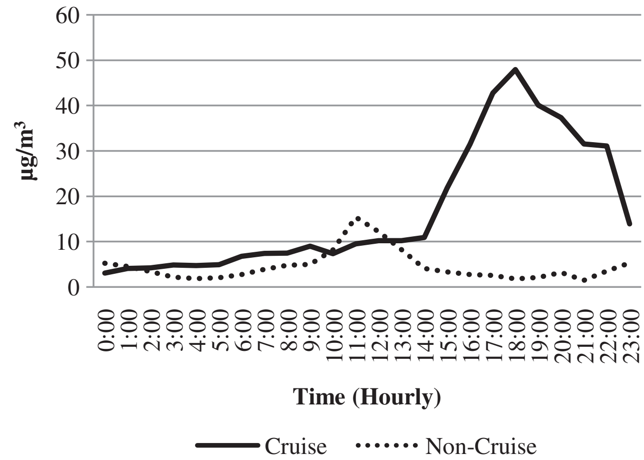

Fig. 9. Hourly average SO_2 concentrations measured by MAML (2009).

consideration, the model predicts within a factor of 2 for all pollutants. In all cases, with the exception of 1-hour NO_2, the model underpredicts.

Underprediction of $PM_{2.5}$ and NO_2 is logical, as there are significant sources of these contaminants near Topaz that were not modeled. The underprediction of SO_2 is more interesting to consider and suggests there is potential that one or more of the modeling assumptions were not accurate. Given the dominance of the cruise ship emission levels, possible sensitive modeling assumptions include the consistent application of 1.6% sulphur in fuel (higher sulphur marine fuel is available in the region and some ships may have used higher sulphur fuel) and time-in-mode/ engine power during manoeuvring adjacent to the berths. For instance, the 10-minute average manoeuvring time underestimates occasions of adverse weather conditions when ships may take up to 45 min to safely approach the dock.

A brief modeling exercise was undertaken to evaluate the potential of emissions originating from an active shipping lane off the coast of Victoria in the Strait of Juan de Fuca (approximately 2.5 km offshore) to impact concentrations at Topaz. Estimated maximum hourly and average emission rates of offshore vessels were compared to cruise ships in James Bay. Maximum hourly emission rates are lower for offshore vessels and are not likely to cause high 1-hour ambient concentrations in the community; however, offshore emissions likely do influence longer-term and background concentrations in the study area.

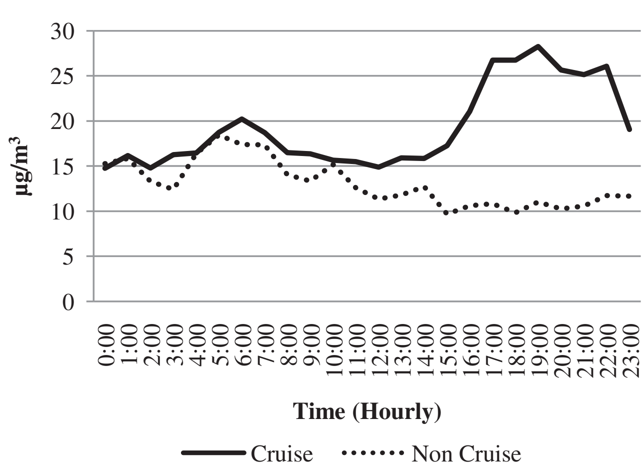

Fig. 8. Hourly average NO_2 concentrations measured by MAML (2009).

4.3. MAML continuous monitoring in James Bay

During the 2009 monitoring period (May 30–August 24), no existing BC Provincial or Canadian air quality objectives were exceeded at either the MAML location or at the Topaz Station (Table 6). Maximum hourly and daily concentrations of SO_2 were higher at the MAML site than at the Topaz Station (2.7 and 2.8 times higher, respectively). The lowest level of a 1-hour guideline proposed by the US Environmental Protection Agency for SO_2 (200 $\mu g\, m^{-3}$) was exceeded on 1.4% of 1-hour periods (50 out of 1962 hours with valid data) in James Bay and once (1 hour out of 1978) at Topaz Station. The WHO 24-hour guideline for SO_2 (20 $\mu g\, m^{-3}$) was exceeded 16 percent of days (14 out of 87) at the MAML site and 3.5 percent of days at Topaz (3 out of 87).

Hourly average NO_2 and SO_2 levels were always higher on days with cruise ships in port than on days without at both MAML (Figs. 6 and 7) and at Topaz (graphs not shown). Diurnal patterns clearly indicate cruise ships as the dominant source, with highest peaks occurring between 17:00 and 01:00 (Figs. 8 and 9). $PM_{2.5}$ was generally similar on days with cruise ships in port and on days without at both sites.

Very short-term SO_2 concentrations (10-minute) at the MAML site reached up to 599 $\mu g\, m^{-3}$. The WHO 10-minute guideline for SO_2 is 500 $\mu g\, m^{-3}$, and was exceeded three times (3 out of 11,678 10-minute periods). These maximum concentrations were all associated with the arrivals of cruise ships.

