SULFUR DIOXIDE LEVELS – 2012

JAMES BAY, VICTORIA, BRITISH COLUMBIA

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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.

Under the International Maritime Organization (IMO) MARPOL Annex VI[6], sulfur content in marine fuel was limited to 1 percent (10,000 ppm) as of August 1st 2012 within the North American Emissions Control Area (ECA), which covers navigable waters within approximately 200 nautical miles of the coast[7]. Prior to August 1st of this year, marine fuels could have contained up to 3.5 percent sulfur. In addition to MARPOL Annex VI, emissions from cruise ships to air are also regulated under the Canadian Shipping

[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

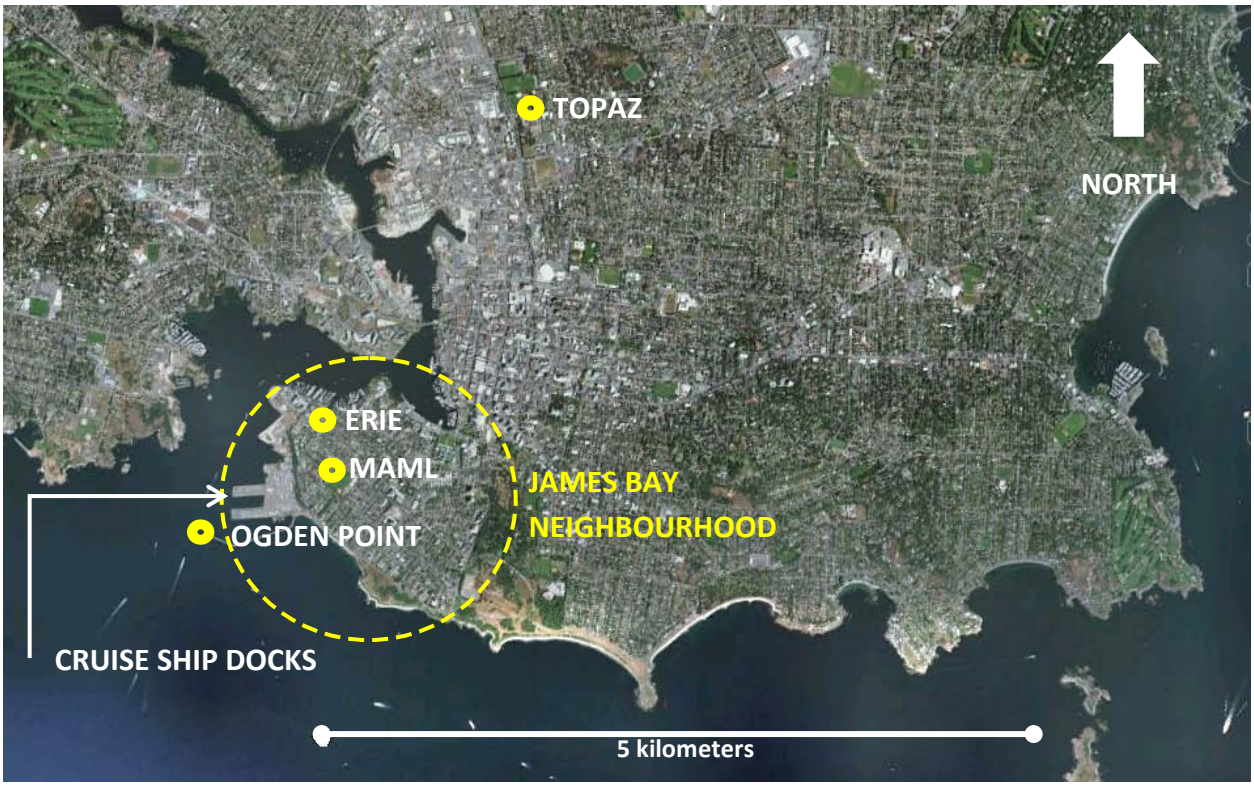
[6] International Maritime Organization. http://www.imo.org/OurWork/Environment/PollutionPrevention/AirPollution/Pages/The-Protocol-of-1997-%28MARPOL-Annex-VI%29.aspx

[7] Sulfur content will be further limited to 0.1 percent (1,000 ppm) as of January 1st, 2015.

Act[8]. 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 September, 2012, in conjunction with data collected at the same site in 2011, the Mobile Air Monitoring Lab (MAML) location in James Bay (2009), the nearby BC MoE Topaz Station (2006 – 2012), and the Ogden Point wind station (2006 – 2012) (see Figure 1 for locations). Also included is additional analysis of measured SO_2 levels before and after August 1st, 2012, when the regulatory change in fuel sulfur content came into effect.

Figure 1. Study area



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

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 2012

- 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)?

Comparison of SO_2 levels - 2006 to 2012

- How do levels measured at Topaz (2006 – 2012), MAML (2009) and Erie (2011-2012) compare?
- What factors influence the observed differences:
  - Were meteorological conditions experienced over the 2012 cruise ship season similar to previous years?
  - If anomalous, in what way (temperature, precipitation, wind speed and direction)?

Comparison of SO_2 levels before and after fuel sulfur content regulation change

- How do levels measured in 2012 at Topaz and Erie stations between April 1st and July 31st compare to levels measured between August 1st and September 30th?
- What factors influence the observed differences:
  - Were meteorological conditions experienced before and after the regulatory change similar?
  - If anomalous, in what way?

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 2012, SO_2 levels were measured continuously 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.

- At Topaz station in 2012, no provincial, federal or WHO air quality guidelines were exceeded. One hour was in the Vancouver Island Health Authority's health risk guide category of 'unhealthy for sensitive groups'[9]. (In 2011, no existing guidelines were exceeded, and there were no measured levels in the 'unhealthy for sensitive groups' range).

