SULFUR DIOXIDE LEVELS – 2011

JAMES BAY, VICTORIA, BRITISH COLUMBIA

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FOR: BRITISH COLUMBIA MINISTRY OF ENVIRONMENT

AUGUST 2012

Acknowledgements

The authors would like to acknowledge the significant contributions made by the following individuals, who provided data, reviewed, and commented on preliminary drafts of this report, which greatly improved the overall content and analyses:

Earle Plain, John Denisinger and Steve Sakiyama	British Columbia Ministry of Environment
Rebecca Penz and Al-Nashir Charania	Greater Victoria Harbour Authority
Marg Gardiner, Bob Vander Steen, and Tim Van Alstine	James Bay Neighbourhood Association
Christine Bender	Vancouver Island Health Authority
Donna Spalding	North West Cruise Ship Association
David Atkinson	University of Victoria, Geography

2011 data were collected at the Erie site under a cost sharing agreement between the British Columbia Ministry of the Environment and the Greater Victoria Harbour Authority.

The British Columbia Ministry of the Environment provided funding for the preparation of this report.

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1. Background and Summary of Results

1.1 Objectives

Since 2006, the British Columbia Ministry of Environment (BC MoE) has been working collaboratively with the Vancouver Island Health Authority (VIHA), the Greater Victoria Harbour Authority (GVHA), the James Bay Neighbourhood Association (JBNA), and researchers at the University of Victoria's Geography department, to investigate local air quality. Previous studies[1,2] have identified sulfur dioxide (SO_2) as an air pollutant of local concern associated with the use of sulfur-containing fuels by cruise ships, and established that short term peaks in the James Bay neighbourhood could exceed the current World Health Organization (WHO) 10-minute and 24-hour guidelines[3] for ambient SO_2 (500 $\mu g/m^3$ and 20 $\mu g/m^3$ respectively)[4]. While no current BC provincial guidelines were exceeded in James Bay in 2009, the maximum 1-hour average measured was 448 $\mu g/m^3$, near to the BC Level A and Canadian 'maximum desirable' guidelines of 450 $\mu g/m^3$. In accordance with recommendations made by the VIHA in 2010[5], the GVHA partnered with the BC MoE to establish a community monitoring site in the James Bay neighbourhood of Victoria, BC (on the roof of the Daniels Electronics Building on Erie Street, referred to as the Erie site or station in this report) to measure levels of SO_2 from 2011 to 2013. The Erie site was selected after considering the results of previous dispersion modelling work and also taking into account security, power, temperature controlled environment, and communications requirements.

Regulations limiting the sulfur content of the fuels used by cruise ships and other ocean going vessels are changing. Marine emissions to air in Canada currently fall under the International Maritime Organization (IMO) MARPOL Annex VI, which came into force on May 19, 2005. Specifically, fuel sulfur content is limited to 3.5 percent (35,000 ppm) globally, with a reduction to 0.5 percent (5,000 ppm) to take place January 1st, 2020, subject to a feasibility review to be completed no later than 2018. Annex VI also allows for the establishment of emission control areas (ECAs), within which fuel sulfur content is further limited. [6] Canada and the United States jointly applied to the IMO to establish the North

[1] James Bay Air Quality Study Phase I (Feb 2008) and James Bay Air Quality Study Phase II (Feb 2009). http://www.viha.ca/mho/air_quality.htm

[2] James Bay Air Quality Study Phase III: MAML – Mobile Air Monitoring Laboratory Data Collection Report – James Bay Air Quality Study June – August 2009 (Jan 2010). http://www.viha.ca/mho/air_quality.htm

[3] WHO (World Health Organization), 2006. WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide – Global Update 2005. Summary of risk assessment. Available at: http://www.who.int/phe/health_topics/outdoorair_aqg/en/

[4] The WHO guideline for SO_2 is relatively new and is substantially more restrictive than the Provincial Air Quality Objectives. MoE has begun the process of developing new provincial guidelines to reflect current standards and science but this process takes time. VIHA has used the WHO guideline in their health assessment as it better reflects current understanding of health effects of SO_2.

[5] Health Review and Response to James Bay Phase III Air Quality Monitoring (June 2010). http://www.viha.ca/mho/air_quality.htm

[6] International Maritime Organization. http://www.imo.org/OurWork/Environment/PollutionPrevention/AirPollution/Pages/The-Protocol-of-1997-%28MARPOL-Annex-VI%29.aspx

American ECA, which was adopted March 26th, 2010. Within the North American ECA, which covers navigable waters within approximately 200 nautical miles of the coast, sulfur content in marine fuel will be limited to 1 percent (10,000 ppm) as of August 1st 2012, and further limited to 0.1 percent (1,000 ppm) as of January 1st, 2015.

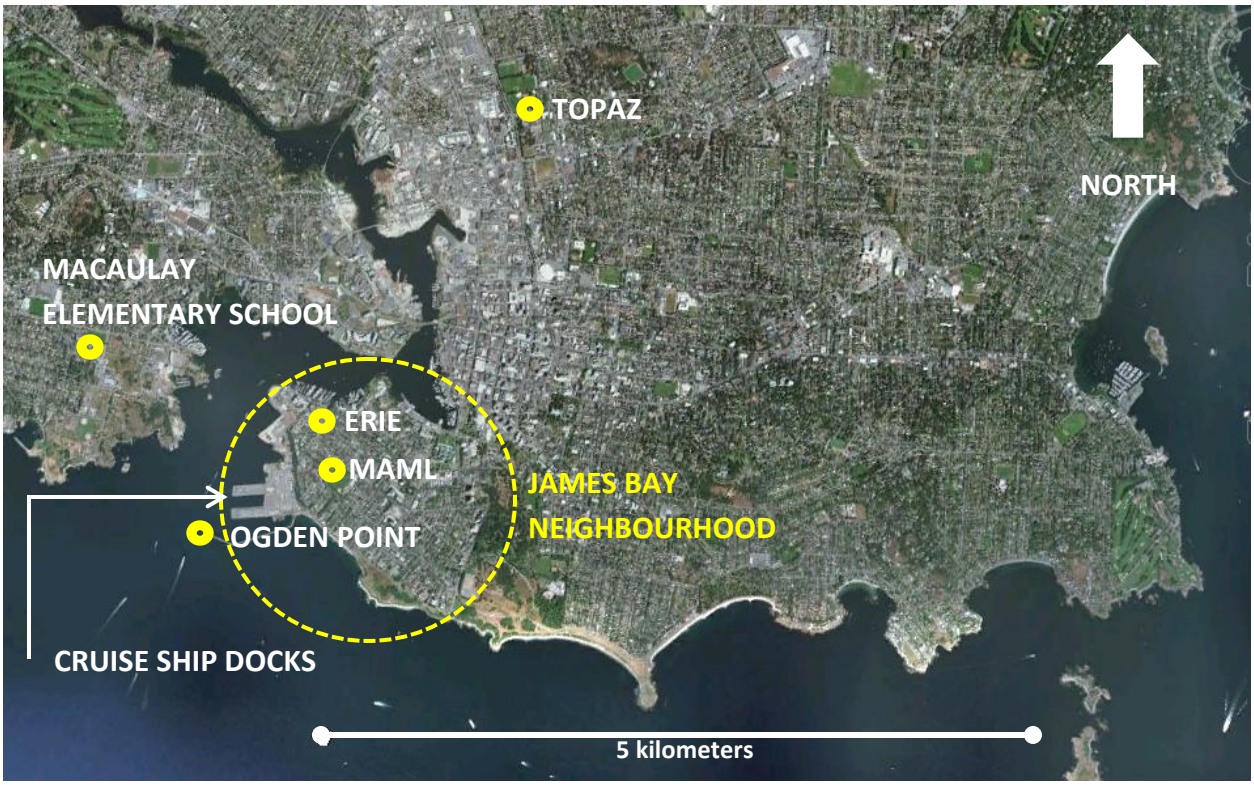
In addition to MARPOL Annex VI, emissions from cruise ships to air are also regulated under the Canadian Shipping Act[7]. Section 119-2 limits the amount of smoke of density level 2 to no more than 4 minutes (total aggregate time) in any 30 minute period, and otherwise (Section 119-1) must not emit smoke of density greater than 1. The measurement of smoke density is described in Section 118-1 and 118-2. No reported smoke density information for cruise ships approaching the Ogden Point terminal was identified for inclusion in this report.

This report provides an analysis of the data collected at the Erie station between April and October, 2011, in conjunction with data collected from the nearby BC MoE Topaz Station (2006 – 2011), the Mobile Air Monitoring Lab (MAML) location in James Bay (2009), Ogden Point wind station (2006 – 2011), and MacAulay Elementary School meteorological station (2006 – 2011) (see Figure 1 for locations). Results from analyses and dispersion modelling conducted for previous studies[8] are also incorporated.

[7] Vessel Pollution and Dangerous Chemicals Regulations (SOR/2012-69). http://laws-lois.justice.gc.ca/eng/regulations/SOR-2012-69/index.html

[8] Poplawski K, Setton E, McEwen B, et al (2011). Impact of cruise ship emissions in Victoria, BC, Canada. Atmospheric Environment 45, pp.824-833.

Figure 1. Study area



Specifically, this report addresses the following questions:

Ambient SO_2 levels and guidelines

- What are the cruise versus non-cruise period SO_2 concentrations at both Erie station and Topaz station (max 10-minute, hourly, 24-hour, period average)?
- How do ambient SO_2 measurements compare to current guidelines and objectives at both the Erie station and Topaz station?
- How often were SO_2 concentrations in the range of concern according to the Vancouver Island Health Authority SO_2 Health Risk Guide at either station?

Characteristics of SO_2 events at Erie station in 2011

- Do the diurnal SO_2 patterns at both sites link to cruise ship visits? Other sources?
- Do higher SO_2 concentrations relate to specific cruise ships?
- Are maximum SO_2 concentrations linked more closely to manoeuvring or to stationary cruise ship activity?
- Under what conditions were maximum SO_2 values experienced at either Erie station or Topaz station? How often did these conditions exist while cruise ships were in port (% of time)?
- What conditions existed on specific dates - May 23rd, June 18th, and July 30th - when resident complaints to the JBNA were noted?

Comparison of SO_2 levels - 2006 to 2011

- How do levels measured at Topaz (2006 – 2011), MAML (2009) and Erie (2011) compare?
- What factors influence the observed differences:
  - Were meteorological conditions experienced over the 2011 cruise ship season similar to previous years?
  - If anomalous, in what way (temperature, precipitation, wind speed, wind direction, atmospheric stability)?

Evaluation of the James Bay monitoring locations

- How representative are the MAML and Erie sites as indicators for SO_2 concentrations in the James Bay neighbourhood?

1.2 Summary of Results

Key findings of this report include:

- Elevated levels of SO_2 were clearly associated with the presence of cruise ships at both Erie and Topaz stations. Measured levels without cruise ships present suggest other minor sources of SO_2 are present in the region, but maximum levels do not reach the same peaks associated with the presence of cruise ships.
- In 2011, SO_2 levels were measured only at Topaz and Erie stations, so it is not possible to establish typical levels, peak levels, or frequency of peaks at other locations of interest in the study region. Additional monitoring is required to better understand the extent and nature of the impact from cruise ship emissions on local air quality.
- At Topaz station in 2011, no provincial, federal or WHO air quality guidelines were exceeded.
- At Erie station in 2011, the WHO air quality guideline for 24-hour average SO_2 levels (20 $\mu g/m^3$) was exceeded twice, and 2 hours were in the Vancouver Island Health Authority's health risk guide category of 'unhealthy for sensitive groups'.
- Peak levels measured at Topaz station in 2011 were the lowest on record since 2006 inclusive.
- Peak levels measured at Erie station in 2011 were much lower than those measured at MAML in 2009.
- The diurnal pattern of hourly average SO_2 levels at Erie station in 2011 is distinctly different that that measured at MAML in 2009 – seasonal average hourly levels were not elevated between evening arrivals and departures in 2011. This change in diurnal pattern was also evident (although not as obvious) at the Topaz site in 2011, compared to previous years (2006 to 2010).

Additional details are summarized here, and full data analyses are presented in each report section.

Ambient levels and guidelines: In 2011, cruise ships were present for 1,165 hours[9] between April 1st and October 31st.

Tables 1 and 2 provide a summary of measured SO_2 levels at Erie and Topaz sites. No Canadian or British Columbia government air quality guidelines were exceeded at either site in 2011 (see Tables 5, 6, 7 and 8 for more details on guidelines and measured levels). At the Erie site, two days (2% of days with cruise ships in port) had 24-hour average levels in excess of 20 $\mu g/m^3$, the current WHO guideline[10], and 2 hourly averages (0.2% of hours with cruise ships in port) were in the Vancouver Island Health Authority

[9] The number of hours with cruise ships in port was estimated for this report using the `first line and last line` times provided by the GVHA for the cruise ship season. Hours with more than one cruise ship in port were counted only once.

[10] WHO (World Health Organization), 2006. WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide – Global Update 2005. Summary of risk assessment. Available at: http://www.who.int/phe/health_topics/outdoorair_aqg/en/

health risk guide category[11] of "unhealthy for sensitive groups". No exceedences of the World Health Organization's guideline[3] for 10-minute average SO_2 (500 μg/m^3) were recorded.

Table 1. Summary of 10-minute, 1-hour, and 24-hour SO_2 levels for 2011

10-minute average	**Maximum** (μg/m^3)	**95th percentile** (μg/m^3)	**Top 40 *** (range μg/m^3)	**Exceedences**
Erie station	438	12.1	199 - 438	None
Topaz station	136	23.3	76 – 136	None
1-hour average	**Maximum** (μg/m^3)	**95th percentile** (μg/m^3)	**Top 20 **** (range μg/m^3)	**Exceedences**
Erie station – hours with cruise ships	235	49	97 - 235	0.2% in VIHA unhealthy 2% in VIHA moderate
Topaz station – hours with cruise ships	66	21	33 - 66	None
Erie station – hours without cruise ships	48	7	none in top 20	None
Topaz station – hours without cruise ships	31	7	none in top 20	None
24-hour average	**Maximum** (μg/m^3)	**95th percentile** (μg/m^3)	**Top 10 ***** (range μg/m^3)	**Exceedences**
Erie station – days with cruise ships	25.5	17.1	14.5 – 25.5	2%
Topaz station – days with cruise ships	17.4	8.4	7.7 – 17.4	None
Erie station – days without cruise ships	7.3	4.2	none in top 10	None
Topaz station – days without cruise ships	7.9	6.0	7.9	None

* 40 top 10-minute levels at Erie and Topaz occurred when cruise ships present

** 20 top 1-hour levels at Erie and Topaz occurred when cruise ships present

*** 10 top 24-hour levels at Erie occurred when cruise ships present; 9 of top 10 levels at Topaz occurred when cruise ships present, 1 occurred when no cruise ships were present at Ogden Point

Table 2. Seasonal average hourly SO_2 levels

Location	**Seasonal average** (μg/m^3)
Erie station – all hours with cruise ships	10
Topaz station – all hours with cruise ships	6
Erie station – all hours without cruise ships	2
Topaz station – all hours without cruise ships	3

Characteristics of events: The diurnal (time of day) pattern at the Erie site shows pronounced evening peaks in SO_2 levels associated with arrivals and departures of cruise ships, and less pronounced, but still obvious, peaks associated with cruise ships at dock during the day. SO_2 levels were lower at Topaz, and

[11] James Bay Sulphur Dioxide Monitoring Program 2011 – 2013 Health Risk Guide, available at: http://www.who.int/phe/health_topics/outdoorair_aqg/en/

only an evening peak associated with cruise ship arrivals is clearly discernible. Non-cruise days at both sites show low levels with little variation between hours.

The highest forty 10-minute average levels, highest twenty 1-hour average levels, and highest ten 24-hour average levels measured at Erie station occurred when cruise ships were present. The same was observed at Topaz, with the exception of one 24-hour average in the top ten, which occurred on a day with no cruise ships in port. While it is difficult to attribute elevated SO_2 levels to particular ships when more than one is in port, a variety of ships were associated with elevated levels when no other ships were nearby or at dock.

Hourly average levels measured at the Erie site depend on a complex relationship among numerous factors, especially wind direction in relation to the cruise ships and the monitoring sites; however, simple analyses suggest the following:

- Higher levels occurred during both daytime and evening hours, sometimes when only one ship was present, but not always when more than one ship was present.
- Higher levels were associated mainly with neutral atmospheric conditions (Pasquill Class D), but also occurred under slightly stable conditions (Pasquill Class E). Under neutral conditions, pollution plumes tend to disperse both vertically and horizontally, in a cone-shaped pattern, while under slightly stable conditions, plumes mix horizontally more readily than vertically.[12]
- Higher hourly average levels were measured at Erie and Topaz most often when winds were from 180^o to 250^o, which occurred about 50 percent of the time.
- Wind speed varied in relation to higher hourly average levels, with no clear relationship apparent, although wind direction may be an important factor to include in future analyses.

Three dates were provided by the JBNA to BC MoE for inclusion in this report, based on anecdotal information from residents on air quality impacts believed to be associated with cruise ship emissions. On two of the dates (May 23rd and July 30th), elevated SO_2 levels were measured at Erie site. On the third date (June 18th), Erie site recorded low levels of SO_2 but was not downwind at the time of the complaint, whereas the complaint originated in an area that was downwind of the terminal at the time.

Trends and Comparisons 2006 – 2011:

Topaz Site: At the Topaz site, the highest peak levels of hourly SO_2 when cruise ships were present were recorded in 2009, and the lowest peak levels were recorded in 2011. For hours without cruise ships present, average hourly levels at Topaz site were typically less than 5 $\mu g/m^3$ in all years. The diurnal pattern recorded at Topaz in each year (2006 to 2011 inclusive) shows reduced evening levels in 2011 compared to all years except 2007.

[12] Pages 246-247: Air pollution: measurement, modelling and mitigation. Tiwary A and Colls J. 3rd Ed. 2010. Routledge, NY.

No clear associations were seen between SO_2 levels and annual differences in temperature, precipitation, wind speed, and atmospheric stability. Other factors that may contribute to these differences include the number of ships arriving and departing concurrently, the type of ship(s) present, ship operations while at dock, and the sulfur content of the fuel burned. Data were not available to allow for evaluation of these factors.

Erie Site: SO_2 levels measured in the James Bay neighbourhood at the Erie site in 2011 when cruise ships were present were lower than those measured at the MAML site in 2009. In 2011, the diurnal pattern shows a distinct drop in average levels between evening arrivals and departures, unlike 2009 when levels dropped off gradually over the evening hours after arrivals. When cruise ships were not present, average hourly SO_2 levels were less than 10 $\mu g/m^3$, but still lower in 2011 than in 2009. No clear associations were seen between SO_2 levels and annual differences in meteorological characteristics, other than wind direction. In 2009, the MAML site was more frequently downwind of the Ogden Point terminal in comparison to Erie site in 2011, and if it is assumed that higher levels are associated with the monitoring site being more directly downwind, MAML may have more frequently recorded higher levels (although a similar change in levels and diurnal pattern was also observed at the Topaz site).