5. Discussion and conclusions

This study presents new data on the impacts of cruise ship emissions on local air quality. Given the intermittent but predictable schedule of cruise ship arrivals and the absence of other large SO_2 sources, episodes of high SO_2 concentrations in the local area (less than 1 km from port) and in the region (3.5 km from port) can be clearly attributed to cruise ship emissions. Few studies have yet to examine the contribution of marine emissions to local community level air concentrations. While some studies focus on commercial and passenger shipping in general, hardly any estimate levels specifically from cruise ship vessels.

Mölders et al. (2010) model the impact of ship emissions on air quality in southern Alaska. Their research, which includes but is not specific to cruise ship emissions, finds increased NO_x and SO_2 within 30 km of sea lanes and significant impacts of PM_{10} localized to the vicinity of port cities. Vutukuru and Dabdub (2008) model the effects of ship emissions on ozone and PM concentrations in the

South Coast Air Basin of California using the most recent North American marine emissions inventory by Corbett et al. (2007). They find increased concentrations of ozone and PM at inland locations and conclude based on future 2020 modeling scenarios that ships could be a major source of air pollution in the region. Isakson et al. (2001) measure particulate and gaseous pollution from ships in Göteborg, Sweden and find mean concentrations of NO_2 and SO_2 within an average distance of 800 meters from ships to be 12 and 4.5 $\mu g\,m^{-3}$ above urban background levels. Lu et al. (2006) measure, identify and characterize ship plumes in Vancouver, Canada. They find increases in SO_2 above 9 ppbv (approximately 24 $\mu g\,m^{-3}$) lasting a few hours associated with ship plumes, accompanied by increased NO, NO_x, CO, VOCs, particulates, black carbon and $PM_{2.5}$. Saxe and Larsen (2004) include cruise ships amongst other marine vessel types in their modeling study of air pollution in the Danish ports of Elsinore, Copenhagen and Køge. Overall, their modeling results show ship emissions do not significantly contribute to SO_2 in populated areas. Cruise ships in this study are assumed to be using fuel with only 0.5% sulphur content. They conclude that NO_x and PM_{10} emissions from ships may pose health problems to local communities and recommend local monitoring.

Although these studies do not isolate the impact from cruise ship emissions on local air quality, they highlight similar relationships between marine emissions and coastal air quality levels as seen in this study: concentrations in close proximity to ship sources are above background levels, concentrations associated with ship emissions remain elevated for some time during and after ship visits, and levels which meet or exceed air quality standards and objective may cause health concerns for local communities.

The Northwest Cruiseship Association and Alaska Department of Environmental Conservation conducted an air quality study in Juneau, Alaska due to concerns regarding possible air quality impacts from cruise ships (RTP Environmental Associates, 2002). This study monitored ambient concentrations of SO_2, NO_x, and $PM_{2.5}$ at three sites from May 2001 to January 2002. Maximum 3-hour and 24-hour SO_2 concentrations at all sites during the monitoring period were 113 ppb and 26 ppb, respectively (approximately 300 $\mu g\,m^{-3}$ and 70 $\mu g\,m^{-3}$). Based on sampling locations, findings suggest that SO_2 emissions from cruise ships were a primary contributor to these maximum SO_2 concentrations. Levels measured in James Bay agree with those measured in Juneau Alaska; the maximum 24-hour SO_2 concentration measured in Juneau falls within the range of 24-hour concentrations in our study (1–122 $\mu g\,m^{-3}$). Measurements from Alaska in 2001 were conducted in part as a baseline of concentrations to assess impacts of future growth, the installation of shoreside power and cleaner technologies adopted by the cruise ship fleet (RTP Environmental Associates, 2002).

The under-estimate of SO_2 concentrations from the CALPUFF model in 2007 (and the relatively high ambient SO_2 measurements from 2009) suggests that additional investigation may be needed to adequately characterize the emissions from cruise ships at and near berth. Additionally, representation of plume characteristics in the model deserves attention. In particular, building downwash was not simulated in the model. The highest near-source concentrations from traditional point sources (stack on a building) often result from building downwash. For cruise ships, simulation of downwash would require use of averaged dimensions representing the vessel structure as a building. Lastly, the use of the CALPUFF line source algorithm may not be the best choice and the alternative representation with a series of volume sources (spaced and configured to represent line source behaviour) should be considered.

Unlike Juneau, James Bay does not currently have shoreside power capabilities at the Ogden Point terminal to mitigate emissions. However, amendments to the International Maritime Organization (IMO) MARPOL Annex VI treaty to adopt a North American Emission Control Area (ECA) will require large marine vessels to use cleaner fuels and cleaner engine technologies (USEPA, 2010). The ECA will extend up to 200 nautical miles along the majority of the Canadian and US coastlines and will require ships operating within this area to use fuel not exceeding 1.0 percent sulphur by 2012, and 0.1 percent sulphur by 2015. In 2016 further requirements for NO_x after-treatment will come into effect. Findings from this study establish levels of emissions from cruise ships in a coastal community using fuel with a higher sulphur content (average 1.6%) than that of the new IMO ECA regulations. These findings are applicable to other areas worldwide where higher sulphur fuels may still be used by cruise ships, and also act as a baseline for comparison to future levels once the ECA is established.

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Appendix. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.atmosenv.2010.11.029.

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