- At Erie station in 2012, one 10-minute interval exceeded the WHO air quality guideline (500 $\mu g/m^3$), two hours were in the Vancouver Island Health Authority's health risk guide category of 'unhealthy for sensitive groups', and three days exceeded the WHO air quality guideline for 24 hour average SO_2 levels (20 $\mu g/m^3$). (In 2011, there were no exceedences of the WHO 10-minute guideline, two days in exceedence of the 24 hour WHO guideline, and two hours with levels in the 'unhealthy for sensitive groups' range).

- Maximum 10 minute average levels were higher in 2012 than in 2011 at Topaz station (269 $\mu g/m^3$ versus 124 $\mu g/m^3$) and at Erie station (636 $\mu g/m^3$ versus 438 $\mu g/m^3$).

- Hourly average levels measured at Topaz and Erie stations in 2012 were similar to those measured in 2011, although the maximums measured in 2012 were higher: 126 $\mu g/m^3$ versus 66 $\mu g/m^3$ at Topaz station, and 266 $\mu g/m^3$ versus 235 $\mu g/m^3$at Erie station.

- The diurnal patterns of hourly average SO_2 levels at Topaz station and Erie stations in 2012 were similar to that in 2011, except for a distinct departure in the early morning at Erie station associated with the arrival of a single cruise ship – the Sea Princess, on June 10th.

- In general, measured levels on or after August 1st, 2012 were similar to or lower than those measured prior to the 1 percent sulfur content fuel regulation. Recorded maximums were lower post-regulation at both Erie and Topaz stations, however elevated levels were still observed post-regulation.

[9] See Appendix A for more information on VIHA health risk guide categories.

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

Ambient levels and guidelines: In 2012, cruise ships were present for 1,136 hours[10] between April 1st and September 30th.

Tables 1 and 2 provide a summary of measured SO_2 levels at Erie and Topaz sites.

Table 1. Summary of 10-minute, 1 hour, and 24 hour SO_2 levels - 2012

10 minute average	**Maximum** ($\mu g/m^3$)	**95th percentile** ($\mu g/m^3$)	**Top 40** (range $\mu g/m^3$)	**Exceedences**
Erie station – days with cruise ships	636	11	155 - 636	0.004% (WHO)
Topaz station – days with cruise ships	269	11	66 - 269	None
Erie station – days without cruise ships	59	6	23 - 59	None
Topaz station – days without cruise ships	45	7	12 - 45	None
1 hour average	**Maximum** ($\mu g/m^3$)	**95th percentile** ($\mu g/m^3$)	**Top 20** (range $\mu g/m^3$)	**Exceedences**
Erie station – hours with cruise ships	266	38	75 - 266	0.2% in VIHA unhealthy 1% in VIHA moderate
Topaz station – hours with cruise ships	126	23	39 - 125	0.1% in VIHA moderate
Erie station – hours without cruise ships	34	5	14 - 34	None
Topaz station – hours without cruise ships	21	6	10 - 21	None
24 hour average	**Maximum** ($\mu g/m^3$)	**95th percentile** ($\mu g/m^3$)	**Top 10** (range $\mu g/m^3$)	**Exceedences**
Erie station – days with cruise ships	26	14	10 – 26	3% (WHO)
Topaz station – days with cruise ships	12	10	9 – 12	None
Erie station – days without cruise ships	7	3	2 – 7	None
Topaz station – days without cruise ships	6	4	3 – 6	None

Table 2. Seasonal average hourly SO_2 levels - 2012 (April – Sept only)

Location	**Seasonal average** ($\mu g/m^3$)
Erie station – all hours with cruise ships	8.3
Topaz station – all hours with cruise ships	6.4
Erie station – all hours without cruise ships	1.3
Topaz station – all hours without cruise ships	2.5

[10] 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. Hours with clearly elevated SO_2 levels immediately preceding an arrival or following a departure hour were also included.

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. A single event, the (June 10, 2012, arrival of the Sea Princess, with measured hourly average levels up to 199 $\mu g/m^3$, accounts for the significant and unusual peak seen in the early morning. SO_2 levels were lower at Topaz, and only an evening peak associated with cruise ship arrivals is clearly discernible. The diurnal patterns on 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 and Topaz station occurred when cruise ships were present. While it is difficult to attribute elevated SO_2 levels to particular ships when more than one is in port, a number of ships were associated with elevated levels when no other ships were nearby or at dock.

Hourly average levels depend on a complex relationship among numerous factors, including wind speed and 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 hourly average levels were measured at Erie and Topaz most often when winds were from 200^o to 250^o, which occurred about 50 percent of the time.
- Elevated levels varied in relation to wind speed recorded at each station, with no clear relationship, but elevated levels at Topaz station were more likely when wind speeds were lower at Ogden Point, and elevated levels at Erie station were more likely when wind speeds were higher.

Trends and Comparisons in hourly levels 2006 – 2012:

Topaz Site: At the Topaz site, the highest peak hourly average levels of SO_2 when cruise ships were present were recorded in 2009, and the lowest peak levels were recorded in 2011. The maximum level recorded in 2012 was the third highest in the seven years included. The diurnal pattern for hours with cruise ships present recorded at Topaz in each year (2006 to 2012 inclusive) shows reduced evening levels in 2012 compared to 2008 and 2009, but higher levels than recorded in 2011. The diurnal pattern for hours without cruise ships is similar in 2011 and 2012, with average levels being typically below 5 $\mu g/m^3$.

No clear associations were seen between SO_2 levels and annual differences in temperature, precipitation, or wind speed and direction measured at Topaz station; however, elevated levels were more likely to occur at Topaz when wind speeds recorded at Ogden Point were less than 6 meters/second (m/s). 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 nearby and at dock, and the sulfur content of the fuel burned. Data were not available to allow for full evaluation of these factors.

Erie Site: SO_2 levels measured in the James Bay neighbourhood at Erie station in 2012 when cruise ships were present were similar to those measured in 2011, with both years having levels significantly lower than those measured at the MAML site in 2009. The diurnal pattern in 2012 was similar to that in 2011, showing a distinct drop in average levels between evening arrivals and departures, unlike in 2009 when levels dropped off gradually over the evening hours after arrivals. In 2012, however, there was a clear peak in the morning hours due to a single event associated with the arrival of the Sea Princess on June 10, 2012. The diurnal pattern for hours without cruise ships at Erie station is similar in 2011 and 2012, with average levels being typically below 5 $\mu g/m^3$.