Representativeness of MAML and Erie sites: SO_2 levels have been measured only at two specific sites (MAML and Erie) in the James Bay neighbourhood. These sites are downwind of the cruise ships at Ogden Point more frequently than many other locations, and it is not unreasonable to expect that most other locations would not be more frequently impacted. Dispersion modelling conducted using meteorological data and the cruise ship schedule for 2007, along with some simple assumptions about manoeuvring time and the sulfur content of marine fuels suggests that the MAML and Erie sites are located in areas expected to more frequently experience higher SO_2 levels. However, the 2007 dispersion modelling and specific resident complaints and observations forwarded by the JBNA also suggest there are areas in addition to the Erie and MAML sites that may be impacted by cruise ship emissions, and additional monitoring is recommended to evaluate the extent and frequency of these impacts under varying meteorological conditions.

2. Methods

SO_2 data from the Erie station for 2011 were provided by BC MoE staff as hourly averages and 10-minute averages in parts per billion (ppb). BC MoE staff reported that the hourly averages had been corrected for instrument drift, but that the 10-minute data had not been corrected and could be +/- 0.5 ppb of the level provided. The raw 10-minute data were adjusted by adding 0.5 ppb to all readings; therefore, the 10-minute average levels of SO_2 may be overestimated by up to 2.6 $\mu g/m^3$ (for example, if raw data reported 1 ppb, the possible error would be +/- 0.5 ppb, the corrected value would be between 0.5 to 1.5 ppb, or 1.31 to 3.93 $\mu g/m^3$. If the actual value was 0.5 ppb (1.31 $\mu g/m^3$) then adding the error factor would overestimate the level by 2.62 $\mu g/m^3$). Both the 1-hour and 10-minute data were then converted to micrograms per cubic meter ($\mu g/m^3$) by multiplying the adjusted value by 2.62. Daily averages (midnight to midnight) were developed using the hourly averages, and were included in analyses only when 18 or more hours of data were available. All instruments were maintained and calibrated by MoE staff. Instrument calibration and audit records for Erie station are provided in Appendix A. Additional documentation is available on request to BC MoE.

Quality assured data for wind direction, wind speed, wind variation (sigmatheta), temperature, precipitation, and SO_2 at Topaz station for 2006 – 2011 were provided by BC MoE staff for Topaz station. Instrument descriptions and maintenance/calibration records are available on request to MoE.

Hourly atmospheric stability classes (Figure 2) were calculated using wind speed and sigmatheta at Topaz station, and solar radiation values from MacAulay school station, using a spreadsheet provided by BC MoE staff.

Figure 2. Atmospheric Stability Classes

Stability class	Definition	Stability class	Definition
A	very unstable	D	neutral
B	unstable	E	slightly stable
C	slightly unstable	F	stable

Table 2: Meteorological conditions that define the Pasquill stability classes

Surface windspeed		Daytime incoming solar radiation			Nighttime cloud cover	
m/s	mi/h	Strong	Moderate	Slight	> 50%	< 50%
< 2	< 5	A	A – B	B	E	F
2 – 3	5 – 7	A – B	B	C	E	F
3 – 5	7 – 11	B	B – C	C	D	E
5 – 6	11 – 13	C	C – D	D	D	D
> 6	> 13	C	D	D	D	D

Note: Class D applies to heavily overcast skies, at any windspeed day or night

Source: (http://en.wikipedia.org/wiki/Air_pollution_dispersion_terminology)

Ten-minute average wind speed (knots) and wind direction (degrees) at Ogden Point were provided by Greater Victoria Harbour Authority staff[13]. Ogden Point wind speeds were converted to meters per second (1 knot = 0.5144 meters per second), then used to develop hourly average speeds. Ogden Point ten-minute wind direction data were used to develop hourly average directions.

Cruise ship arrivals and departures (recorded as first line and last line) for 2006 to 2011 were provided by Greater Victoria Harbour Authority staff.

Dispersion modelling results, as described in Poplawski, Setton, McEwen et al (2011)[14], were used to assess the frequency of predicted hourly average SO_2 levels at 25 locations in the James Bay neighbourhood and surrounding area, and the associated potential representativeness of the Erie and MAML monitoring sites.

[13] Instrument descriptions are available on request to the Greater Victoria Harbour Authority.
[14] Poplawski K, Setton E, McEwen B, et al (2011). Impact of cruise ship emissions in Victoria, BC, Canada. Atmospheric Environment 45, pp.824-833.

3. Ambient SO_2 concentrations - 2011

Distributions of 10-minute average, 1-hour average, 24-hour average and seasonal hourly average levels of SO_2 are presented in Tables 3 and 4. Ten minute average levels ranged from <1 to 438 μg/m^3 at Erie station, and from 1 to 124 μg/m^3 at Topaz station. Hourly averages when cruise ships were present ranged from <1 to 235 μg/m^3 and <1 to 66 μg/m^3 at Erie and Topaz stations respectively, compared to <1 to 48 μg/m^3 and 1 to 31 μg/m^3 on hours without cruise ships. Average 24-hour levels ranged from 1 to 17 μg/m^3 at Topaz station and 1 to 21 μg/m^3 at Erie station on days with cruise ships present, and were lower on days without cruise ships present: 1 to 8 μg/m^3 at Topaz station and <1 to 17 μg/m^3 at Erie station.

Measured levels without cruise ships present suggest other sources of SO_2 are present in the region, but levels do not reach the same peaks associated with the presence of cruise ships.

In general:

- 10-minute average levels were higher at Erie station than at Topaz station 5 percent of the time. This reflects the very short duration but high peaks of SO_2 in the James Bay neighbourhood associated with cruise ship activity.

- 1-hour average levels were higher at Erie station on hours with cruise ships than on hours without 75 percent of the time.
- 1-hour averages were higher at Erie station than at Topaz station on hours with cruise ships in port 75 percent of the time
- 1-hour averages when no cruise ships were in port were similar at Erie station and Topaz station; higher levels observed at Erie station at 98th percentile and higher represent hours close to arrivals and departures of cruise ships but not classified as having cruise ships actually docked.

- 24-hour average[15] levels were higher at Erie station on days with cruise ships than on days without 75 percent of the time.
- 24-hour average levels were higher at Erie station than at Topaz station on days with cruise ships in port 50 percent of the time.
- 24-hour averages were very similar but always slightly lower at Erie station that at Topaz station on days without cruise ships, suggesting there may be more small sources of SO_2 in the Topaz area, such as diesel-fuelled vehicles.

[15] 24-hour averages were calculated only for days with 18 hours or more of data.

SO_2 levels were below current Provincial Ambient Air Quality Objectives (see Tables 6, 7 and 8). Two 24-hour averages of 24μg/m^3 and 26μg/m^3 (2% of days with cruise ships in port) exceeded the World Health Organization guideline of 20μg/m^3. In addition, two 1-hour averages (0.2 % of hours with cruise ships in port) and twenty 1-hour averages (2% of hours with cruise ships in port) were in the Vancouver Island Health Authority health risk guide categories of 'unhealthy for sensitive groups' and 'moderate' , respectively (Tables 5 – 8).

Table 3. Distribution of SO_2 levels (10-minute, 1-hour and 24-hour)- 2011

	10-minute* (μg/m^3)		1-hour (μg/m^3)				24-hour** (μg/m^3)			
	all	all	**Cruise**		No Cruise		**Cruise**		No Cruise	
Percentile	Erie	Topaz	**Erie**	**Topaz**	Erie	Topaz	**Erie**	**Topaz**	Erie	Topaz
5	<1	1	**< 1**	**< 1**	< 1	1	**1**	**1**	< 1	1
25	<1	2	**1**	**1**	< 1	1	**2**	**2**	1	2
50	2	4	**3**	**3**	1	3	**4**	**3**	1	3
75	3	7	**8**	**6**	2	4	**7**	**5**	2	4
90	7	9	**22**	**13**	5	6	**14**	**8**	3	5
95	12	11	**49**	**21**	7	7	**16**	**8**	3	6
96	15	12	**58**	**26**	8	8	**18**	**9**	4	6
97	19	14	**74**	**29**	9	8	**18**	**10**	4	6
98	30	18	**93**	**33**	12	10	**19**	**11**	4	7
100	438	124	**235**	**66**	48	31	**21**	**17**	7	8
Total intervals	27,876	30,817	1,165	1,165	3,970	3,970	105	105	109	109
Total with valid data	26,578 (95%)	27,793 (90%)	1,035 (89%)	1,002 (86%)	2,809 (71%)	3,496 (88%)	102 (97%)	94 (90%)	95 (87%)	102 (94%)

*0.5 ppb (1.3 μg/m^3) was added to all raw 10-minute data to account for possible instrument drift over time – these values may be overestimated by as much as 2.6 μg/m^3 and should be considered a 'worst case scenario'.
** Distribution of 24-hour averages includes only days with data for 18 or more hours (75% or higher data completeness).

Table 4. Seasonal hourly average SO_2 levels – April to October 2011 inclusive

Erie Cruise (μg/m^3)	Erie No cruise (μg/m^3)	Erie All (μg/m^3)	Topaz Cruise (μg/m^3)	Topaz No cruise (μg/m^3)	Topaz All (μg/m^3)
10	2	4	6	3	4

Table 5. 10-minute average levels at or above guidelines

Guideline	Level (μg/m^3)	Erie Station	Topaz Station
World Health Organization	500	0	0

Table 6. 1-hour average levels at or above guidelines

Guideline	Level ($\mu g/m^3$)	Erie Cruise	Topaz Cruise	Erie No Cruise	Topaz No Cruise
VIHA health risk guide - good	<=92	1,013 (98%)	1,002 (100%)	2,809 (100%)	3,496 (100%)
Moderate	93 - 197	20 (2%)	0	0	0
Unhealthy for sensitive groups	198 - 485	2 (0.2%)	0	0	0
Unhealthy	>485	0	0	0	0
Canada – max desirable	450	0	0	0	0
Canada – max acceptable	900	0	0	0	0
BC level A	450	0	0	0	0
BC level B	900	0	0	0	0
BC level C	900-1300	0	0	0	0

Table 7. 24-hour average levels at or above guidelines

Guideline	Level ($\mu g/m^3$)	Erie Cruise	Topaz Cruise	Erie No Cruise	Topaz No Cruise
World Health Organization	20	2 (2%)	0	0	0
Capital Regional District	125	0	0	0	0
Canada – max desirable	150	0	0	0	0
Canada – max acceptable	300	0	0	0	0
Canada – max tolerable	800	0	0	0	0
BC level A	160	0	0	0	0
BC level B	260	0	0	0	0
BC level C	360	0	0	0	0

Table 8. Annual hourly average levels at or above guidelines

Guideline	Level ($\mu g/m^3$)	Erie Cruise	Topaz Cruise	Erie No Cruise	Topaz No Cruise
Canada – max desirable	30	0	0	0	0
Canada – max acceptable	60	0	0	0	0
BC level A	25	0	0	0	0
BC level B	50	0	0	0	0
BC level C	80	0	0	0	0

Note: averages were calculated using hours only from April 1st to October 31st and would be lower if all hours in 2011 were included.

4. Characteristics of SO_2 events - 2011

4.1 Diurnal patterns - 2011

In 2011, diurnal (time of day) patterns at Erie station for hours with cruise ships in port showed a clear association with cruise ship activity, particularly evening arrivals and departures, but also notably during mid-day hours (Figure 3). At Topaz station (Figure 4), the most prominent peak in SO_2 levels occurred at 7pm, coinciding with cruise ship arrivals, but was much lower than the peaks observed at Erie station. Modest elevation of SO_2 levels during the mid-day hours at Topaz station on days with cruise ships is also present.

SO_2 levels were low and relatively constant for all times of day at both Erie stations and Topaz station when cruise ships were not present (Figures 2 and 3).

Figure 3. Diurnal SO_2 levels with and without cruise ships– Erie Station 2011

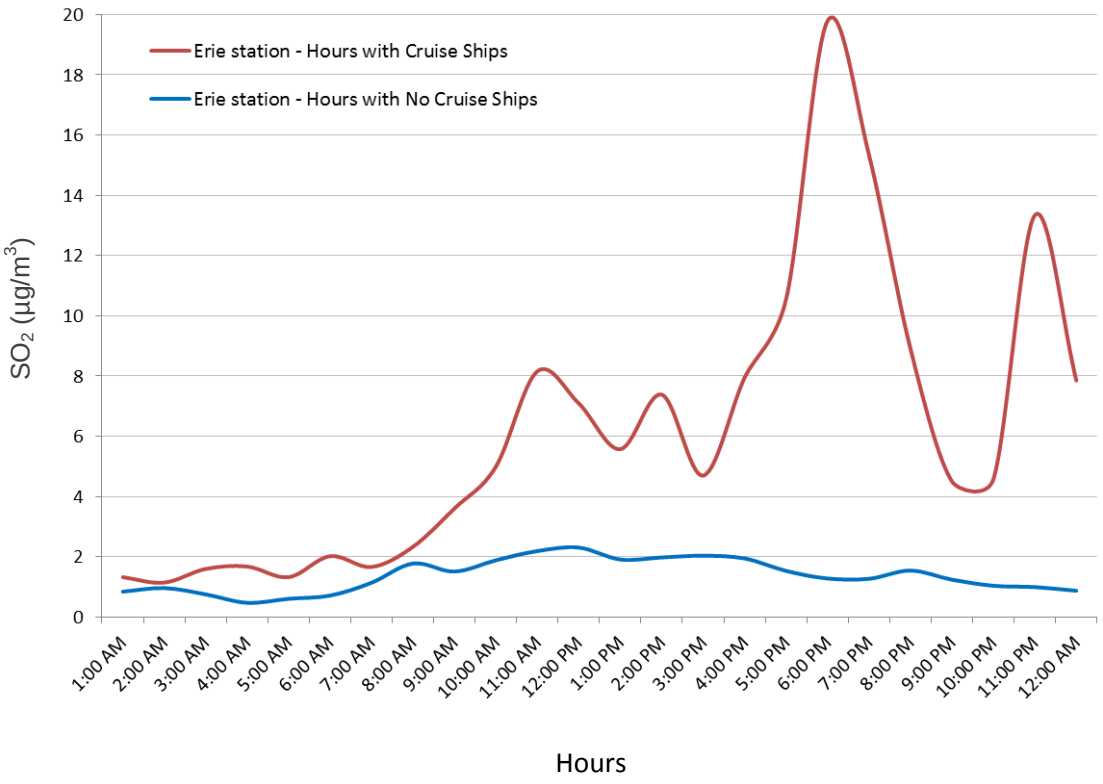
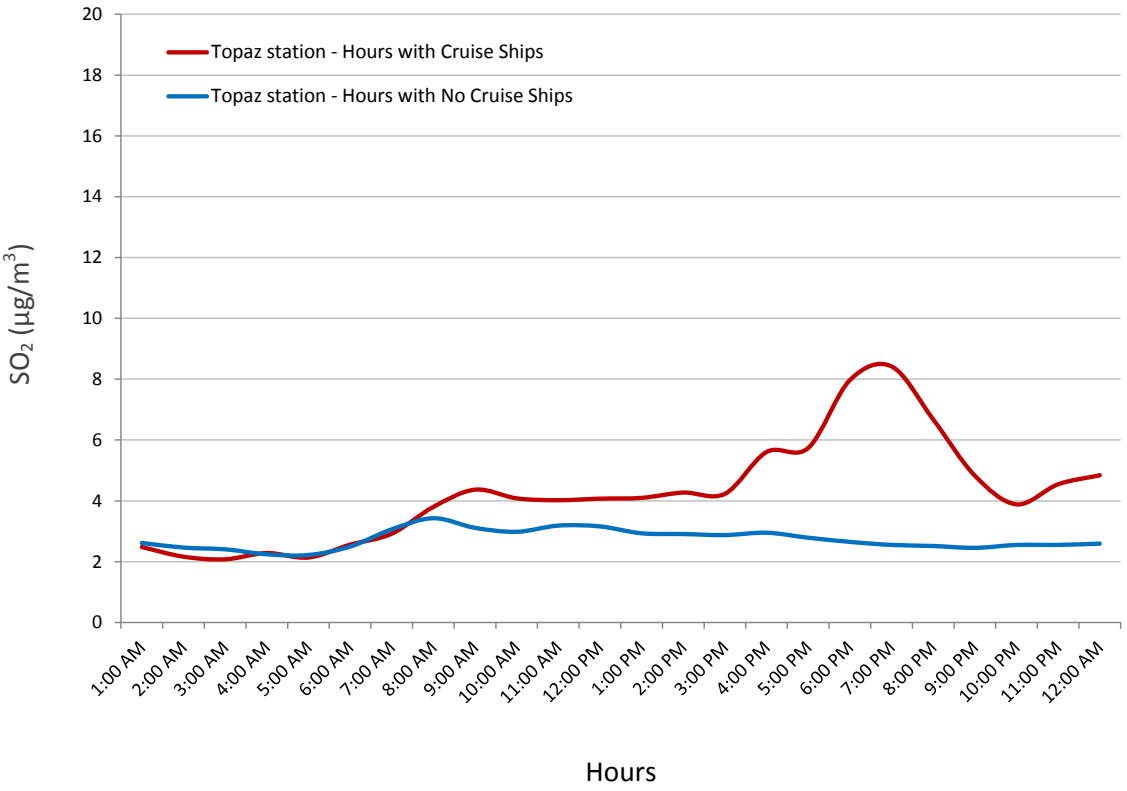


Figure 4. Diurnal SO_2 levels with and without cruise ships– Topaz Station 2011



4.2 Maximum events – 2011

The highest forty 10-minute averages at both Erie station (199 to 438 µg/m^3) and Topaz station (64 to 124 µg/m^3) occurred when cruise ships were present (Tables 9 and 10) and were associated with arrivals, departures, and ships at dock. When more than one cruise ship was nearby or present, it is not possible to attribute elevated levels to one particular vessel; however, elevated 10-minute average levels were measured when the following ships were alone at or near dock:

Erie station:

- Disney Wonder (May 2nd)
- Crystal Symphony (May 23rd, June 24th and 28th, Aug 15th)
- Carnival Spirit (July 11th, Aug 8th)
- Sea Princess (July 31st, Sept 5th)

Topaz station:

- Zaandam (May 14th)
- Norwegian Pearl (June 11th)
- Crystal Symphony (Aug 3rd)
- Sea Princess (Aug 26th)
- Seven Seas Navigator (Sept 9th)

The highest twenty 1-hour averages at both Erie station (97 to 235 μg/m^3) and Topaz station (33 to 66 μg/m^3) occurred when cruise ships were present (Tables 11 and 12) and were similar in nature to the 10-minute peaks – more often associated with arrivals and departures, but also occasionally with ships at dock during the day. A variety of cruise ships were present during the highest SO_2 1-hour events recorded; however, elevated levels were also recorded when the following ships were the only ones in or near port:

Erie station:

- Crystal Symphony (May 23rd, June 24th and 28th)
- Carnival Spirit (July 11th)
- Sea Princess (July 31st)

Topaz station:

- Westerdam (July 29th)
- Crystal Symphony (July 23rd)
- Seven Seas Navigator (Sept 9th)

The highest ten 24-hour averages at Erie station all occurred on days with cruise ship activity (Table 13) as did nine of the ten highest 24-hour averages as Topaz station (Table 14).