No clear associations were seen between SO_2 levels and annual differences in meteorological characteristics (temperature, precipitation) recorded at Topaz station, however elevated levels were more likely to occur when wind speeds recorded at Ogden Point were 6m/s or higher. Erie station was more frequently directly downwind of the terminals in 2012 (~ 17 percent of hours with ships) than in 2011 (~ 13 percent), and MAML in 2009 (~ 15 percent). Given measured levels are relatively comparable at Erie station in 2011 and 2012, the location of the monitor with respect to prevailing wind direction is not the only (or most important) reason for differences observed between levels measured at MAML and Erie stations.

Comparison of levels before and after fuel regulation: Prior to August 1st, 2012, sulfur content in marine fuel for ocean going vessels could have been as high as 3.5 percent. Fuel availability suggests that lower sulfur content fuels could have been used by ships visiting Victoria earlier than August 1st. After this date marine fuel was regulated to contain no more than 1 percent sulfur. While there are not enough data to establish a statistical difference pre- and post-regulation in 2012, peak levels at Erie station were lower post-regulation. At Topaz, peak levels were also lower after regulation, but not as markedly as at Erie Station (Table 3). Elevated levels were, however, observed post-regulation and fuel sulfur content should be confirmed for each ship for future analyses.

Table 3. Summary of 10-minute, 1 hour, and 24 hour SO_2 Peak Levels – Pre-and Post-regulation 2012

	Pre-regulation		**Post-regulation**	
10 minute average	**Maximum** ($\mu g/m^3$)	**95th percentile** ($\mu g/m^3$)	**Maximum** ($\mu g/m^3$)	**95th percentile** ($\mu g/m^3$)
Erie station – days with cruise ships	636	20	182	13
Topaz station – days with cruise ships	269	14	133	15
1 hour average				
Erie station – hours with cruise ships	266	38	134	36
Topaz station – hours with cruise ships	126	23	88	23
24 hour average				
Erie station – days with cruise ships	26	13	14	12
Topaz station – days with cruise ships	12	10	12	10

2. Methods

All SO_2 data from Topaz and Erie stations for 2012 were downloaded from the BC MoE website and adjusted from Pacific Standard Time to Pacific Daylight Savings Time[11]. Data recorded between 8am and 11am on May 15th, 2012 were removed from the 10-minute and hourly average data sets as anomalously high levels were included that were associated with instrument calibration[12]. May 15th was also excluded from the 24 hour average data set for the same reason.

All SO_2 levels were converted from parts per billion (ppb) to micrograms per cubic meter ($\mu g/m^3$) by multiplying by 2.62, and all negative data were removed and left blank. Prior to conversion, 0.5 ppb was added to all 10 minute averages; therefore, these 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 $\mu g/m^3$). All instruments were maintained and calibrated by MoE staff. Instrument calibration and audit records for Erie station are available on request to BC MoE.

Data for wind direction, wind speed, temperature, and precipitation at Topaz station for 2006 – 2012 were also downloaded from the BC MoE website and adjusted from Pacific Standard Time to Pacific Daylight Savings Time. Instrument descriptions and maintenance/calibration records are available on request to MoE.

Ten-minute average wind speed (knots) and wind direction (degrees) at Ogden Point were provided by the Greater Victoria Harbour Authority[13]. Ogden Point wind speeds were adjusted from Universal Time to Pacific Daylight Savings Time and 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 in Pacific Daylight Savings Time) for 2006 to 2012 were provided by the Greater Victoria Harbour Authority.

[11] Data download at http://envistaweb.env.gov.bc.ca/
[12] Personal communication, May 15, 2012. John Deniseger, BC Ministry of Environment.
[13] Instrument descriptions are available on request to the Greater Victoria Harbour Authority.

3. Ambient SO_2 concentrations - 2012

Distributions of 10 minute average, 1 hour average, 24 hour average and seasonal hourly average levels of SO_2 are presented in Tables 4 and 5. On days with cruise ships present, 10-minute average levels ranged from 1 to 636 $\mu g/m^3$ at Erie station, and from 1 to 269 $\mu g/m^3$ at Topaz station, in comparison to days without cruise ships present when levels ranged from 1 to 59 $\mu g/m^3$ and 0 to 45 $\mu g/m^3$ at Erie station and Topaz station respectively.

Hourly averages when cruise ships were present ranged from <1 to 266 $\mu g/m^3$ and 1 to 126 $\mu g/m^3$ at Erie and Topaz stations respectively, compared to 1 to 34 $\mu g/m^3$ and 1 to 21 $\mu g/m^3$ during hours without cruise ships.

Average 24 hour levels ranged from 1 to 26 $\mu g/m^3$ at Erie station and from 2 to 12 $\mu g/m^3$ at Topaz station on days with cruise ships present, and were lower on days without cruise ships present: 0 to 7 $\mu g/m^3$ at Erie station and 1 to 6 $\mu g/m^3$ at Topaz 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:

- The distribution of 10 minute average levels was higher at Erie station on days with cruise ships than days without cruise ships from the 75th percentile upward. At Topaz station, the distribution was higher on days with cruise ships than on days without from the 25th percentile upward.
- The distribution of 10 minute average levels was higher at Erie station than at Topaz station from the 95th percentile on days with cruise ships, and from the 98th percentile on days without cruise ships present.

- The distributions of 1 hour average levels at both Erie and Topaz stations were higher during hours with cruise ships than during hours without cruise ships at every percentile.
- The distribution of 1 hour averages was higher at Erie station than at Topaz station during hours with cruise ships in port from the 90th percentile upward, and from the 98th percentile upward during hours without cruise ships.

- The distributions of 24 hour average levels at both Erie and Topaz stations were higher during hours with cruise ships than during hours without cruise ships at every percentile.
- The distribution of 24 hour average levels was consistently higher at Erie station than at Topaz station on days with cruise ships in port from the 90th percentile.
- 24 hour averages were very similar (+/- 1 $\mu g/m^3$) at both Erie station and Topaz station on days without cruise ships.

SO_2 levels were below current Provincial Ambient Air Quality Objectives (see Tables 7, 8 and 9). Three 24 hour averages (3% 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' [14], respectively (Tables 6 – 9).

Table 4. Distribution of SO_2 levels (10 minute, 1 hour and 24 hour) - 2012

	10-minute* (ug/m^3)				1 hour (ug/m^3)				24 hour (ug/m^3)			
	Cruise days		**Non-cruise days**		**Cruise hours**		Non-cruise hours		**Cruise days**		Non-cruise days	
Percentile	**Erie**	**Topaz**	**Erie**	**Topaz**	**Erie**	**Topaz**	Erie	Topaz	**Erie**	**Topaz**	Erie	Topaz
5	**1**	**0**	1	0	**< 1**	**1**	0	1	**1**	**2**	0	1
25	**2**	**3**	2	0	**1**	**2**	< 1	1	**2**	**2**	1	2
50	**2**	**4**	2	0	**2**	**3**	<1	2	**3**	**4**	1	2
75	**4**	**6**	3	4	**7**	**7**	1	3	**5**	**5**	2	3
90	**9**	**10**	4	5	**21**	**14**	3	5	**9**	**8**	3	4
95	**18**	**15**	6	7	**38**	**23**	5	6	**12**	**10**	3	4
96	**21**	**17**	6	7	**43**	**26**	6	6	**14**	**11**	3	5
97	**29**	**20**	7	7	**53**	**30**	6	7	**15**	**11**	4	5
98	**42**	**26**	9	8	**71**	**37**	8	7	**22**	**12**	5	6
99	**75**	**37**	14	9	**97**	**44**	10	9	**24**	**12**	6	6
100	**636**	**269**	59	45	**266**	**126**	34	21	**26**	**12**	7	6
Total intervals	**15,120**	**15,120**	11,232	11,232	1,121	1,121	3,272	3,272	107	107	76	76
Total with valid data	**14,168 (94%)**	**14,134 (94%)**	10,716 (95%)	10,639 (95%)	1,087 (97%)	1,064 (95%)	3,189 (97%)	3,113 (95%)	100 (94%)	107 (100%)	75 (100%)	75 (100%)

*0.5 ppb (1.3 ug/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 ug/m^3 and should be considered a 'worst case scenario'. Data for Cruise days includes 10-minute intervals with no ships present.

Table 5. Seasonal hourly average SO_2 levels – 2012 (April – September)

Erie Cruise (ug/m^3)	Erie No cruise (ug/m^3)	Erie All (ug/m^3)	Topaz Cruise (ug/m^3)	Topaz No cruise (ug/m^3)	Topaz All (ug/m^3)
8.3	1.3	3.1	6.5	2.5	3.5

[14] See Appendix A for more information on VIHA health risk categories.

Table 6. 10 minute average levels at or above guidelines - 2012

Guideline	Level (ug/m^3)	Erie Station Cruise days	Topaz Station Cruise days	Erie Station Non-cruise days	Topaz Station Non-cruise days
World Health Organization	500	1 (0.004%)	0	0	0

Table 7. 1 hour average levels at or above guidelines - 2012

Guideline[15]	Level (ug/m^3)	Erie Cruise	Topaz Cruise	Erie No Cruise	Topaz No Cruise
VIHA health risk guide - good	<=92	1,074 (99%)	1,063 (99.9%)	3,188 (100%)	3,113 (100%)
Moderate	93 - 197	11 (1%)	1 (0.1%)	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 8. 24 hour average levels at or above guidelines - 2012

Guideline	Level (ug/m^3)	Erie Cruise	Topaz Cruise	Erie No Cruise	Topaz No Cruise
World Health Organization	20	3 (3%)	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 9. Annual hourly average levels at or above guidelines - 2012

Guideline	Level (ug/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 September 30th and would be lower if all hours in 2011 were included.

[15] See Appendix A for more information on VIHA health risk categories.

4. Characteristics of SO_2 events - 2012

4.1 Diurnal patterns - 2012

In 2012, the diurnal (time of day) pattern at Erie station for hours with cruise ships in port showed a clear association with cruise ship activity, particularly during evening arrivals and departures, but also slightly elevated between 10am and 3pm (Figure 2). An unusual spike is also evident in the early morning hours. On June 10th, 2012, the cruise ship Sea Princess arrived (first line) at 6:40am. Elevated levels of SO_2 were recorded at Erie station in both the hour leading up to 7am (84 μg/m^3), and the hour leading up to 8am (199 μg/m^3), indicating the influence of emissions from approaching and manoeuvring prior to first line, as well as while at dock following arrival. These two elevated levels create the large peak seen in the diurnal pattern, because the average is based on the relatively few hours that cruise ships were present in the early morning (Figure 3).

At Topaz station (Figure 4), the most prominent peak in average SO_2 levels occurred at 8pm, 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 4).