Table 9. 40 highest 10-minute average levels- Erie station 2011 (*__bold__ indicates highest 10 levels)

Date	SO_2 ($\mu g/m^3$)	Ship(s) present or nearby during peak levels	First Line	Last Line	Activity (+/- 1-hour)
2011-05-02 15:50	210	Disney Wonder	10:17	18:28	At dock
2011-05-16 22:50	212	Carnival Spirit	19:38	23:48	Departure
2011-05-16 23:00	**313**	Statendam	11:41	0:05	
2011-05-16 23:10	217				
2011-05-23 17:40	264	Crystal Symphony	9:37	23:50	At dock
2011-05-23 17:50	**329**				
2011-05-23 18:00	273				
2011-05-27 19:10	256	Westerdam	18:24	0:06	Arrival
2011-05-27 19:20	199	Golden Princess	19:05	23:52	
2011-06-09 15:50	220	Rhapsody of the Seas	9:04	18:01	Departure and arrival
2011-06-09 16:00	**304**	Amsterdam	11:41	22:57	
2011-06-09 16:10	**295**	Celebrity Infinity	17:36	23:44	
2011-06-09 16:20	264				
2011-06-09 16:40	205				
2011-06-09 16:50	259				
2011-06-24 10:10	240	Crystal Symphony	6:28	12:53	At dock and departure during day
2011-06-24 10:30	229				
2011-06-24 12:00	239				
2011-06-28 17:30	238	Crystal Symphony	9:45	23:46	At dock
2011-06-28 18:20	222				
2011-07-09 17:30	**283**	Norwegian Pearl	17:53	23:41	Arrival and departure
2011-07-09 23:20	**290**	Oosterdam	18:26	23:52	
		Sapphire Princess	18:03	0:07	
2011-07-11 22:40	250	Carnival Spirit	19:16	23:40	Departure
2011-07-11 22:50	264				
2011-07-31 17:40	230	Sea Princess	11:16	18:54	Departure
2011-07-31 17:50	243				
2011-07-31 18:00	220				
2011-08-06 18:10	229	Norwegian Pearl	17:38	23:37	Arrival
		Oosterdam	18:48	23:46	
		Sapphire Princess	18:44	23:59	
2011-08-08 18:40	204	Carnival Spirit	19:30	23:55	Arrival
2011-08-12 22:40	**366**	Golden Princess	18:15	23:42	Departure
2011-08-12 22:50	**438**	Westerdam	18:37	23:50	
2011-08-12 23:00	**288**				
2011-08-15 13:40	248	Crystal Symphony	9:41	23:42	At dock and arrival
2011-08-15 13:50	236	Carnival Spirit	19:26	23:55	
2011-08-15 19:50	**283**				
2011-08-15 20:00	214				
2011-08-25 16:50	224	Rhapsody of the Seas	8:35	17:58	Arrival and departure
		Celebrity Infinity	17:31	23:40	
2011-09-05 13:20	207	Sea Princess	6:59	15:08	At dock
2011-09-05 13:30	281				
2011-09-05 13:40	205				

Table 10. 40 highest 10-minute average levels- Topaz station 2011(*__bold__ indicates highest 10 levels)

Date	SO_2 ($\mu g/m^3$)	Ship(s) present or nearby at time of peak levels	First Line	Last Line	Activity (+/- 1-hour)
2011-05-14 08:30	76	Zaandam	7:32	23:30	Arrival
2011-05-14 18:00	66	Regatta	13:53	19:35	
2011-06-11 17:00	71	Norwegian Pearl	17:35	23:37	Arrival
2011-07-01 19:00	**105**	Golden Princess	19:00	23:50	Arrival
2011-07-01 19:10	70	Westerdam	19:17	0:07	
2011-07-22 23:00	67	Golden Princess	18:30	23:42	Departure
2011-07-22 23:10	73	Westerdam	18:47	0:28	
2011-07-29 18:10	69				
2011-07-29 18:20	**83**	Golden Princess	18:31	23:44	Arrival
2011-07-29 18:30	75	Westerdam	18:52	23:35	
2011-07-29 18:40	77				
2011-07-29 18:50	65				
2011-08-03 15:50	71				
2011-08-03 16:00	76				
2011-08-03 20:00	72	Crystal Symphony	9:29	0:06	At dock
2011-08-03 21:20	69				
2011-08-03 21:30	71				
2011-08-06 17:50	67				
2011-08-06 18:00	**103**	Norwegian Pearl	17:38	23:37	Arrival
2011-08-06 18:10	**83**	Sapphire Princess	18:44	23:59	
2011-08-06 18:50	74	Oosterdam	18:48	23:46	
2011-08-11 17:30	**98**	Rhapsody of the Seas	8:26	18:00	Arrival and departure
		Celebrity Infinity	17:33	23:42	
2011-08-12 17:40	65				
2011-08-12 17:50	**124**				
2011-08-12 18:00	**106**				
2011-08-12 18:10	**83**	Golden Princess	18:15	23:42	Arrival and departure
2011-08-12 18:20	**97**	Westerdam	18:37	23:50	
2011-08-12 18:30	73				
2011-08-12 23:20	80				
2011-08-18 15:20	71				
2011-08-18 15:30	80				
2011-08-18 15:40	73				
2011-08-18 15:50	70	Rhapsody of the Seas	8:31	18:09	At dock and arrival
2011-08-18 16:00	76	Amsterdam	12:02	23:02	
2011-08-18 16:10	74	Celebrity Infinity	17:38	23:50	
2011-08-18 16:20	72				
2011-08-18 16:50	73				
2011-08-19 17:30	83	Golden Princess	18:10	23:31	Arrival
		Westerdam	18:30	23:42	
2011-08-26 13:50	64	Sea Princess	6:48	14:12	Departure
2011-09-09 16:00	**86**	Seven Seas Navigator	7:43	17:00	Departure

Table 11. 20 highest 1-hour average levels- Erie station 2011

Date	SO_2 ($\mu g/m^3$)	Ship(s) present or nearby at time of peak levels	First Line	Last Line	Activity (+/- 1-hour)
2011-5-14 19:00	104	Zaandam Regatta Oosterdam	7:32 13:53 18:44	23:30 19:35 23:44	Arrival and departure
2011-5-16 23:00	97	Statendam Carnival Spirit	11:41 19:38	0:05 23:48	Departure
2011-5-23 18:00	165	Crystal Symphony	9:37	23:50	At dock
2011-5-27 20:00	157	Westerdam Golden Princess	18:24 19:05	0:06 23:52	Arrival
2011-6-9 16:00	125	Rhapsody of the Seas	9:04	18:01	At dock and arrival
2011-6-9 17:00	235	Amsterdam Celebrity Infinity	11:41 17:36	22:57 23:44	
2011-6-17 18:00	112	Westerdam Golden Princess	17:58 18:45	0:03 23:47	Arrival
2011-6-24 11:00	186	Crystal Symphony	6:28	12:53	At dock and departure
2011-6-24 12:00	179				
2011-6-28 18:00	119	Crystal Symphony	9:45	23:46	At dock
2011-7-9 18:00	162	Norwegian Pearl	17:53	23:41	Arrival and departure
2011-7-9 24:00	101	Sapphire Princess Oosterdam	18:03 18:26	0:07 23:52	
2011-7-11 23:00	100	Carnival Spirit	19:16	23:40	Departure
2011-7-31 18:00	142	Sea Princess	11:16	18:54	Departure
2011-8-6 19:00	114	Norwegian Pearl Sapphire Princess Oosterdam	17:38 18:44 18:48	23:37 23:59 23:46	Arrival
2011-8-12 23:00	224	Golden Princess Westerdam	18:15 18:37	23:42 23:50	Departure
2011-8-15 14:00	121	Crystal Symphony	9:41	23:42	At dock and arrival
2011-8-15 19:00	121	Carnival Spirit	19:26	23:55	
2011-8-18 17:00	116	Rhapsody of the Seas Amsterdam Celebrity Infinity	8:31 12:02 17:38	18:09 23:02 23:50	Arrival
2011-9-5 14:00	157	Sea Princess	6:59	15:08	At dock

Table 12. 20 highest 1-hour average levels- Topaz station 2011

Date	SO_2 ($\mu g/m^3$)	Ship(s)	First Line	Last Line	Activity (+/- 1-hour)
2011-7-1 19:00	34	Golden Princess	19:00	23:50	Arrival
2011-7-1 20:00	35	Westerdam	19:17	0:07	
2011-7-22 24:00	36	Golden Princess	18:30	23:42	Departure
		Westerdam	18:47	0:28	
2011-7-29 19:00	66	Westerdam	18:52	23:35	Arrival
2011-8-3 15:00	41				
2011-8-3 16:00	53				
2011-8-3 17:00	49	Crystal Symphony	9:29	0:06	At dock
2011-8-3 20:00	39				
2011-8-3 22:00	45				
2011-8-6 19:00	44	Norwegian Pearl	17:38	23:37	Arrival
		Sapphire Princess	18:44	23:59	
		Oosterdam	18:48	23:46	
2011-8-11 18:00	33	Rhapsody of the Seas	8:26	18:00	Arrival and departure
		Celebrity Infinity	17:33	23:42	
2011-8-12 18:00	54	Golden Princess	18:15	23:42	Arrival
2011-8-12 19:00	55	Westerdam	18:37	23:50	
2011-8-18 16:00	62	Rhaposdy of the Seas	8:31	18:09	At dock and arrival
2011-8-18 17:00	65	Amsterdam	12:02	23:02	
		Celebrity Infinity	17:38	23:50	
2011-8-19 18:00	41	Golden Princess	18:10	23:31	Arrival
		Westerdam	18:30	23:42	
2011-8-26 18:00	35	Westerdam	17:50	23:34	Arrival
2011-8-26 19:00	42	Golden Princess	18:12	23:48	
2011-9-3 19:00	34	Norwegian Pearl	17:32	23:28	Arrival
		Sapphire Princess	18:37	23:50	
		Oosterdam	18:52	23:37	
2011-9-9 16:00	51	Seven Seas Navigator	7:34	17:00	Departure

Table 13. 10 highest 24-hour average levels- Erie station 2011

Date	SO_2 ($\mu g/m^3$)	Ship(s)*	First Line	Last Line
2011- 5-23	17.8	Crystal Symphony	9:37	23:50
		Carnival Spirit	19:24	23:40
2011-6-9	18.7	Rhapsody of the Seas	9:04	18:01
		Amsterdam	11:41	22:57
		Celebrity Infinity	17:36	23:44
2011-6-24	19.8	Crystal Symphony	6:28	12:53
		Westerdam	17:48	0:06
		Golden Princess	18:27	23:44
2011-6-27**	13.6	Sea Princess	6:50	14:19
		Carnival Spirit	19:40	23:52
2011-6-28	14.5	Crystal Symphony	9:45	23:46
2011-7-9	21.0	Norwegian Pearl	17:53	23:41
		Sapphire Princess	18:03	0:07
		Oosterdam	18:26	23:52
2011-7-30**	13.6	Crystal Symphony	6:26	13:14
		Norwegian Pearl	17:40	23:44
		Oosterdam	19:13	23:56
		Sapphire Princess	18:30	0:07
2011-8-4	15.6	Rhapsody of the Seas	8:39	18:31
		Celebrity Infinity	17:56	0:08
		Amsterdam	19:06	23:55
2011-8-12	15.7	Golden Princess	18:15	23:42
		Westerdam	18:37	23:50
2011-8-15	17.7	Crystal Symphony	9:41	23:42
		Carnival Spirit	19:26	23:55
2011-8-18	15.5	Rhapsody of the Seas	8:31	18:09
		Amsterdam	12:02	23:02
		Celebrity Infinity	17:38	23:50

*Note: All ships present on the specified date are listed, but may not be associated with the peak 1-hour or 10-minute levels recorded on that date.

** Dates tied for 10th highest average.

Table 14. 10 highest 24-hour average levels- Topaz station 2011

Date	SO_2 ($\mu g/m^3$)	Ship(s)*	First Line	Last Line
2011-6-28	8.1	Crystal Symphony	9:45	23:46
2011-8-3	17.4	Crystal Symphony	9:29	0:06
2011-8-12	10.7	Golden Princess Westerdam	18:15 18:37	23:42 23:50
2011-8-26	10.3	Sea Princess Westerdam Golden Princess	6:48 17:50 18:12	14:12 23:34 23:48
2011-9-5	7.8	Sea Princess Carnival Spirit	6:59 20:10	15:08 0:08
2011-9-8	7.7	Celebrity Infinity	17:31	23:29
2011-9-9	12.0	Seven Seas Navigator Golden Princess Westerdam	7:34 18:24 18:24	17:00 23:25 23:41
2011-9-23	8.6	Westerdam Golden Princess	8:43 11:40	20:44 23:07
2011-9-24	8.0	Amsterdam Oosterdam	7:46 8:50	22:50 23:06
2011-9-29	7.9	**No ships**	---	---

*Note: All ships present on the specified date are listed, but may not be associated with the peak 1-hour or 10-minute levels recorded on that date

4.3 Factors influencing hourly levels - 2011

Additional analyses of factors associated with hourly average SO_2 levels suggest the following:

- Higher levels at Erie and Topaz stations occurred during both daytime and evening hours, sometimes when only one ship was present, but not always when more than one ship was present (Figures 5, 6, 7 and 8).
- Higher levels were associated mainly with neutral atmospheric conditions (Pasquill Class D), but also occurred under slightly stable conditions (Pasquill Class E) (Figures 9 and 10). Under neutral conditions, pollution plumes tend to disperse both vertically and horizontally, in a cone-shaped pattern, while under slightly stable conditions, plumes mix horizontally more readily than vertically.[16]
- Higher hourly average levels were measured at Erie and Topaz stations most often when winds were from 180° to 250°, which occurred about 50 percent of the time (Figures 11 and 12).

[16] Pages 246-247: Air pollution: measurement, modelling and mitigation. Tiwary A and Colls J. 3rd Ed. 2010. Routledge, NY.

- Wind speed varied in relation to higher hourly average levels, with no clear relationship apparent (Figures 13 and 14). Wind direction may be an important factor to include in future analyses.

In general, factors that may contribute to these differences include the number of ships arriving and departing concurrently, the type of ship(s) present, ship operations while at dock, and the sulfur content of the fuel burned. Data were not available to allow for evaluation of these factors.

Figure 5. Hourly SO_2 levels by time of day when cruise ships present – Erie 2011

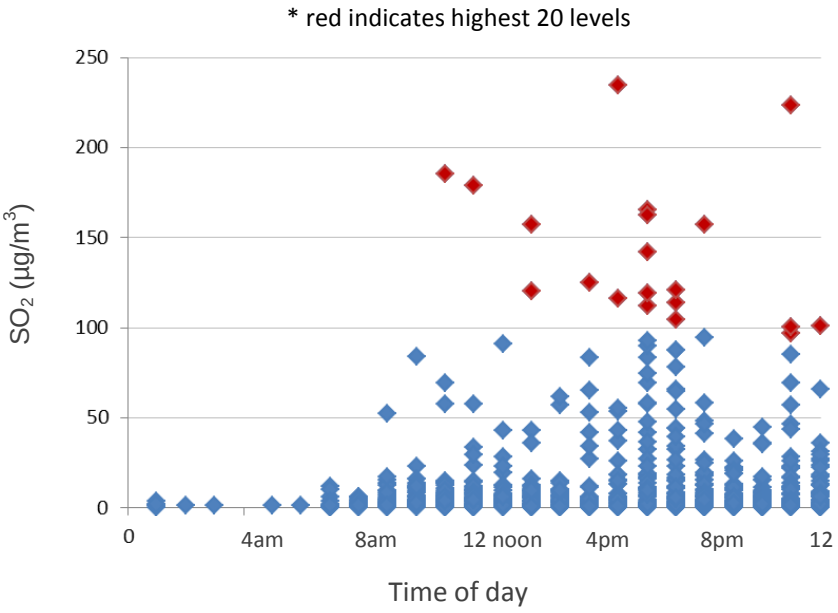


Figure 6. Hourly SO_2 levels by time of day when cruise ships present – Topaz 2011

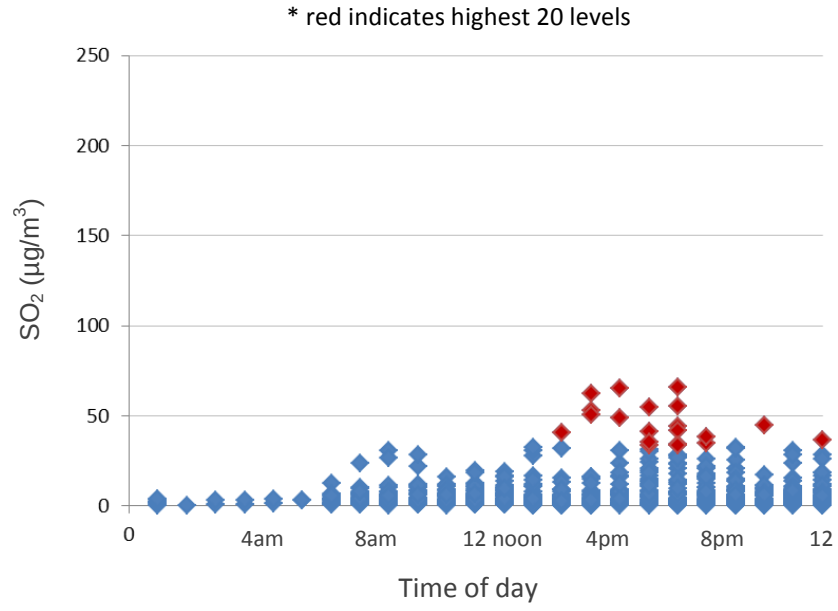


Figure 7. Hourly SO_2 levels by number of cruise ships present – Erie 2011

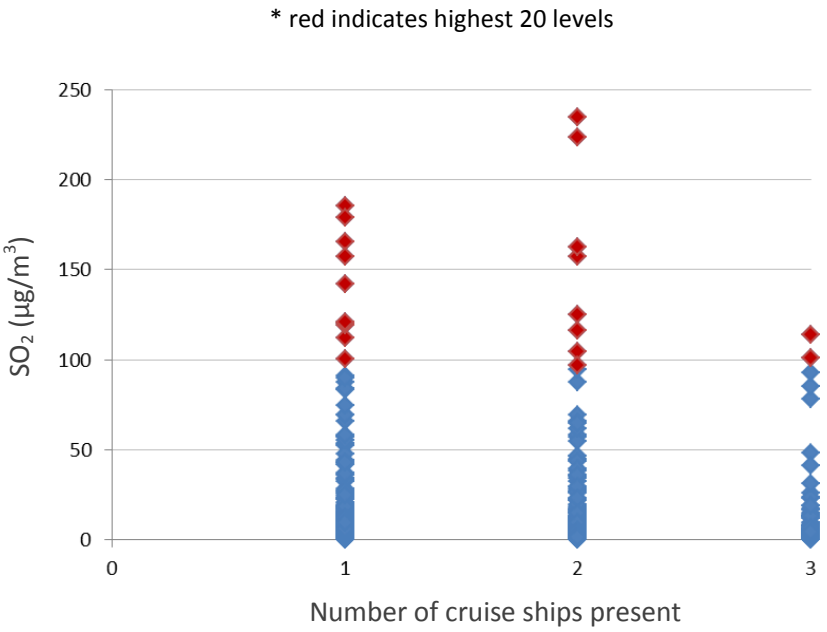


Figure 8. Hourly SO_2 levels by number of cruise ships present – Topaz 2011

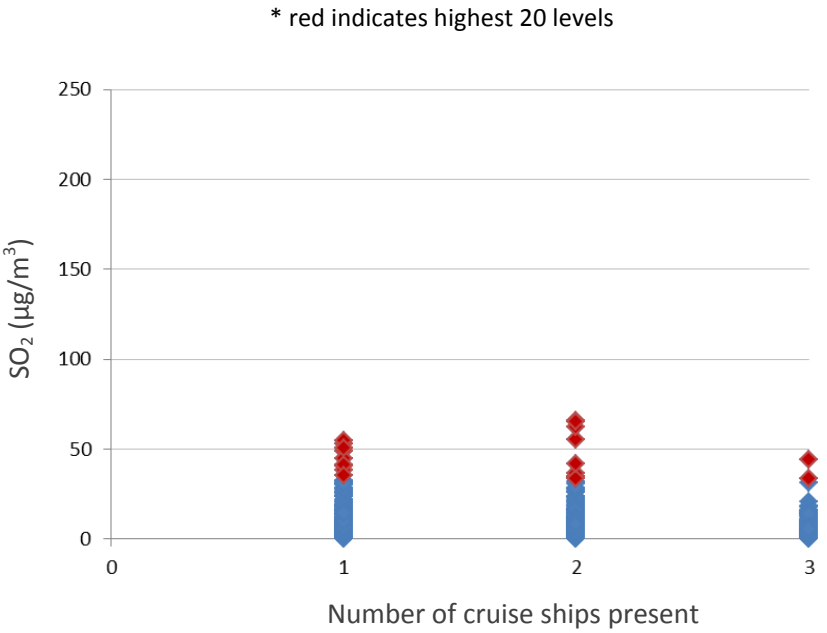


Figure 9. Hourly SO_2 levels by stability class at Topaz when cruise ships present – Erie 2011