Figure 2. Diurnal SO_2 levels with and without cruise ships– Erie Station 2012

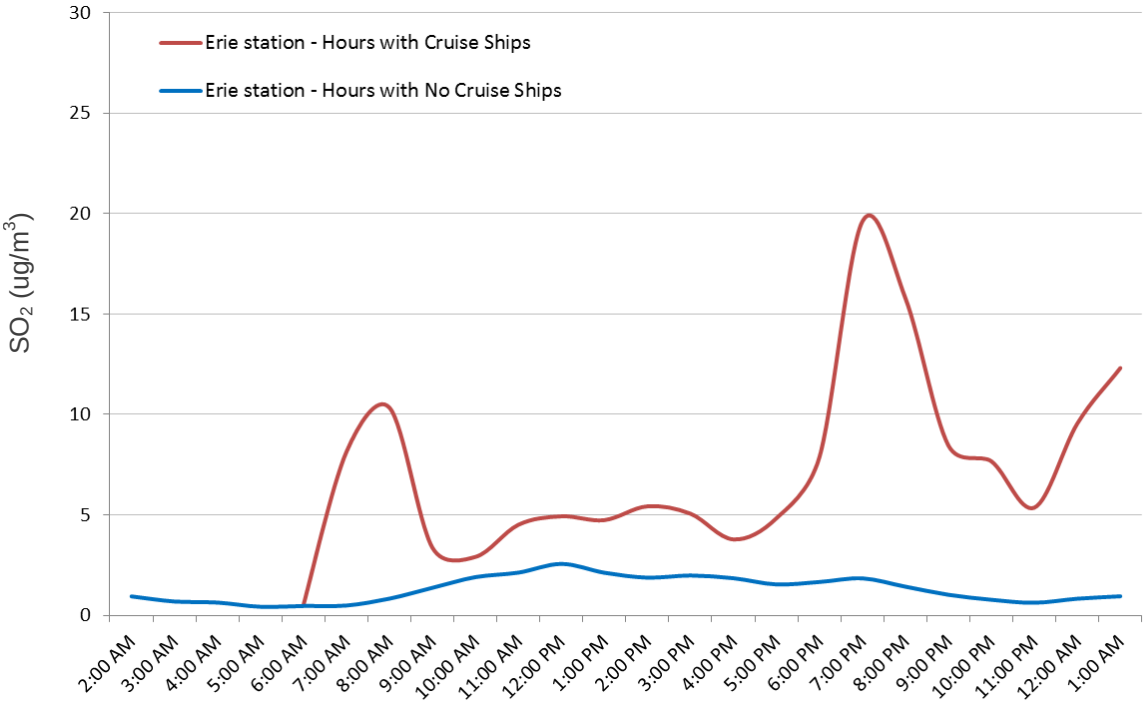


Figure 3. Count of Hours with Ships Present on Days with Cruise Ships- 2012

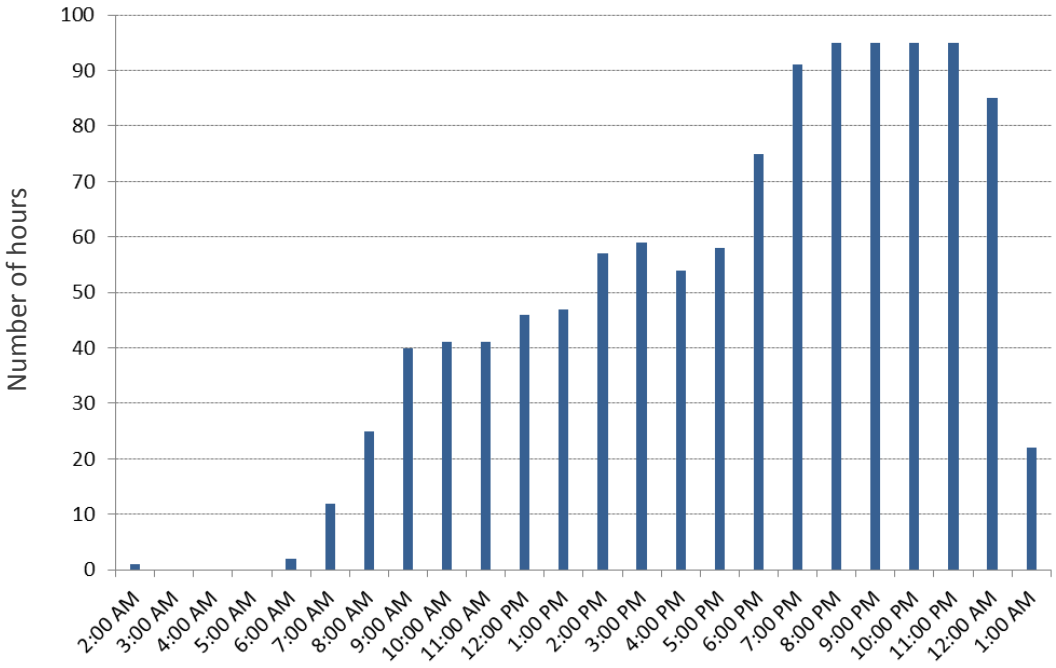
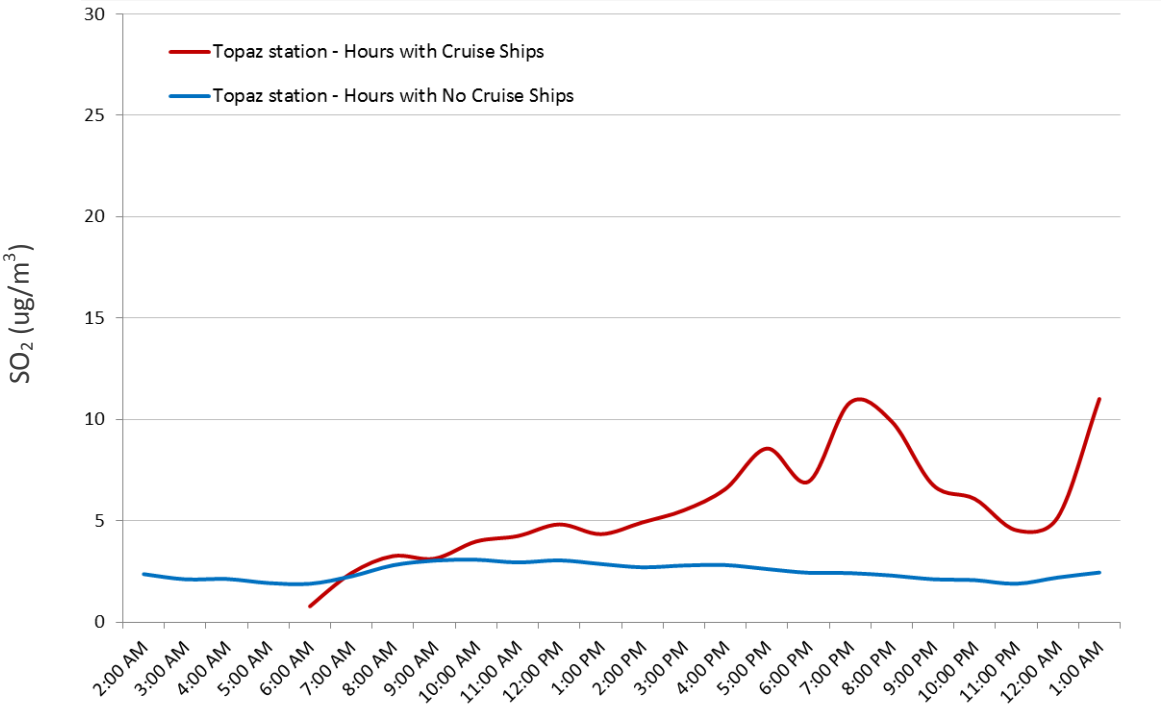


Figure 4. Diurnal SO_2 levels with and without cruise ships– Topaz Station 2012



4.2 Maximum events – 2012

The highest forty 10 minute averages at both Erie station (155 to 636 μg/m^3) and Topaz station (66 to 269 μg/m^3) occurred when cruise ships were present (Tables 10 and 11). At Erie station, these events were more typically associated with arrivals and departures. At Topaz station, events were also associated with arrivals, and more frequently when ships were at dock. Elevated 10 minute average levels were measured when the following ships were alone at or near dock:

Erie station:

- Carnival Spirit (May 14th, July 9th, August 13th)
- Sea Princess (June 10th)
- Rhapsody of the Seas (August 23rd)

Topaz station:

- Norwegian Pearl (May 12th)
- Carnival Spirit (June 11th)
- Rhapsody of the Seas (June 21st)

When more than one cruise ship was nearby or present, it is not possible to attribute elevated levels to one particular vessel; however, eleven of the highest forty 10 minute average levels at Topaz station occurred when the Norwegian Pearl and Star Princess together were the only two ships at port.

The highest twenty 1 hour averages at both Erie station (75 to 266 μg/m^3) and Topaz station (39 to 125 μg/m^3) occurred when cruise ships were present (Tables 12 and 13) and were similar in nature to the 10 minute peaks – more often associated with arrivals, some departures, and 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 recorded when the following ships were the only ones in or near port:

Erie station:

- Carnival Spirit (May 14th, July 9th, August 13th)

Topaz station:

- Norwegian Pearl (May 12th)
- Disney Wonder (June 10th, August 5th)
- Carnival Spirit (June 11th, July 16th)

The highest ten 24 hour averages at Erie station (14 to 34 μg/m^3) and Topaz station (10 to 21 μg/m^3) occurred on days with cruise ship activity (Tables 14 and 15).

In general, the dates and times of the highest levels are not the same at Erie and Topaz stations, with a few exceptions:

- 10 minute average levels were elevated at both sites at the same time on July 14th and July 21st
- 1 hour average levels were elevated at the same time at both sites on July 21st

This suggests different conditions are related to elevated levels at Erie station in comparison to Topaz station (See Section 4.3 for analysis of events according to wind speed and direction at Ogden Point).

Table 10. 40 highest 10 minute average levels at Erie station - 2012 (*__bold__ indicates highest 10 levels)

Date	Time	SO_2 (ug/m^3)	Ships present or nearby during peak levels	First Line	Last Line	Activity +/- 1 hour
05/14/2012	20:00	222	Carnival Spirit	19:30	23:42	Arrival
	20:10	193				
05/18/2012	18:30	216	Sapphire Princess	7:14	22:28	At Dock
	18:40	**242**	Westerdam	18:05	23:56	Arrival
	18:50	**270**				
	19:00	190				
	19:10	209				
	19:20	209				
	19:30	168				
05/25/2012	18:50	155	Norwegian Jewel	13:35	20:55	At Dock
			Westerdam	18:15	0:04	Arrival
06/08/2012	18:50	226	Norwegian Jewel	14:00	21:34	At Dock
	19:00	**241**	Westerdam	18:16	23:59	Arrival
			Golden Princess	18:33	23:35	Arrival
06/10/2012	6:50	227	Sea Princess	6:40	14:07	Arrival
	7:00	226				
	7:10	198				
	7:20	233				
	7:30	216				
	7:40	198				
	7:50	226				
06/24/2012	18:30	160	Sea Princess	11:32	19:02	Departure
	18:50	**249**	Disney Wonder	18:30	23:06	Arrival
07/06/2012	18:00	**407**	Norwegian Jewel	13:55	21:30	At Dock
	18:10	**636**	Westerdam	17:45	0:05	Arrival & Departure
	18:20	**321**	Golden Princess	18:12	23:35	Arrival & Departure
	18:40	**237**				
	18:50	**256**				
	23:50	207				
07/09/2012	19:20	191	Carnival Spirit	19:17	23:48	Arrival
	19:30	187				
	19:40	206				
07/14/2012	23:40	170	Norwegian Pearl	17:42	23:40	Departure
	24:00	181	Star Princess	18:14	0:05	Departure
	00:10	167	Oosterdam	19:35	23:51	Departure
07/20/2012	19:50	190	Norwegian Jewel	13:55	21:29	At Dock
			Golden Princess	17:42	23:48	At Dock
			Westerdam	18:02	0:00	At Dock
07/21/2012	18:30	**319**	Norwegian Pearl	17:40	23:41	Arrival
			Star Princess	18:16	0:08	Arrival
08/13/2012	19:30	182	Carnival Spirit	19:14	23:38	Arrival
08/23/2012	11:10	161	Rhapsody of the Seas	8:13	17:44	At Dock
09/01/2012	18:00	160	Norwegian Pearl	17:41	23:59	Arrival
	18:10	155	Star Princess	18:07	23:50	Arrival
09/08/2012	18:20	171	Norwegian Pearl	17:40	23:39	Arrival
			Star Princess	18:12	23:54	Arrival