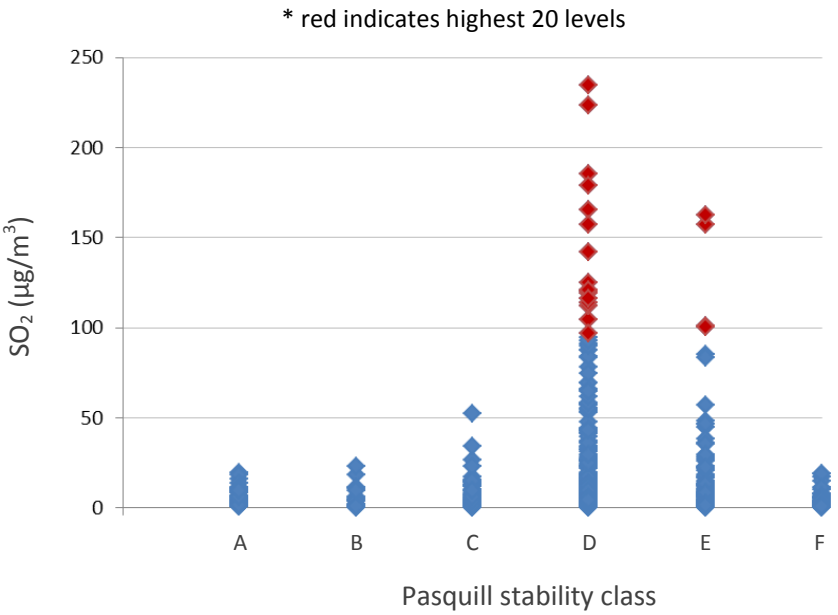


Figure 10. Hourly SO_2 levels by stability class at Topaz when cruise ships present – Topaz 2011

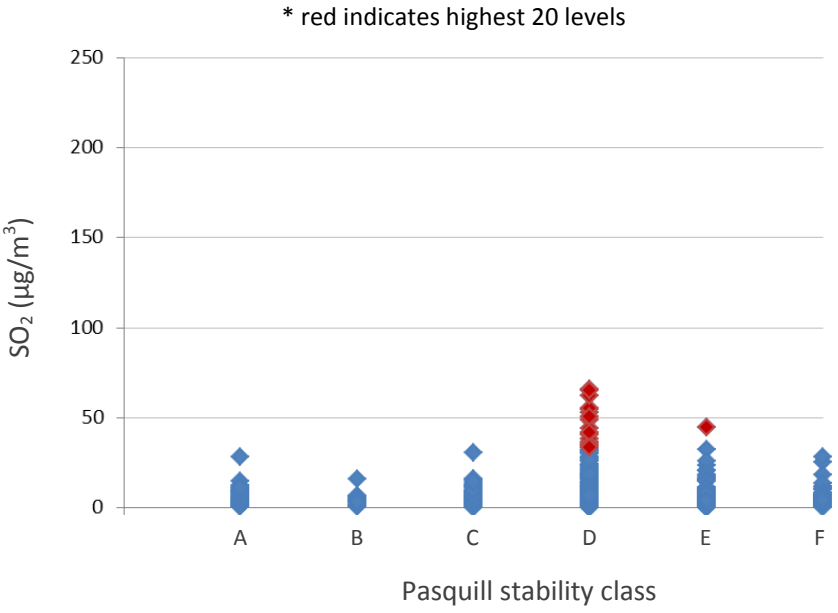


Figure 11. Hourly SO_2 levels by wind direction when cruise ships present– Erie 2011

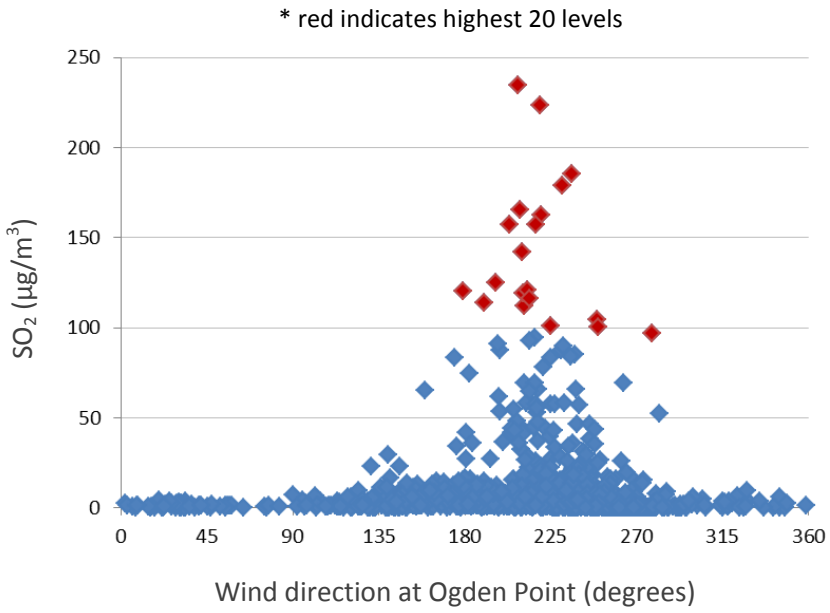


Figure 12. Hourly SO_2 levels by wind direction when cruise ships present – Topaz 2011

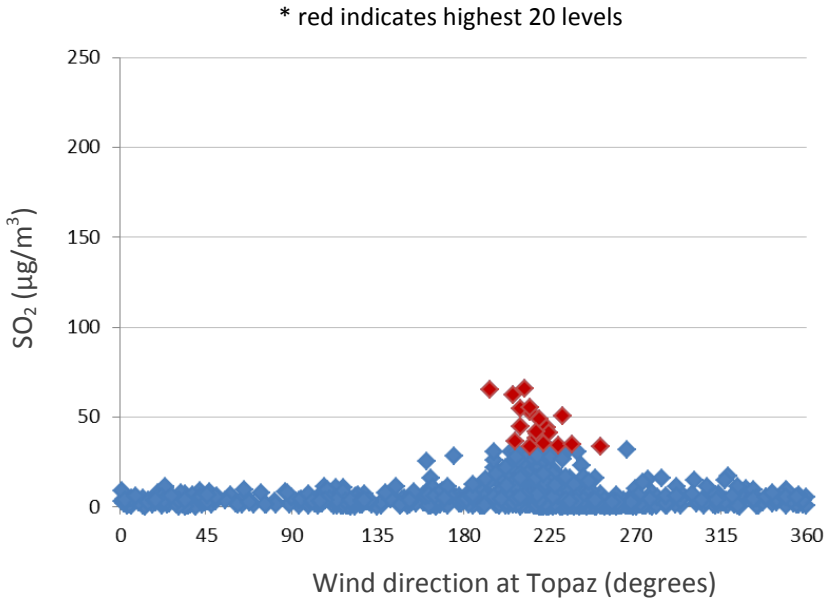


Figure 13. Hourly SO_2 levels by wind speed at Ogden Point when cruise ships present – Erie 2011

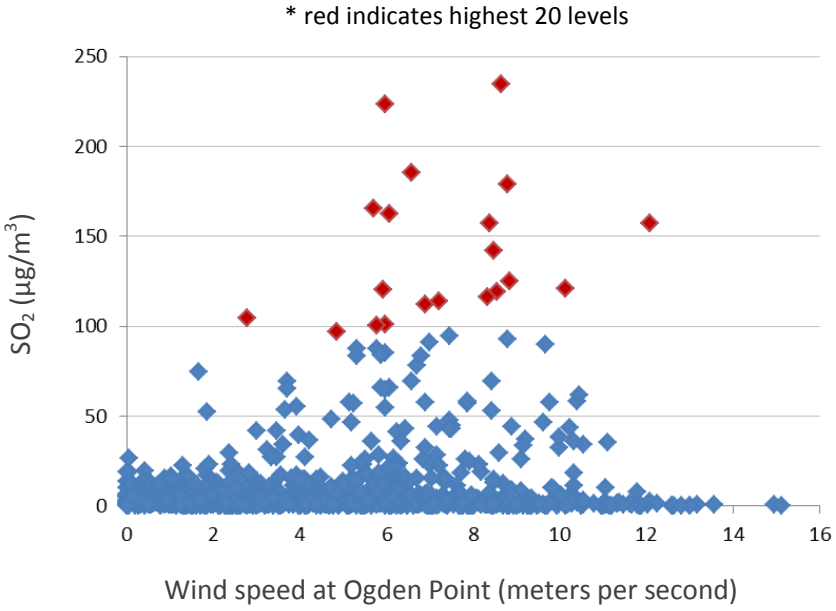
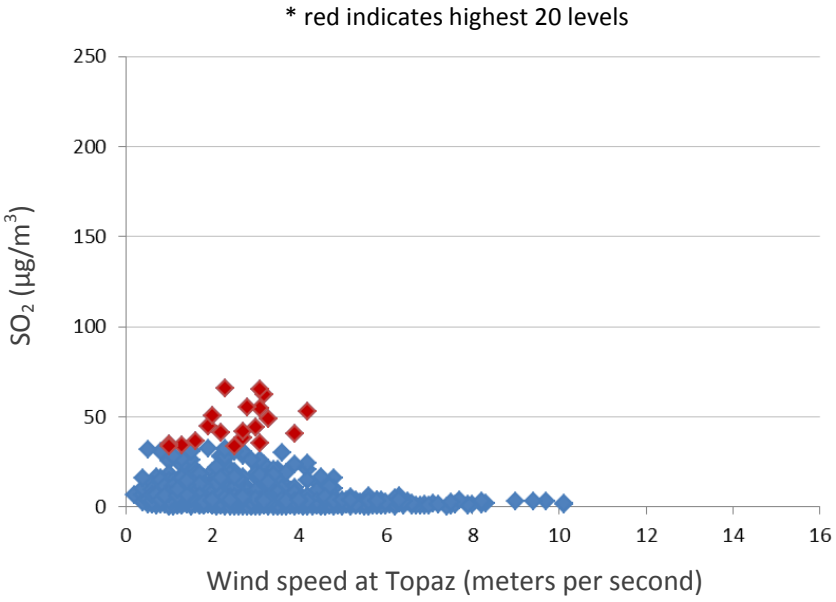


Figure 14. Hourly SO_2 levels by wind speed at Topaz when cruise ships present – Topaz 2011



4.4 Specific dates

Three dates associated with resident complaints were provided by the JBNA for further analysis – May 23rd, June 18th, and July 30th, 2011.

On May 23rd (Figure 15), Crystal Symphony was in port between 9am and midnight, and Carnival Spirit was in port between 7pm and midnight. At the Erie station, small peaks in 10-minute average SO_2 levels occurred in the morning and early afternoon, with significant peaks occurring between 4pm and 7 pm. A small peak was also recorded in the hour before departures. Wind direction was more southerly prior to the late afternoon peaks, and shifted back to more southwesterly in the evening. Wind speed was between 2.5 and 7.5 metres per second throughout the period. This day provides a good example of the daytime peaks associated with ships in port during the day, and specifically the Crystal Symphony. The 3rd highest 10-minute average, 4th highest 1-hour average, and 4th highest daily average of the season recorded at Erie station occurred on this day. Also of interest is the timing and location of a resident complaint – early evening, east of the terminal. While levels at Erie are low after approximately 6pm, wind direction shifts at this point from approximately 200° (Erie downwind) to 250°, which would move cruise ship plumes in a more easterly direction toward the complaint area. This suggests that elevated levels can occur at locations other than the Erie site depending on wind direction, which would not necessarily be reflected in the Erie station data.

On June 18th (Figure 16), the Norwegian Pearl, Sapphire Princess and Oosterdam were in port between approximately 6pm and midnight. Wind speed was generally above 7.5 metres per second in the evening and consistently from almost west. 10-minute average SO_2 levels were not elevated at either the Erie station or the Topaz station. A small peak at Erie station was observed just prior to arrivals. Again, winds were generally from 250° which would tend to move the cruise ship plumes in a more easterly direction and so higher levels than were measured at Erie site may have occurred.

On July 30th (Figure 17), Crystal Symphony was in port from approximately 6am to 2pm, and Norwegian Pearl, Sapphire Princess and Oosterdam were in port between approximately 6pm and midnight. Winds were southwesterly and between 2.5 and 7.5 metres per second during the morning. Moderately high peaks of 10-minute average SO_2 were recorded during the morning, when resident complaints were registered. Winds then shifted to a more southerly direction and picked up to 10 meters per second and higher between noon and 4pm, and SO_2 levels dropped to background levels at both Erie and Topaz stations. By 5pm, just before the arrival of Norwegian Pearl, Sapphire Princess and Oosterdam, wind speed slowly dropped to a low of about 2 metres per second by 11pm, and wind direction became more variable, generally shifting between west and south over the evening. Small peaks in 10-minute average SO_2 were recorded around arrival and departure times. The 10th highest daily average of the season recorded at Erie station occurred on this day (tied with June 27th).