Table 11. 40 highest 10 minute average levels at Topaz station - 2012 (*__bold__ indicates highest 10 levels)

Date	Time	SO_2 (ug/m^3)	Ships present or nearby during peak levels	First Line	Last Line	Activity +/- 1 hour
05/12/2012	18:40	99	Norwegian Pearl	17:49	23:53	Arrival
05/31/2012	18:30	**152**	Rhapsody of the Seas	8:28	17:26	Departure
	18:40	93	Celebrity Millennium	15:07	21:08	At Dock
06/10/2012	19:20	68	Disney Wonder	18:40	23:01	Arrival & At Dock
	21:40	73				
	21:50	66				
06/11/2012	19:30	66	Carnival Spirit	19:02	23:58	Arrival
06/21/2012	15:00	**164**	Rhapsody of the Seas	8:17	17:51	At Dock
	15:10	**115**				
	16:00	84				
06/28/2012	13:40	68	Rhapsody of the Seas	8:14	18:04	At Dock
	13:50	67				
	14:20	80	Amsterdam	11:41	22:55	At Dock
	14:30	71				
	14:40	72				
06/29/2012	19:10	**166**	Norwegian Jewel	13:54	21:18	At Dock
			Westerdam	18:27	0:08	Arrival
			Golden Princess	18:47	23:46	Arrival
07/05/2012	16:30	80	Rhapsody of the Seas	8:22	17:47	At Dock & Departure
	16:40	**266**				
	16:50	**269**				
	17:00	**137**	Celebrity Infinity	17:25	23:50	Arrival
	17:30	82				
	17:40	78				
07/07/2012	18:10	109	Star Princess	16:30	0:25	At Dock
	18:20	**136**				
	18:30	95	Norwegian Pearl	17:35	23:45	Arrival
07/14/2012	24:00	76	Norwegian Pearl	17:42	23:40	Departure
			Star Princess	18:14	0:05	Departure
			Oosterdam	19:35	23:51	Departure
07/21/2012	18:50	67	Norwegian Pearl	17:40	23:41	Arrival
			Star Princess	18:16	0:08	
08/11/2012	18:50	87	Norwegian Pearl	17:43	23:29	Arrival & At Dock
	19:00	96				
	19:10	94	Star Princess	18:16	23:58	Arrival & At Dock
	19:20	**128**				
	19:30	71				
08/17/2012	18:40	71	Norwegian Jewel	13:56	21:20	At Dock
	19:20	69				
	19:30	75	Golden Princess	18:06	23:50	Arrival & At Dock
	19:40	103				
	19:50	**133**	Westerdam	18:30	0:00	Arrival & At Dock
	20:00	97				
08/25/2012	18:40	96	Norwegian Pearl	17:40	23:29	Arrival & At Dock
	18:50	78	Star Princess	18:11	23:50	Arrival

Table 12. 20 highest 1 hour average levels at Erie station - 2012

Date	Time	SO_2 (ug/m^3)*	Ships present or nearby during peak levels	First Line	Last Line	Activity +/- 1 hour
05/14/2012	20:00	100	Carnival Spirit	19:13	23:42	Arrival
05/18/2012	19:00	**154**	Sapphire Princess	7:14	22:28	At Dock & Departure
	21:00	**122**	Westerdam	18:05	23:56	Arrival & At Dock
	22:00	**102**				
06/08/2012	19:00	89	Norwegian Jewel	14:00	21:43	At Dock
			Westerdam	18:16	23:59	Arrival
			Golden Princess	18:33	23:35	Arrival
06/10/2012	7:00	84	Sea Princess	6:40	14:07	Arrival & At Dock
	8:00	**199**	Disney Wonder	18:40	23:01	At Dock
	20:00	78	Carnival Spirit	19:02	23:58	Arrival
06/14/2012	21:00	91	Amsterdam	11:44	22:57	At Dock
			Celebrity Infinity	17:38	23:50	At Dock
06/24/2012	19:00	**112**	Sea Princess	11:32	19:02	Departure
			Disney Wonder	18:30	23:06	Arrival
07/06/2012	18:00	80	Norwegian Jewel	13:55	21:30	At Dock
	19:00	**266**	Westerdam	17:45	0:05	Arrival & Departure
	24:00	93	Golden Princess	18:12	23:25	Arrival & Departure
07/09/2012	20:00	**140**	Carnival Spirit	19:17	23:48	Arrival
07/14/2012	24:00	**120**	Norwegian Pearl	17:42	23:40	Departure
			Star Princess	18:14	0:05	Departure
			Oosterdam	19:35	23:51	Departure
07/20/2012	20:00	75	Norwegian Jewel	13:55	21:29	At Dock
			Golden Princess	17:42	23:48	At Dock
			Westerdam	18:02	0:00	At Dock
07/21/2012	19:00	90	Norwegian Pearl	17:40	23:41	At Dock
			Star Princess	18:16	0:08	Arrival
08/13/2012	20:00	97	Carnival Spirit	19:14	23:38	Arrival
09/01/2012	19:00	**119**	Norwegian Pearl	17:41	23:59	At Dock
			Star Princess	18:07	23:50	Arrival
09/08/2012	19:00	**134**	Norwegian Pearl	17:40	23:39	At Dock
			Star Princess	18:12	23:54	Arrival