Figure 15. May23rd, 2011

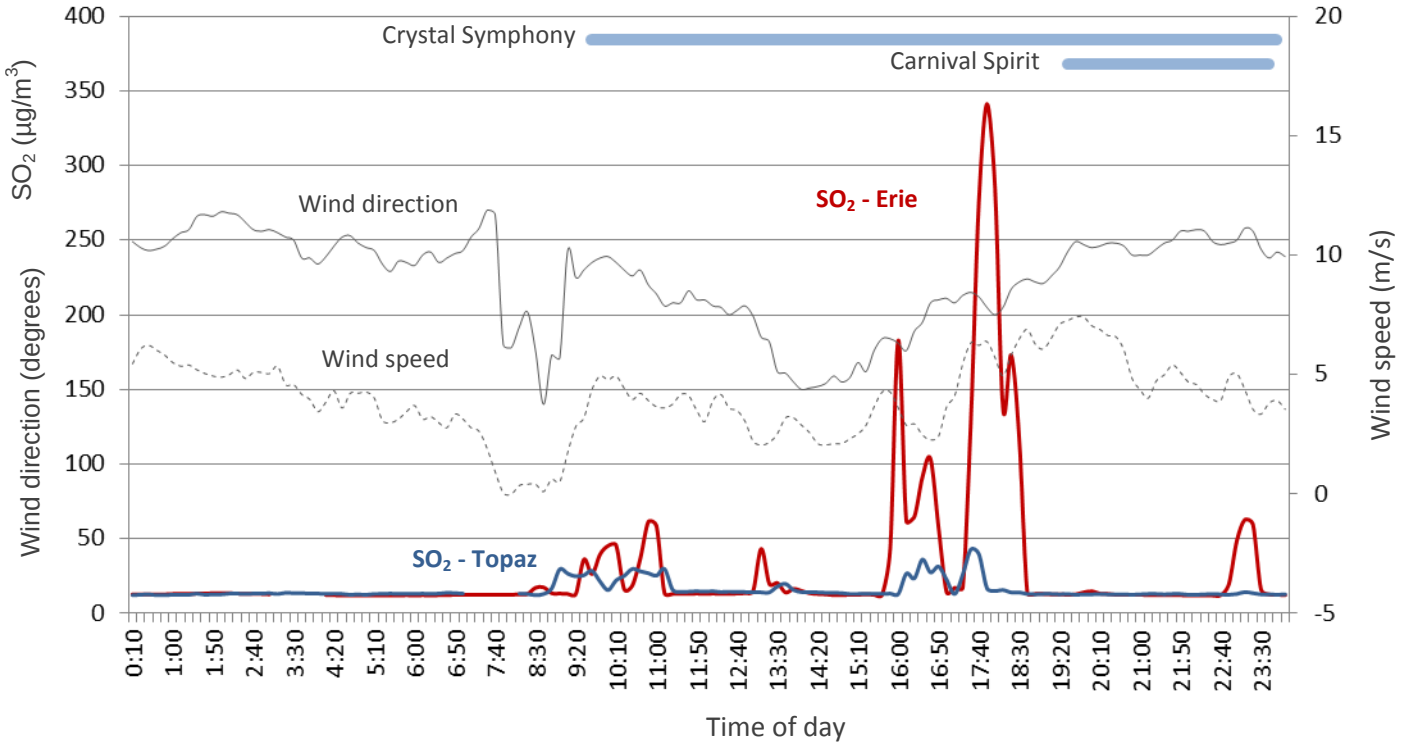


Figure 16. June 18th , 2011

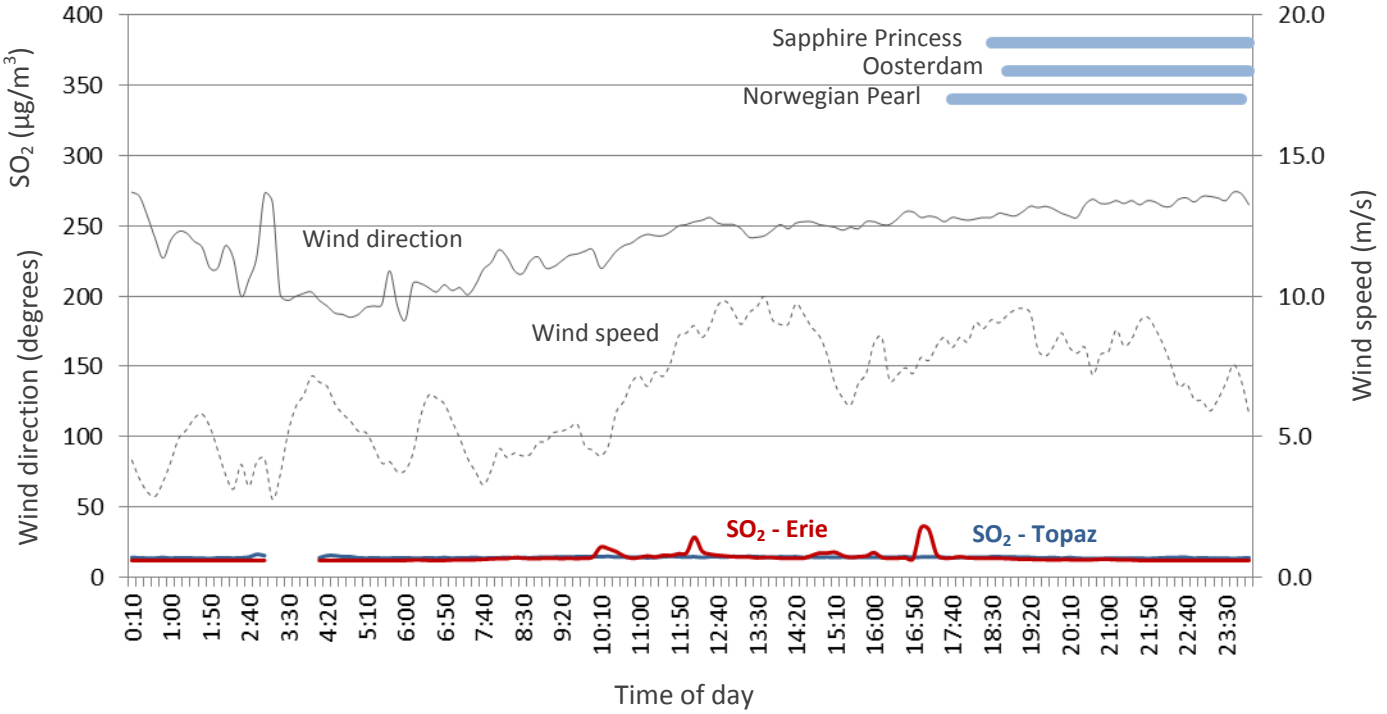
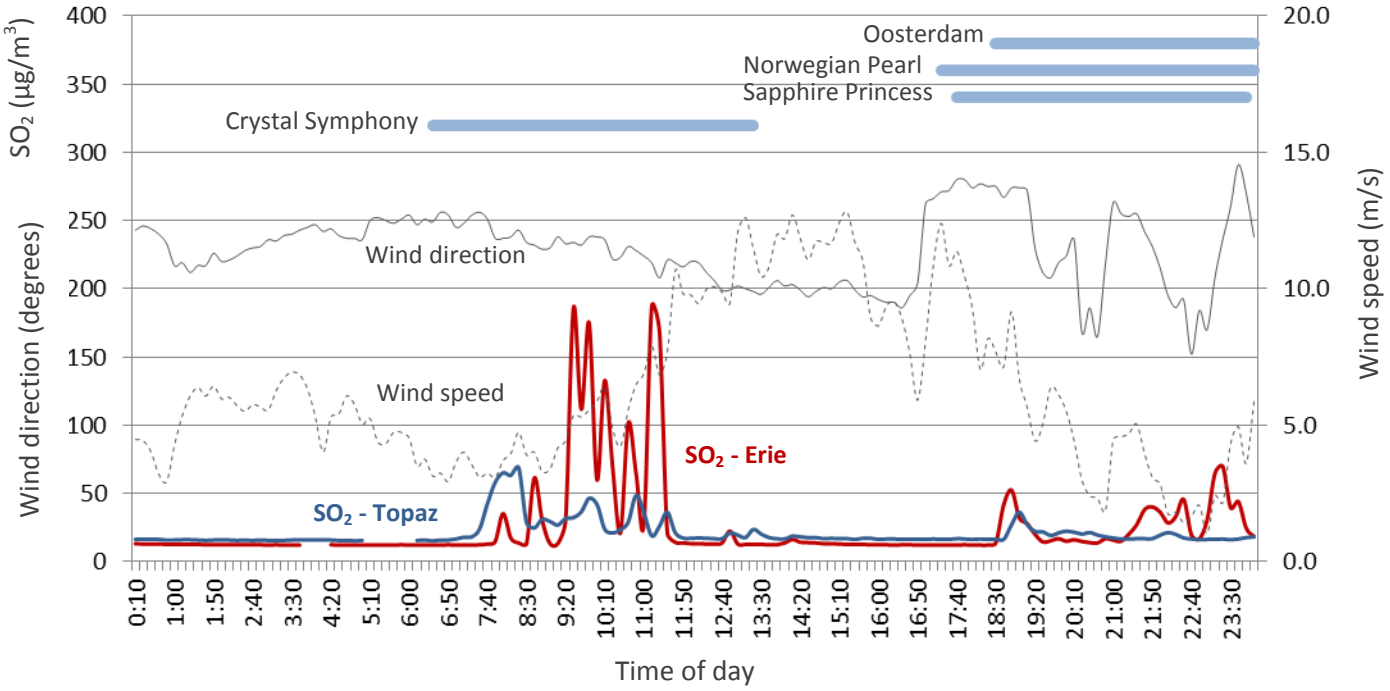


Figure 17. July 30th, 2011



5. Trends and comparisons

The number of hours with cruise ships in port reached a peak in 2009 compared to previous years, and dropped slightly in 2010 and 2011 (Table 15).

Table 15. Number of hours with cruise ships present – 2006 to 2011

	2006	2007	2008	2009	2010	2011
Hours with cruise ships April 1 – Oct 31	962 (19%)	816 (16%)	982 (19%)	1188 (23%)	1160 (23%)	1165 (23%)

5.1 Topaz 2006 to 2011

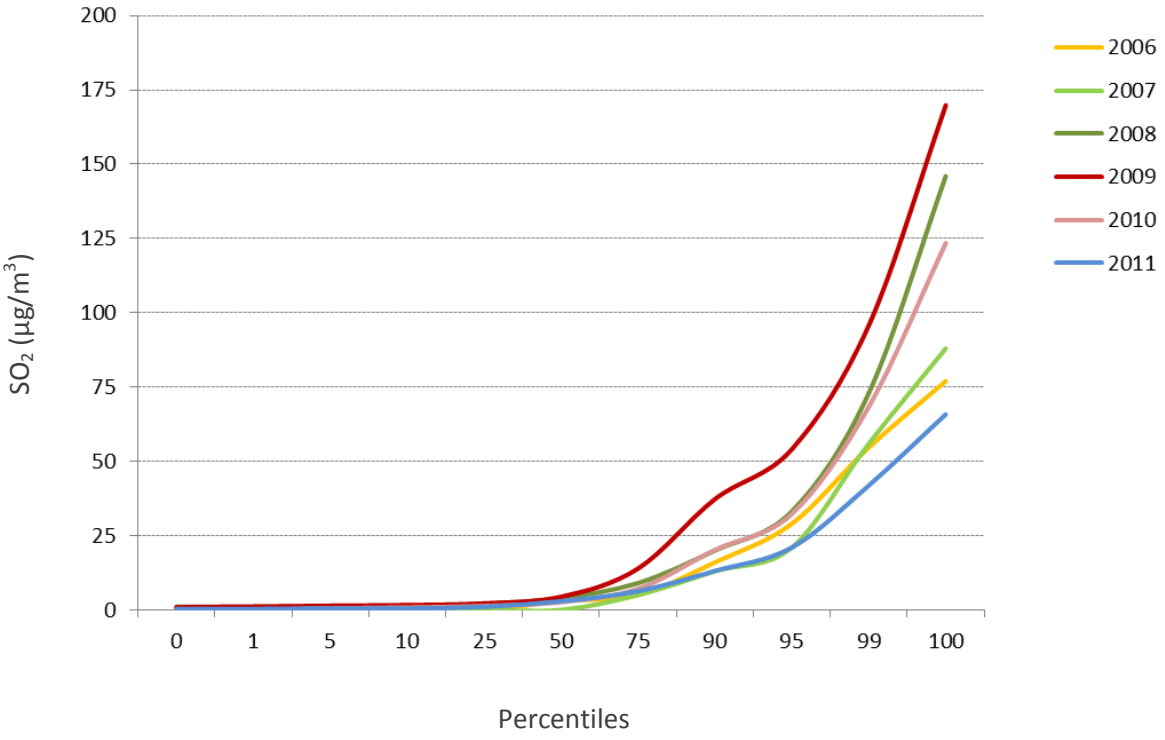
When comparing the highest 25 percent of hourly average levels from Topaz station in 2006 to 2011 when cruise ships were present (data at and above the 75th percentile), levels were highest in 2009, followed by 2008 and 2010 (Figure 18), and the lowest in 2011. Levels below the 75th percentile were similar in all years.

The distinct drop in average hourly levels between evening arrivals and departures seen in the diurnal patterns at Erie site in 2011 was also present at Topaz in 2011, 2010 and in 2007, although not as obvious, given the distance and lower concentrations (Figure 19). For hours without cruise ships present, average hourly levels at Topaz site were typically less than 5 $\mu g/m^3$ in all years (Figure 20). Factors that may contribute to these differences include:

- Average temperatures - during hours with cruise ships, temperatures were highest during June and July of 2009, but were lowest during the same period in 2008 (Figures 21 and 22). It is not clear how temperature relates to hourly average SO_2 levels at Topaz.
- Monthly precipitation - precipitation patterns during hours with cruise ships are markedly different between years (Figure 23), but do not appear to relate to higher or lower SO_2 levels.
- Atmospheric stability - the percent of hours with cruise ships in each atmospheric stability class was relatively similar between years (Figure 24), with between 63 and 68 percent of hours in Class 4 (Pasquill Class D – neutral).
- Wind speed and direction – these were remarkable similar at Topaz between years (Figure 25 and 26), and winds blew from Ogden Point toward the Topaz site most frequently in all years (Figure 27).

Other than wind direction, which directly influences the direction of the cruise ship emission plume, it is not clear how differences in meteorological characteristics from year to year contribute to difference in SO_2 levels measured at the Topaz site.

Figure 18. Percentiles of hourly SO_2 levels for hours with cruise ships – Topaz 2006 to 2011



SO_2 levels measured at Topaz Site (µg/m^3) on hours with cruise ships

Percentile	2006	2007	2008	2009	2010	2011
minimum	0	0	1	1	0	< 1
1	0	0	1	1	0	< 1
5	0	0	1	1	< 1	< 1
10	0	0	1	2	1	< 1
25	0	0	2	1	1	1
50	3	0	4	4	3	3
75	5	5	9	14	7	6
90	16	13	20	37	20	13
95	29	21	33	54	32	21
99	55	56	73	96	68	42
maximum	77	88	146	170	123.4	66

Figure 19. Diurnal SO_2 levels on days with cruise ships – Topaz 2006 to 2011

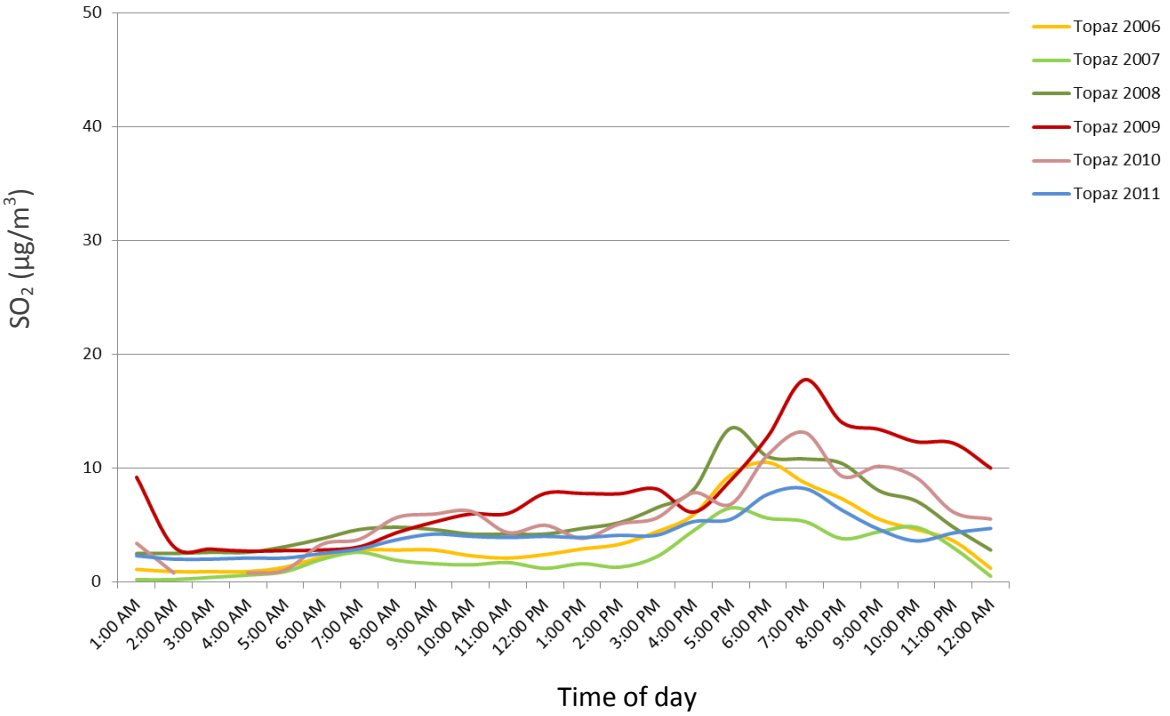


Figure 20. Diurnal SO_2 levels on days without cruise ships – Topaz 2006 to 2011

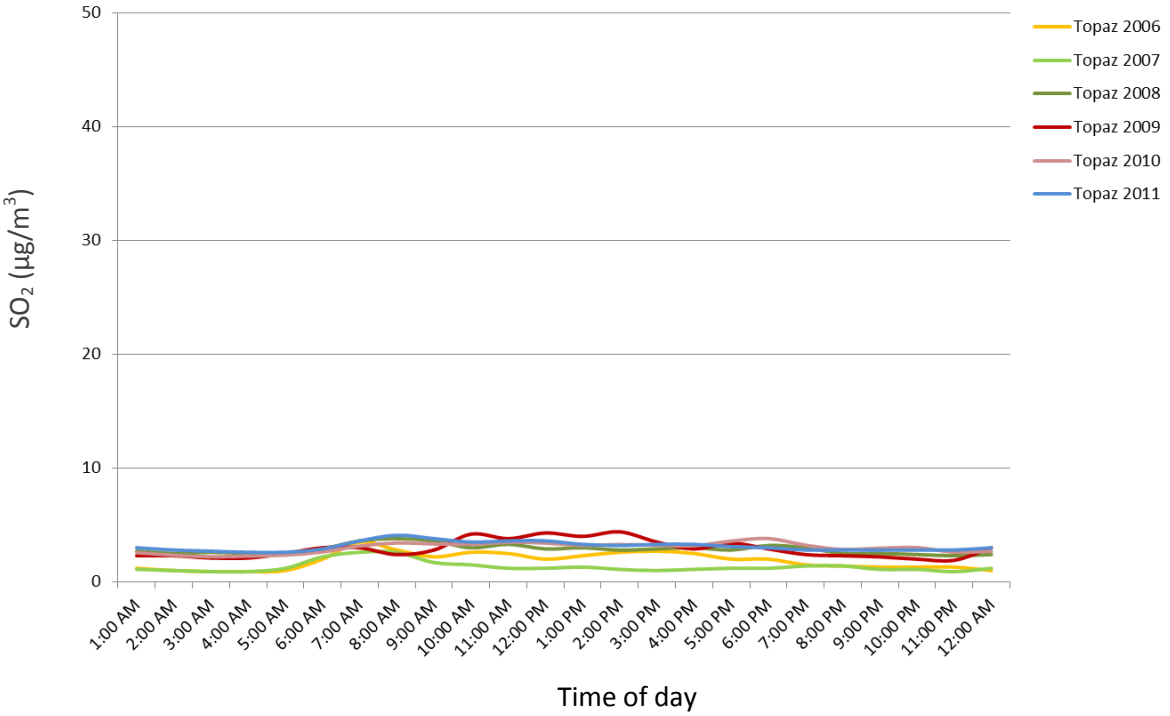
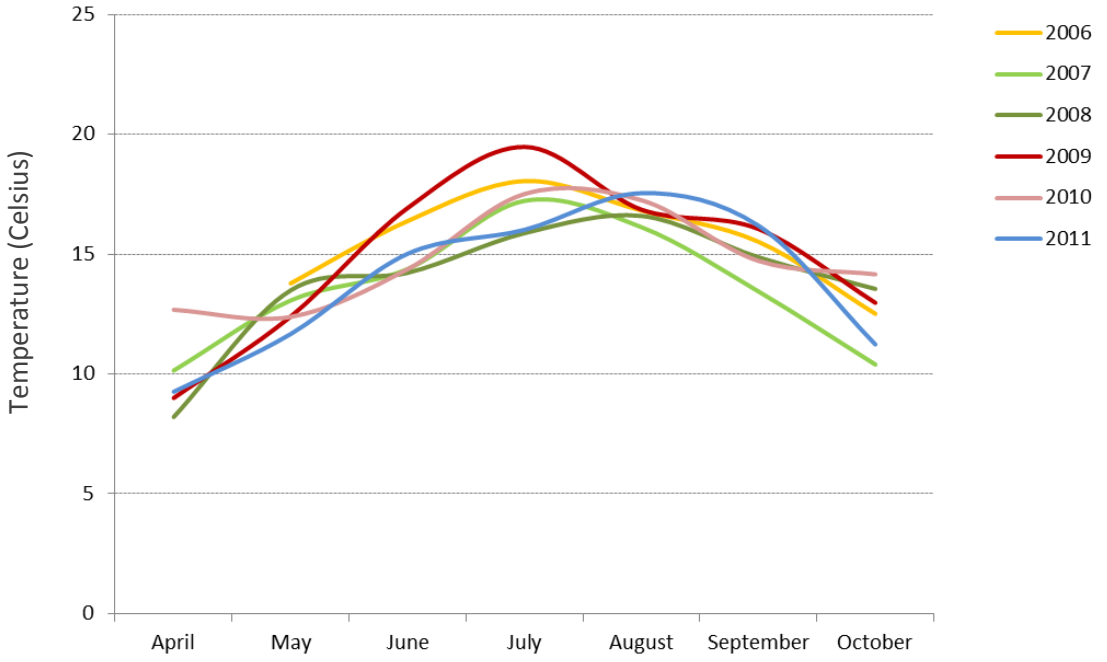


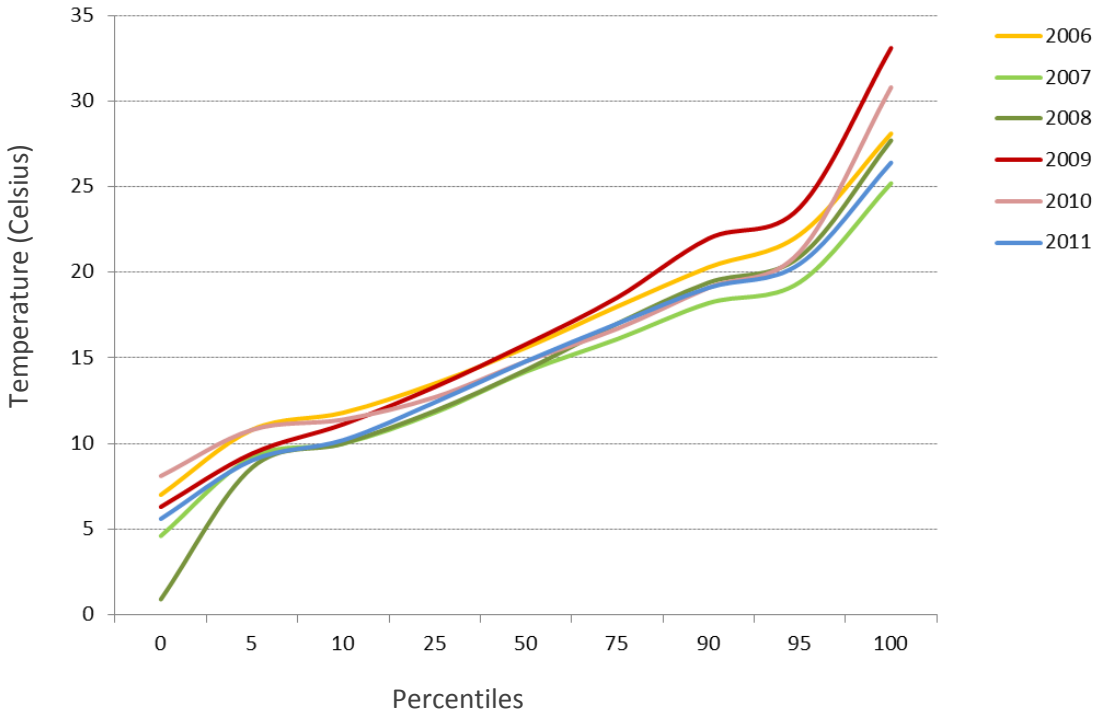
Figure 21. Average hourly temperature for hours with cruise ships – Topaz 2006 to 2011



Temperature recorded at Topaz Site (Celsius)

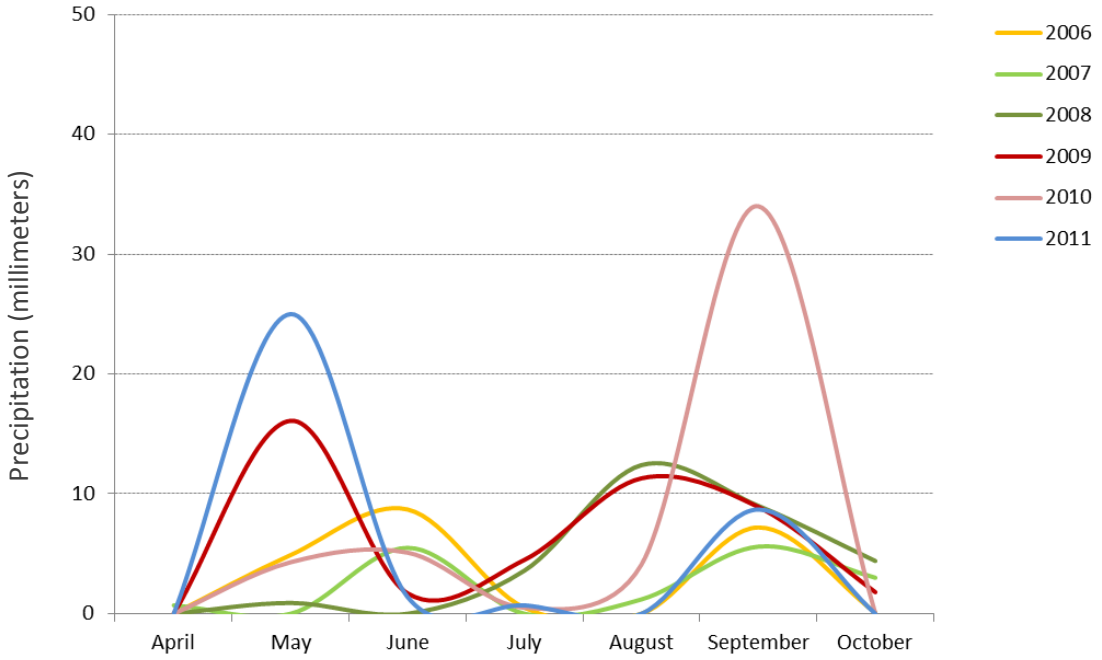
Year	April	May	June	July	August	September	October
2006	--	14	16	18	17	16	13
2007	10	13	14	17	16	13	10
2008	8	13	14	16	17	15	14
2009	9	12	17	19	17	16	13
2010	13	12	14	18	17	15	14
2011	9	12	15	16	18	16	11

Figure 22. Percentiles of average hourly temperature for hours with cruise ships – Topaz 2006 to 2011



Temperature recorded at Topaz Site (Celsius)						
Percentile	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**
0	7	5	1	6	8	6
5	11	9	9	9	11	9
10	12	10	10	11	11	10
25	14	12	12	13	13	12
50	16	14	14	16	15	15
75	18	16	17	19	17	17
90	20	18	19	22	19	19
95	22	19	21	24	21	21
100	28	25	28	33	31	26

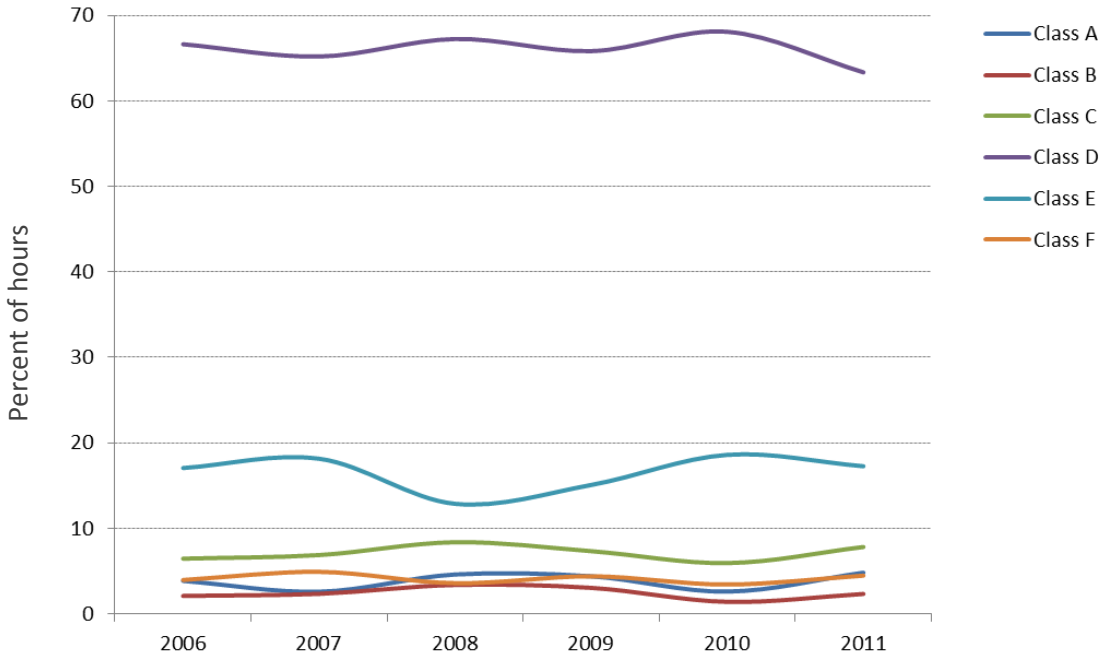
Figure 23. Total monthly precipitation for hours with cruise ships – Topaz 2006 to 2011



Total monthly precipitation recorded at Topaz (millimeters)

	April	May	June	July	August	September	October
2006	0	4.9	8.7	0.5	0	7.2	0.1
2007	0.7	0	5.5	0	1.2	5.6	3
2008	0	0.9	0	3.6	12.4	9	4.4
2009	0	16.1	1.7	4.5	11.3	8.9	1.8
2010	0	4.3	5.1	0.5	4.1	34	0
2011	0	25	1.4	0.7	0	8.7	0

Figure 24. Percent of hours by atmospheric stability class for hours with cruise ships – Topaz 2006 to 2011



Percent of hours in each Pasquill stability class

	Class A	Class B	Class C	Class D	Class E	Class F
2006	4	2	6	67	17	4
2007	3	2	7	65	18	5
2008	5	3	8	67	13	4
2009	4	3	7	66	15	4
2010	3	1	6	68	19	3
2011	5	2	8	63	17	4

Figure 25. Wind speed and direction for hours with cruise ships - Topaz 2006 to 2011

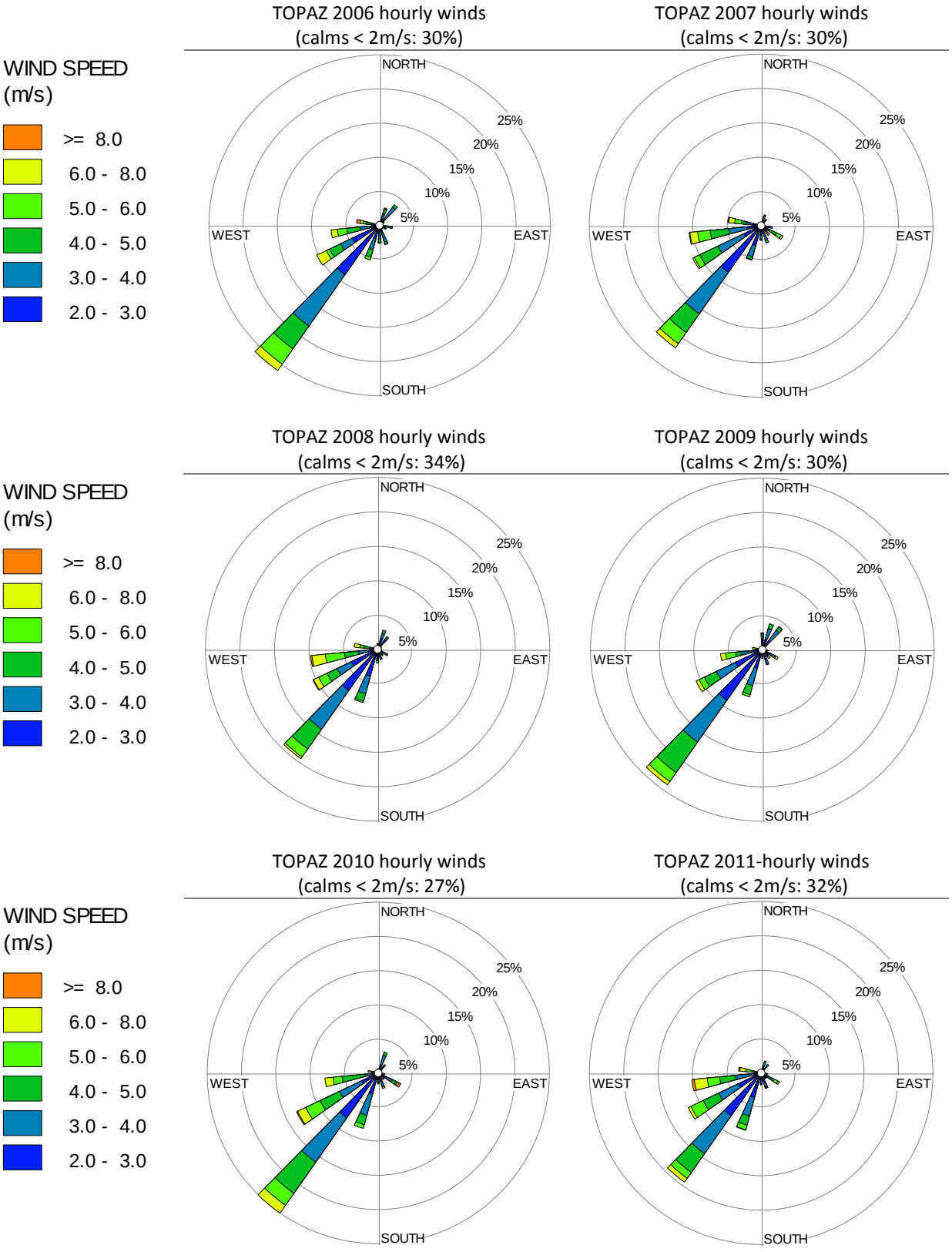


Figure 26. Percent of time by wind speed for hours with cruise ships - Topaz 2006 to 2011

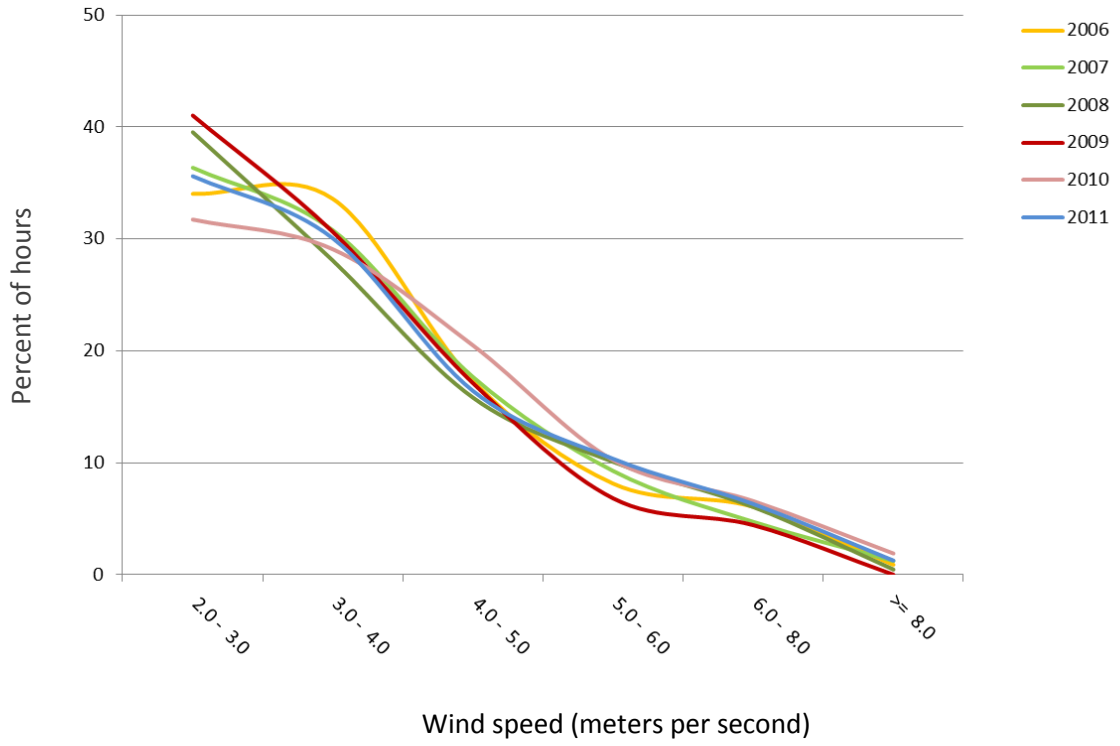
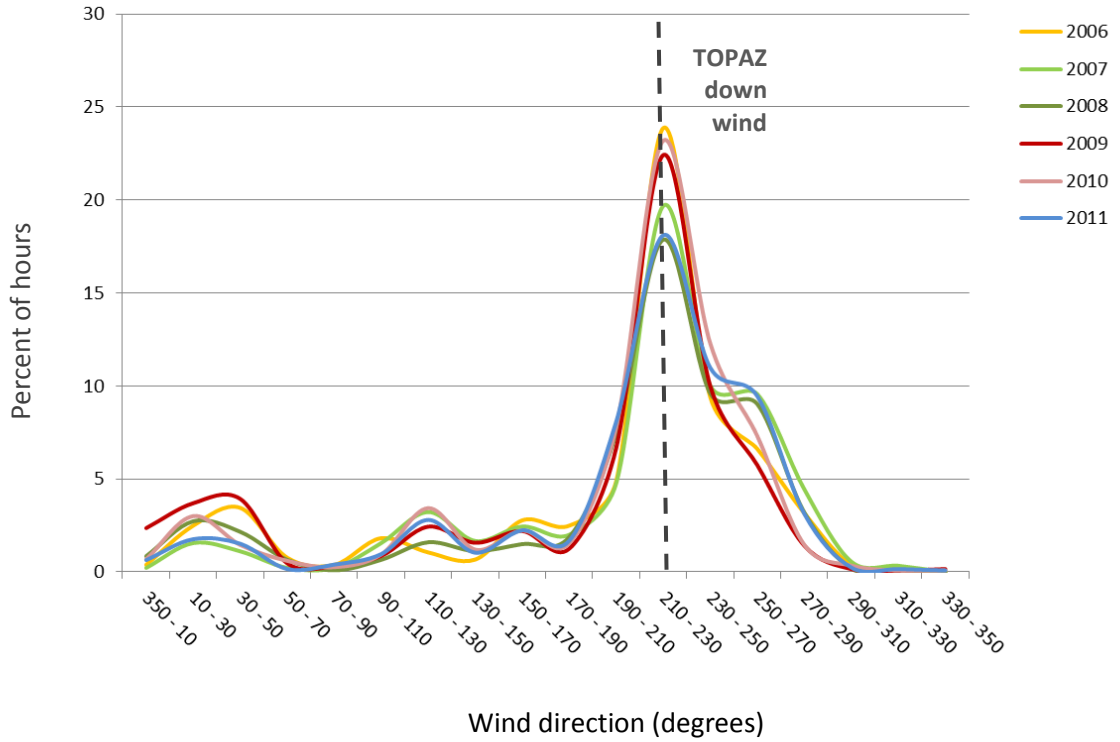


Figure 27. Percent of time by wind direction for hours with cruise ships - Topaz 2006 to 2011



5.2 MAML 2009 and Erie 2011

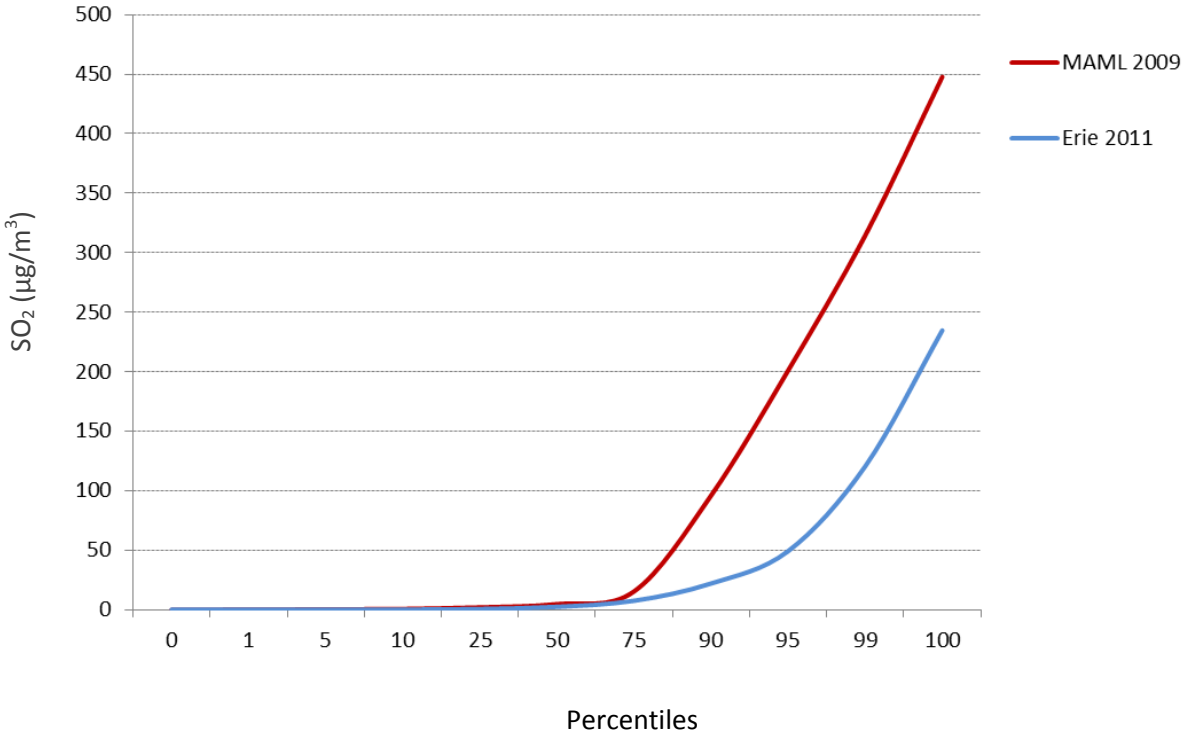
SO_2 levels at and above the 75th percentile measured in the James Bay neighbourhood at the Erie site in 2011 when cruise ships were present were markedly lower than those measured at the MAML site in 2009 (Figure 28). In 2011, the diurnal pattern shows a distinct drop in average levels between evening arrivals and departures, unlike 2009 when levels dropped off gradually over the evening hours after arrivals (Figure 29). When cruise ships were not present, average hourly SO_2 levels were less than 10 $\mu g/m^3$, but still lower in 2011 than in 2009 (Figure 30).

Factors that may contribute to these differences include:

- Wind direction - compared to the Erie site, the MAML site was more frequently downwind during hours with cruise ships present. Assuming that higher levels are measured when the station is more directly downwind, MAML may have recorded higher levels more often (Figures 31 and 32), but this cannot be confirmed.
- Wind speeds - these were more frequently below 3 to 4 m/s in 2009 during MAML reporting, and more frequently above 6 to 8 m/s in 2011 during Erie reporting (Figure 33). It is not clear what effect this difference may have had on SO_2 levels.

Other factors that could influence SO_2 levels include the type of ship present, ship operations while at dock, and the sulfur content of the fuel burned. Data were not available to allow for evaluation of these factors.

Figure 28. Percentiles of hourly average SO_2 levels for hours with cruise ships – Erie and MAML



SO_2 levels measured at Erie Site (µg/m^3) on hours with cruise ships

Percentile	MAML 2009	Erie 2011
0	0	<1
1	<1	<1
5	<1	<1
10	1	<1
25	2	1
50	5	3
75	16	8
90	96	22
95	201	49
99	315	121
100	448	235

Figure 29. Diurnal SO_2 levels on days with cruise ships – Erie and MAML

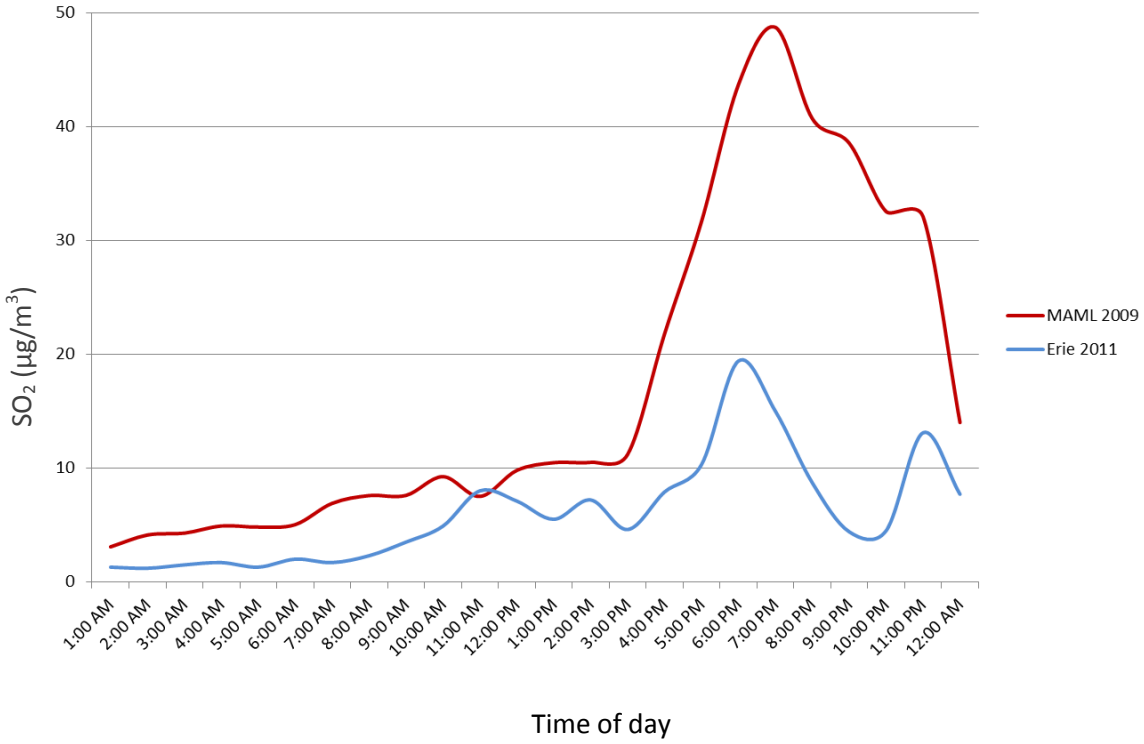


Figure 30. Diurnal SO_2 levels on days without cruise ships – Erie and MAML

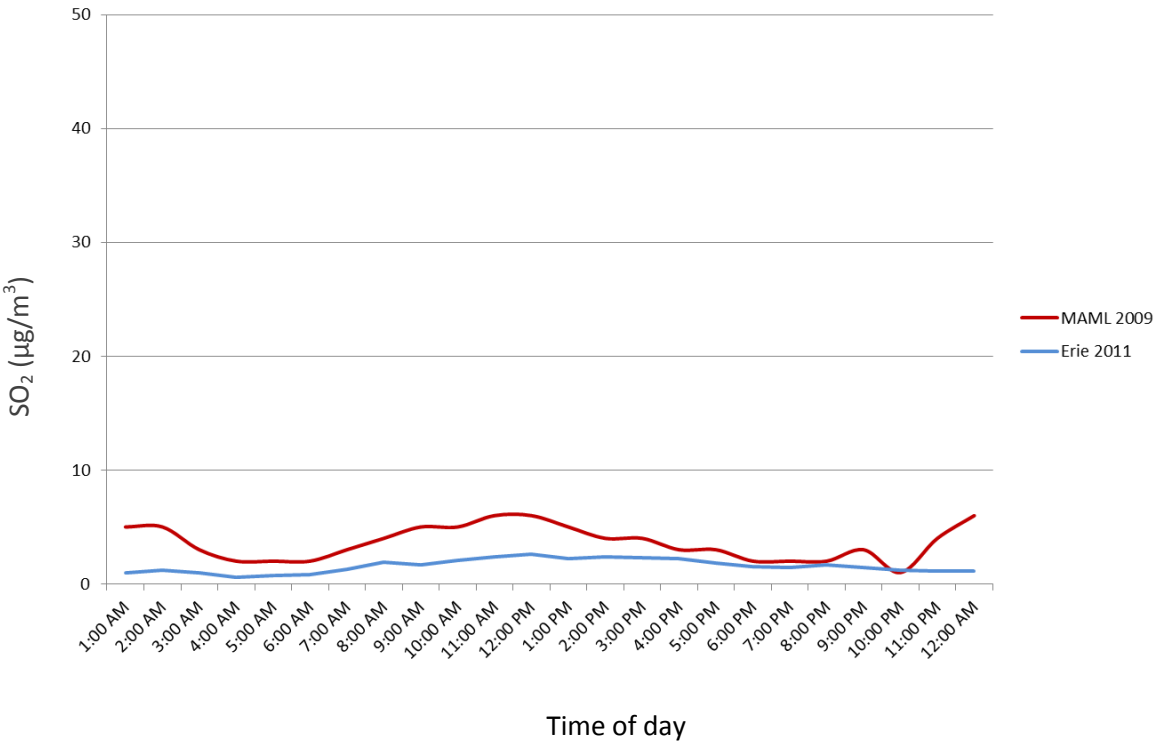


Figure 31. Wind speed and direction at Ogden Point – hours with cruise ships in 2009 and 2011

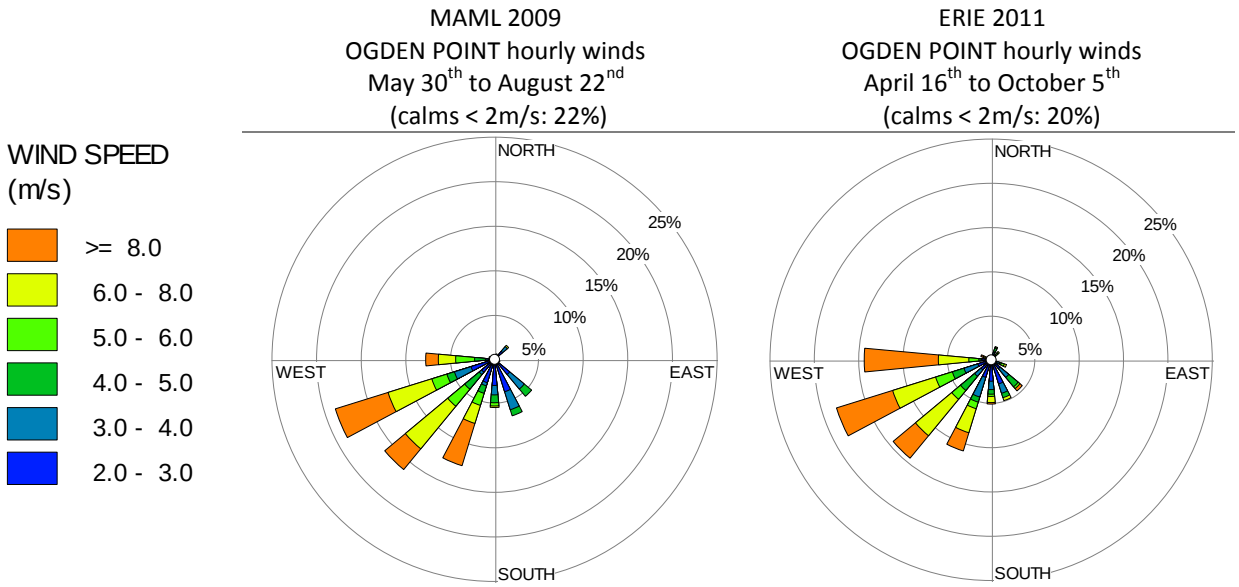


Figure 32. Percent of time by wind direction for hours with cruise ships – Erie and MAML

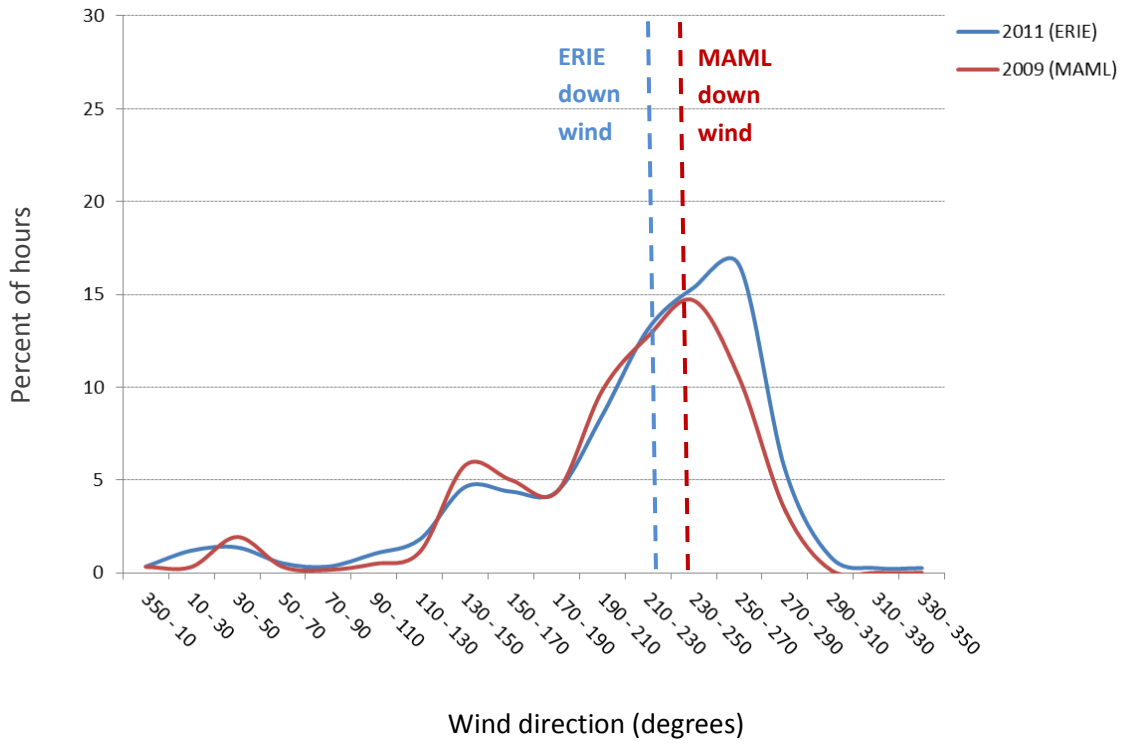
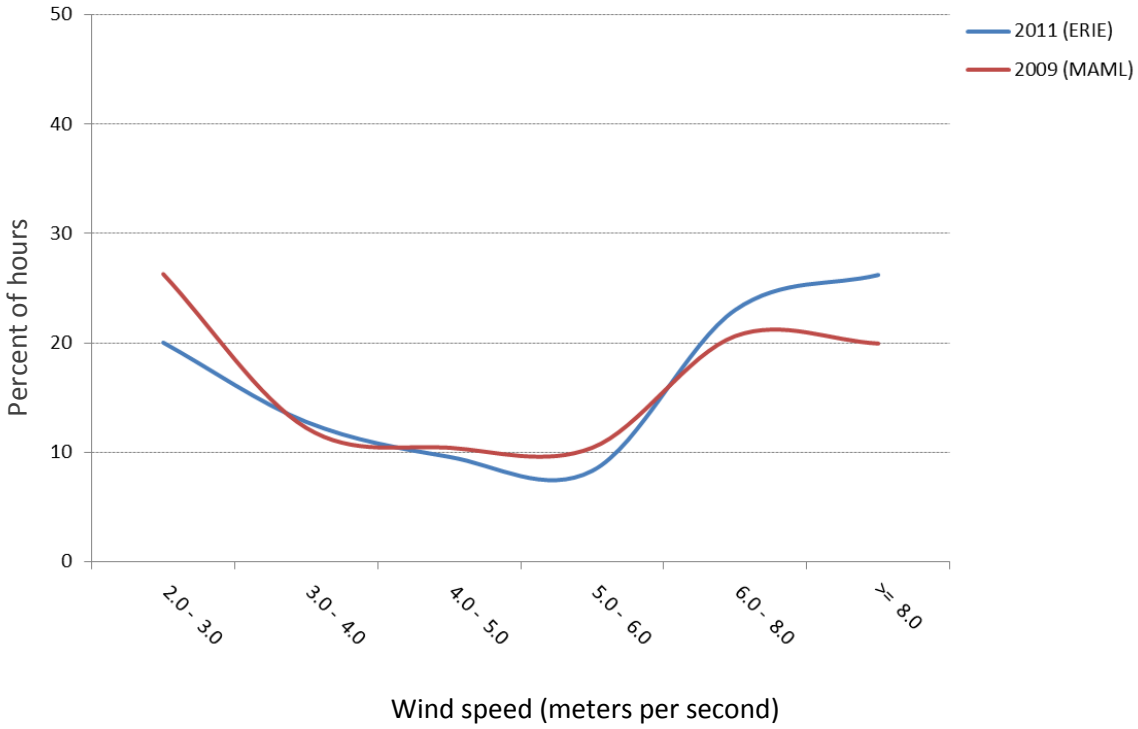


Figure 33. Percent of time by wind speed for hours with cruise ships – Erie and MAML



6. Representativeness of MAML and Erie Sites

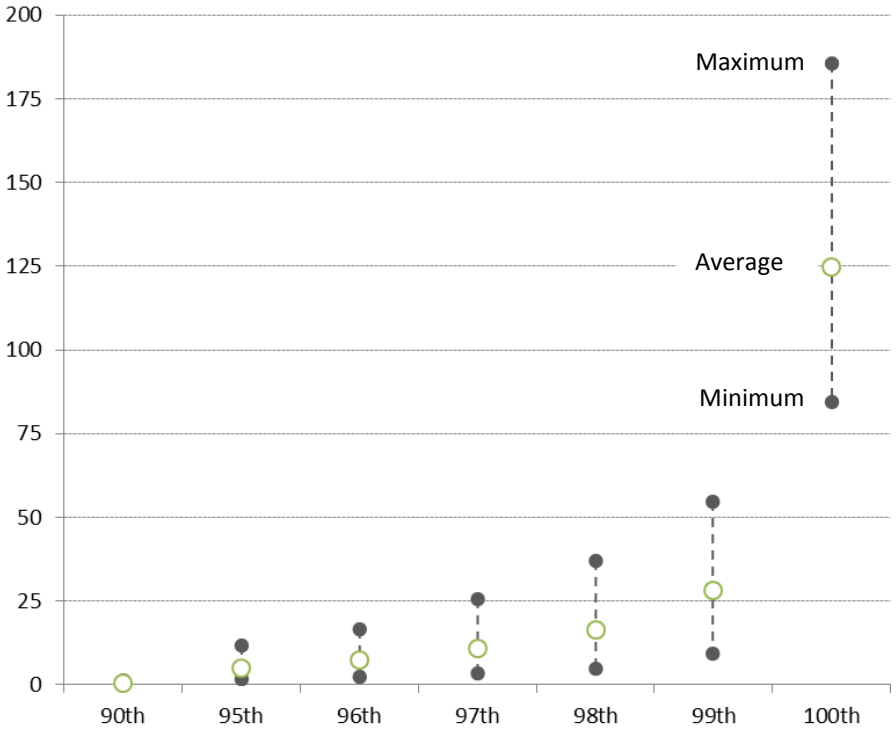
Dispersion modelling conducted using data for 2007[17] and CALPUFF (the California Puff Modelling System) software suggested higher average hourly SO_2 levels could occur across a relatively large part of the James Bay neighbourhood. At each of 25 locations in and around the James Bay neighbourhood, hourly average SO_2 levels were predicted using the 2007 cruise ship schedule and hourly meteorological data. In general, the modelling results under-predicted actual measured levels at the Topaz site in 2007, and no monitoring was available in the James Bay neighbourhood to evaluate prediction accuracy closer to the Ogden Point terminal. The range of predicted values at selected percentiles for the 25 receptors is shown in Figure 34. For example, the 90th percentile hourly SO_2 levels predicted for the 25 receptor points range from 0.1 to 1.4 $\mu g/m^3$ (average 0.6 $\mu g/m^3$), and the 100th percentile (maximum) hourly SO_2 levels range from 84.7 to 185.6 $\mu g/m^3$.

The maps shown in Figures 35 and 36 provide an indication of geographic pattern of predicted levels. Figure 35 shows the number of hours predicted to have hourly average SO_2 levels above 50 $\mu g/m^3$ in 2007. Assuming the model outputs represent the correct pattern (although perhaps under-predicting levels), the Erie site is in close proximity to the location predicted to be most frequently impacted and the MAML location coincides with the predicted second most impacted location. Figure 36 shows the number of hours predicted to have hourly average SO_2 levels above 100 $\mu g/m^3$. Again, the Erie site is in the general area predicted to be most impacted; while, the MAML location is predicted to be slightly lower. Notably, the number of hours predicted to exceed 100 $\mu g/m^3$ are very low (between 1 and 11-hours out of a total of 4,655 hours modelled).

The Erie and MAML sites are downwind of the cruise ships at Ogden Point more frequently than many other locations in James Bay, and so it is not unreasonable to expect that most other locations would not be more frequently impacted. However, resident complaints and the 2007 dispersion modelling also suggest there are areas in addition to the Erie and MAML sites which can be impacted, and additional monitoring is recommended to evaluate the actual extent and frequency of these impacts under varying meteorological conditions.

[17] Poplawski K, Setton E, McEwen B, et al (2011). Impact of cruise ship emissions in Victoria, BC, Canada. Atmospheric Environment 45, pp.824-833.

Figure 34. Range (minimum, average, maximum) of predicted hourly average SO_2 levels at 25 model receptor locations for selected percentiles



	Predicted hourly average SO_2 ($\mu g/m^3$)		
	Minimum	**Average**	**Maximum**
90th	0.1	0.6	1.4
95th	1.7	5	11.7
96th	2.4	7.3	16.7
97th	3.6	10.9	25.6
98th	5	16.4	37
99th	9.5	28.2	54.7
100th	84.7	124.8	185.6

Figure 35. Number of hours predicted to be above 50 μg/m³ by 2007 CALPUFF model

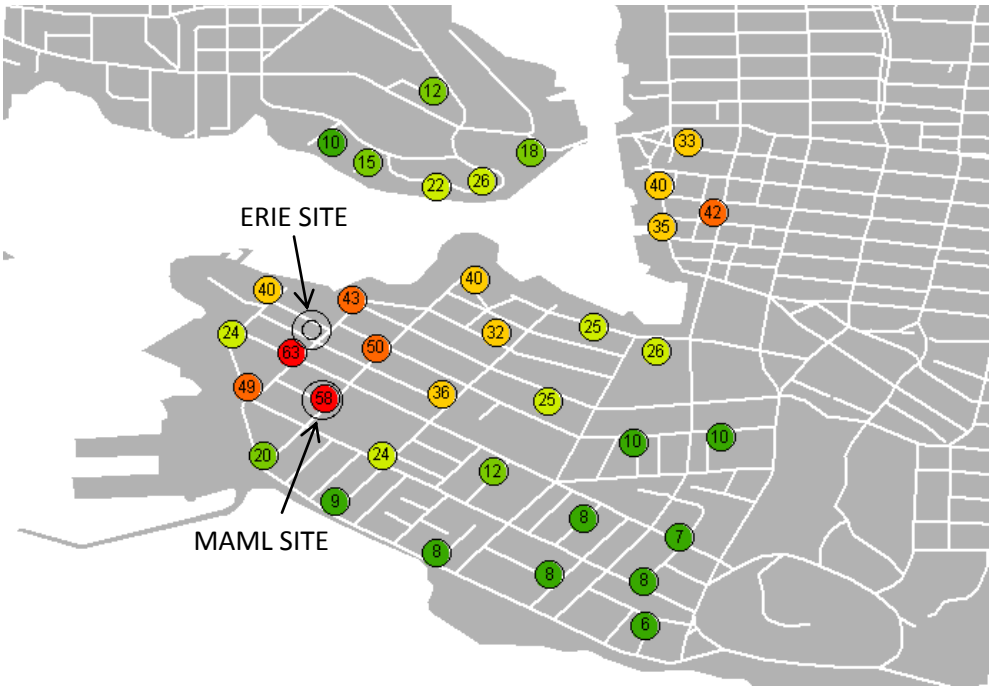
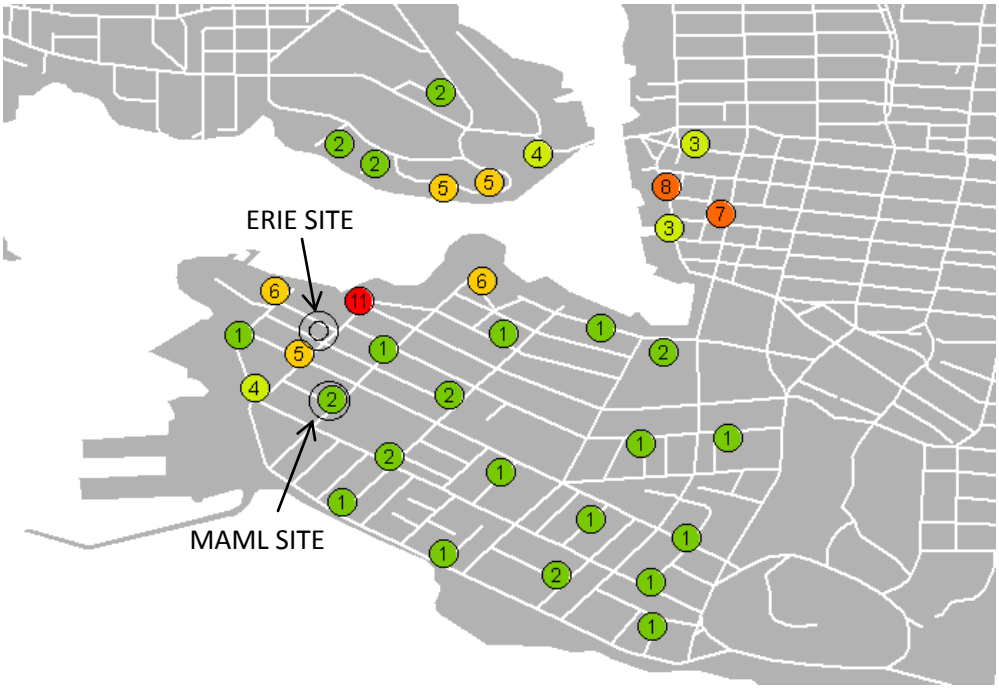


Figure 36. Number of hours predicted to be above 100μg/m³ by 2007 CALPUFF model



Appendix A. Instrument calibration information

Instrument descriptions are available from the BC Ministry of Environment on request.

Calibrations were performed by BC Ministry of Environment staff as recorded in the documents on the following pages:

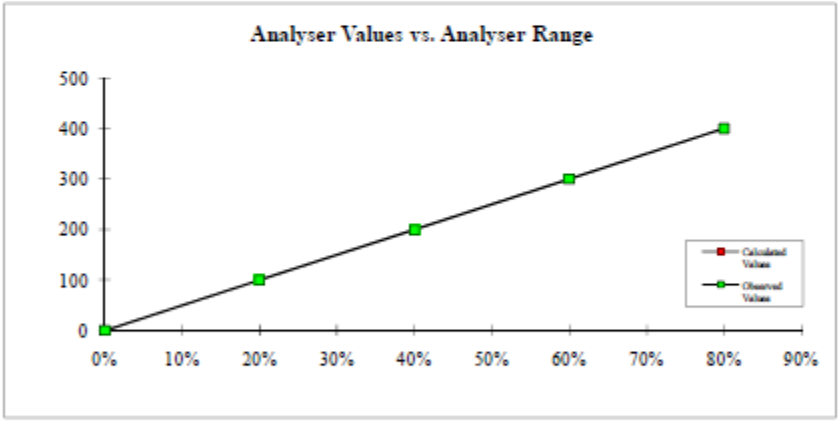
JC ANDELLE

Ambient Air Monitor Calibration Report

Parameter: SO_2

Date: 2011-04-08	**Regression Output:**
Location: James Bay	**SO_2**
Client: BC Environment - Victoria	**Intercept:** -0.2
Analyser Code:	**Slope:** 1.0000
Method: UV Fluorescence	**Correlation Coefficient:** 1.0000
Make: TEII	
Model: 43i-TLE	
Serial #: 1007641138	

Calibrator: JC Andelle			SN: 104		**Calibrator**	**Analyser**	
Cyl Number: JJ8581			Cyl Pressure: 1080 psig		**Output (ppb)**	**Reading (ppb)**	**% Difference**
Gas Type:	SO_2	**Target**	**(F1)**	**(F2)**	SO_2	SO_2	SO_2
Gas Conc:	40.90 ppm	0	4000	0.00	0	0	0.0%
Range(0):	500 ppb	400	4000	39.51	400	400	0.0%
Pressure:	760 mmHg	300	4000	29.56	300	300	0.0%
Lab Temp:	25 °C	200	4000	19.66	200	199	-0.5%
K-Factor:	1.00	100	4000	9.80	100	100	0.0%
						Average Error:	-0.1%



Service Time: Starts @ PST Ends @ 1545 PST

	Found	**Left**
BKG:		1.58
COEF:		1.051

	Found	**Left**
Zero Reading:		0.0
80% FS (ppb):		400
Daily Span (ppb):		401

Comments: New installation.

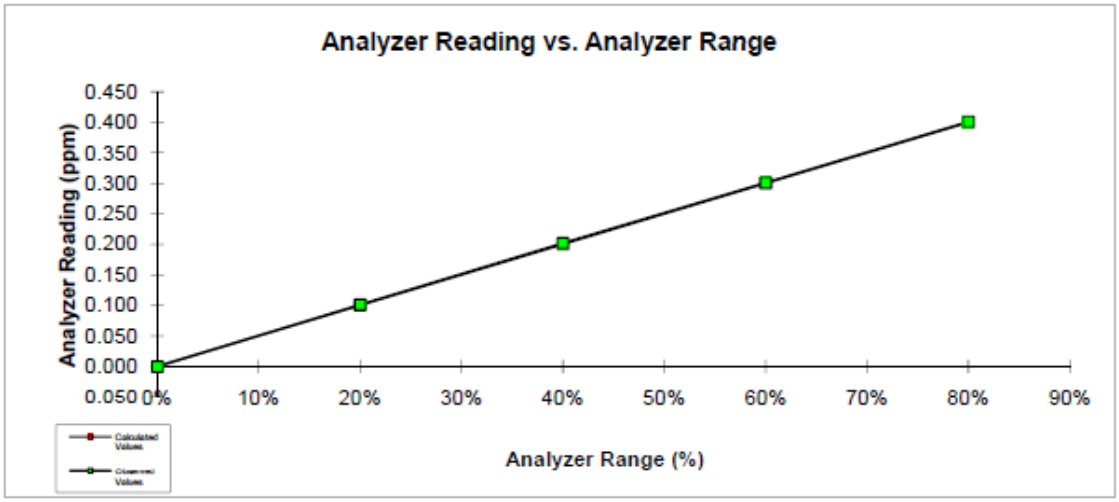
Technician: Jesse Wong

Continuous Ambient Monitor Audit Certificate

Date: June 23, 2011	**Regression Output:**
Location: Victoria	
: James Bay	**Intercept:** 0.0003
Site Code: MA498-1	**Slope:** 1.0030
Auditors: Todd/Kubotani	**Correlation Coeff.:** 1.0000
Method: U.V. Fluorescence	
Make: Thermo	Coef: 1.051
Model: 43i-TLE	BKG: 1.58
Serial #: 1007641138	
Cylinder Number: FF17440	Calibrator: Environics 4620
Cylinder Volume: 1100	

Gas Type:	SO2		Target	(F1)	(F2)	(CV)	(OV)	Error
Gas Conc:	52.4	ppm	0.000	5000	0.0	0.000	-0.001	N/A
Range(0):	0.500	ppm	0.100	5000	9.6	0.100	0.101	1.0%
Start:	12:00	PST	0.200	5000	19.2	0.200	0.202	1.0%
Finish:	13:15	PST	0.300	5000	28.8	0.300	0.301	0.3%
			0.400	5000	38.5	0.400	0.401	0.3%

Comments: **Average Error:** 0.6%



Audit Results: Pass

Air Audit Programme
Environmental Quality Branch

JC ANDELLE

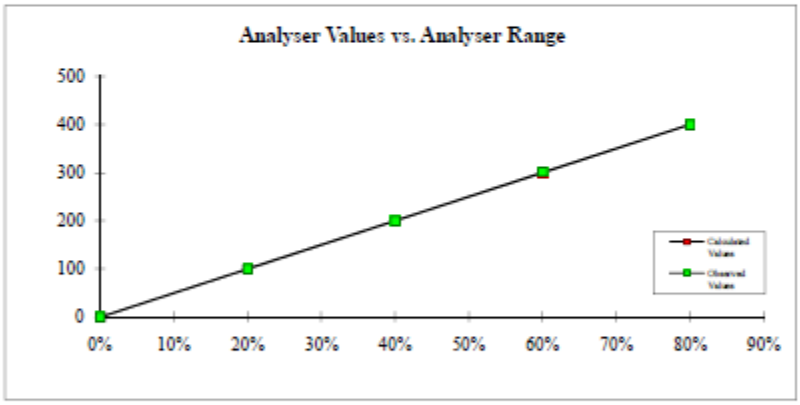
Ambient Air Monitor Calibration Report

Parameter: SO_2

Date: 2011-08-16	**Regression Output:**
Location: James Bay	**SO_2**
Client: BC Environment - Victoria	**Intercept:** 0.0
Analyser Code:	**Slope:** 1.0010
Method: UV Fluorescence	**Correlation Coefficient:** 1.0000
Make: TEII	
Model: 43i-TLE	
Serial #: 1007641138	

Calibrator: JC Andelle — SN: 104
Cyl Number: JJ8581 — Cyl Pressure: 1010 psig

		Target	(F1)	(F2)	Calibrator Output (ppb)	Analyser Reading (ppb)	% Difference
Gas Type:	SO_2				SO_2	SO_2	SO_2
Gas Conc:	40.90 ppm	0	4000	0.00	0	0	0.0%
Range(0):	500 ppb	400	4000	39.51	400	400	0.0%
Pressure:	760 mmHg	300	4000	29.56	300	301	0.3%
Lab Temp:	25 °C	200	4000	19.66	200	200	0.0%
K-Factor:	1.00	100	4000	9.80	100	100	0.0%
						Average Error:	0.1%



Service Time: Starts @ 0905 PST Ends @ 1135 PST

	Found	Left
BKG:	1.57	1.18
COEF:	1.051	1.051

	Found	Left
Zero Reading:	-0.33	0.00
80% FS (ppb):	417	400
Daily Span (ppb):		

Comments: 0 to 200 ppb: within 2% in 3'54"; within 1% in 7'14"
200 to 100 ppb: within 2% in 4'04"; within 1% in 7'08"

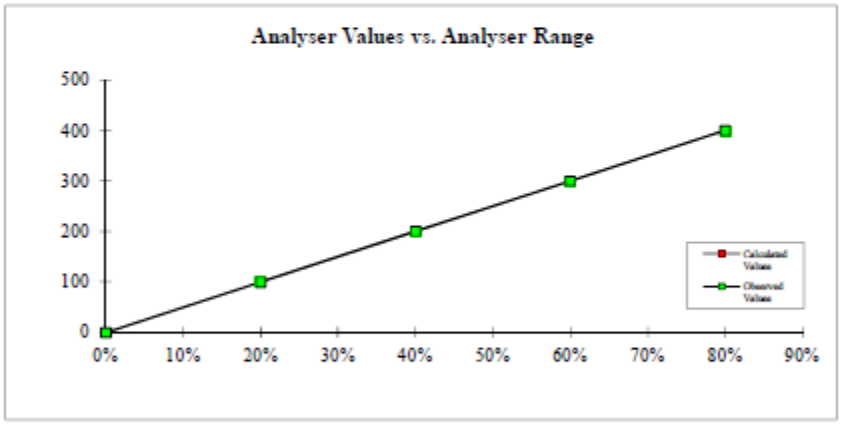
Technician: Jesse Wong

JC ANDELLE

Ambient Air Monitor Calibration Report

Parameter: SO_2

Date: 2011-12-09					**Regression Output:**		
Location: James Bay					**SO_2**		
Client: BC Environment - Victoria					**Intercept:**	0.2	
Analyser Code:					**Slope:**	1.0000	
Method: UV Fluorescence					**Correlation Coefficient:**	1.0000	
Make: TEII							
Model: 43i-TLE							
Serial #: 1007641138							
Calibrator: JC Andelle			SN: 104		**Calibrator Output (ppb)**	**Analyser Reading (ppb)**	**% Difference**
Cyl Number: JJ8581			Cyl Pressure: 1010 psig				
Gas Type:	SO_2	**Target**	**(F1)**	**(F2)**	SO_2	SO_2	SO_2
Gas Conc:	40.90 ppm	0	4000	0.00	0	0	0.0%
Range(0):	500 ppb	400	4000	39.51	400	400	0.0%
Pressure:	760 mmHg	300	4000	29.56	300	300	0.0%
Lab Temp:	25 °C	200	4000	19.66	200	201	0.5%
K-Factor:	1.00	100	4000	9.80	100	100	0.0%
						Average Error:	0.1%



Service Time: Starts @ 0905 PST Ends @ 1130 PST

	Found	**Left**
BKG:	1.19	1.14
COEF:	1.003	0.917

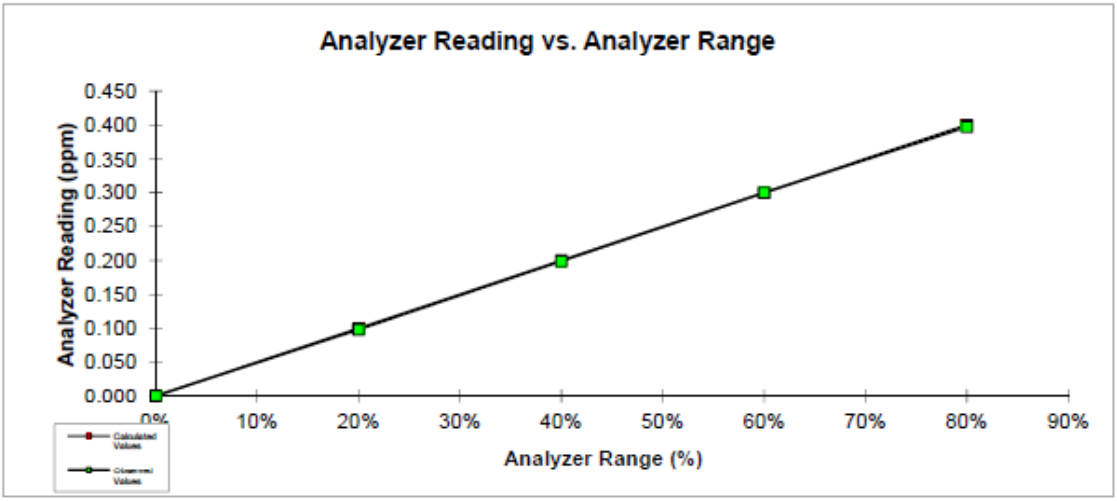
	Found	**Left**
Zero Reading:	0.08	0.00
80% FS (ppb):	433	400
Daily Span (ppb):		

Comments:

Technician: Jesse Wong

Continuous Ambient Monitor Audit Certificate

Date: February 8, 2012			Regression Output:					
Location: Victoria								
: James Bay						Intercept:		-0.0001
Site Code: MA498-2						Slope:		0.9950
Auditors: Todd/Kubotani						Correlation Coeff.:		1.0000
Method: U.V. Fluorescence								
Make: Thermo					Coef: 0.917			
Model: 43i-TLE					BKG: 1.14			
Serial #: 1007641138								
Cylinder Number: FF01207					Calibrator: Environics 4620			
Cylinder Volume: 1800								
Gas Type:	SO2		Target	(F1)	(F2)	(CV)	(OV)	Error
Gas Conc:	51.4	ppm	0.000	5000	0.0	0.000	0.001	N/A
Range(0):	0.500	ppm	0.100	5000	9.7	0.100	0.098	-2.0%
Start:	15:15	PST	0.200	5000	19.5	0.200	0.199	-0.5%
Finish:	14:30	PST	0.300	5000	29.4	0.300	0.300	0.0%
			0.400	5000	39.2	0.400	0.397	-0.7%
Comments:							Average Error:	-0.8%



Audit Results: Pass

Air Audit Programme
Environmental Quality Branch