*** bold** indicates top ten levels

Table 13. 20 highest 1 hour average levels at Topaz station - 2012

Date	Time	SO_2 (ug/m^3)*	Ships present or nearby during peak levels	First Line	Last Line	Activity +/- 1 hour
05/12/2012	19:00	39	Norwegian Pearl	17:49	23:53	At Dock
05/31/2012	19:00	**61**	Celebrity Millennium	15:07	21:08	At Dock
			Celebrity Infinity	18:54	23:50	Departure
			Amsterdam	19:23	0:11	Arrival
06/10/2012	22:00	43	Disney Wonder	18:40	23:01	At Dock
06/11/2012	20:00	45	Carnival Spirit	19:02	23:58	Arrival
06/21/2012	16:00	**54**	Rhapsody of the Seas	8:17	17:51	At Dock & Departure
	18:00	39	Celebrity Infinity	17:27	23:52	Arrival
06/28/2012	14:00	41	Rhapsody of the Seas	8:14	18:04	At Dock
	15:00	**61**	Amsterdam	11:41	22:55	At Dock
06/29/2012	20:00	**72**	Norwegian Jewel	13:54	21:18	At Dock
			Westerdam	18:27	0:08	At Dock
			Golden Princess	18:47	23:46	At Dock
07/05/2012	17:00	**125**	Rhapsody of the Seas	8:22	17:47	Departure
	18:00	**55**	Celebrity Infinity	17:25	23:50	Arrival
07/07/2012	19:00	**73**	Star Princess	16:30	0:25	At Dock
			Norwegian Pearl	17:35	23:45	At Dock
07/13/2012	19:00	43	Norwegian Jewel	13:55	21:18	At Dock
			Westerdam	17:49	23:55	At Dock
			Golden Princess	18:20	23:42	Arrival
07/16/2012	20:00	39	Carnival Spirit	19:01	23:47	Arrival
07/21/2012	19:00	41	Norwegian Pearl	17:40	23:41	At Dock
			Star Princess	18:16	0:08	Arrival
08/05/2012	19:00	43	Disney Wonder	18:11	23:02	Arrival
08/11/2012	19:00	40	Norwegian Pearl	17:43	23:29	At Dock
	20:00	**73**	Star Princess	18:16	23:58	Arrival & At Dock
08/17/2012	20:00	**88**	Golden Princess	18:06	23:50	At Dock
			Westerdam	18:30	0:00	At Dock
08/25/2012	19:00	**47**	Norwegian Pearl	17:40	23:29	At Dock
			Star Princess	18:11	23:50	Arrival

*** bold** indicates top ten levels

Table 14. 10 highest 24 hour average levels at Erie station 2012

Date	SO_2 (ug/m^3)*	Ships present at any time during day	First Line	Last Line
05/18/2012	21.7	Sapphire Princess	7:14	22:28
		Norwegian Jewel	7:36	16:50
		Westerdam	18:05	23:56
06/10/2012	24.1	Sea Princess	6:40	14:07
		Disney Wonder	18:40	23:01
		Carnival Spirit	19:02	23:58
06/24/2012	11.0	Sea Princess	11:32	19:02
		Disney Wonder	18:30	23:06
07/06/2012	26.2	Norwegian Jewel	13:55	21:30
		Westerdam	17:45	0:05
		Golden Princess	18:12	23:35
07/09/2012	11.5	Carnival Spirit	19:17	23:48
07/14/2012	11.0	Norwegian Pearl	17:42	23:40
		Star Princess	18:14	0:05
		Oosterdam	19:35	23:51
08/13/2012	14.4	Carnival Spirit	19:14	23:38
09/01/2012	12.1	Norwegian Pearl	17:41	23:59
		Star Princess	18:07	23:50
		Oosterdam	20:08	23:28
09/08/2012	9.7	Norwegian Pearl	17:40	23:39
		Star Princess	18:12	23:54
		Oosterdam	20:23	23:31
09/20/2012	13.6	Amsterdam	11:55	22:48
		Celebrity Infinity	17:13	23:35

*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.

Table 15. 10 highest 24 hour average levels at Topaz station 2012

Date	SO_2 (ug/m^3)*	Ships present at any time during day	First Line	Last Line
05/31/2012	8.6	Sea Princess	6:37	14:30
		Celebrity Infinity	18:54	23:50
		Amsterdam	19:23	0:11
06/21/2012	9.4	Rhapsody of the Seas	8:17	17:51
		Celebrity Infinity	17:27	23:52
06/28/2012	11.0	Rhapsody of the Seas	8:14	18:04
		Amsterdam	11:41	22:55
		Celebrity Infinity	17:21	23:55
07/05/2012	12.1	Rhapsody of the Seas	8:22	17:47
		Celebrity Infinity	17:25	23:50
07/07/2012	8.6	Star Princess	16:30	0:25
		Norwegian Pearl	17:35	23:45
		Oosterdam	19:35	23:53
07/25/2012	11.8	Silver Shadow	7:45	23:50
07/26/2012	10.5	Rhapsody of the Seas	8:08	17:39
		Celebrity Infinity	17:10	23:49
		Amsterdam	19:46	0:07
08/05/2012	10.7	Disney Wonder	18:11	23:02
08/11/2012	10.0	Norwegian Pearl	17:43	23:29
		Star Princess	18:16	23:58
		Oosterdam	20:41	23:46
08/17/2012	11.8	Norwegian Jewel	13:56	21:20
		Golden Princess	18:06	23:50
		Westerdam	18:30	0:00

*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 - 2012

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, 9 and 10).
- Higher hourly average levels were measured at Erie and Topaz stations most often when winds were blowing from the cruise ship terminal toward the monitoring locations (from 200^o to 250^o),which occurred about 50 percent of the time when ships were nearby or in port (Figures 7 and 8).
- In general, wind speed varied in relation to hourly average levels, with no clear relationship apparent. Elevated levels were observed with both lower and higher wind speeds at Erie station (Figures 11), and while wind speeds were lower and less variable at Topaz station, the same pattern can be observed (Figure 12).
- Analysis of the highest forty 10 minute events and highest twenty 1 hour events indicates these are more likely to occur at Erie station when wind speed recorded at Ogden Point is 6 m/s or more, and at Topaz station when wind speed recorded at Ogden Point is lower than 6 m/s (Figures 13 and 14).

Additional 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 2012

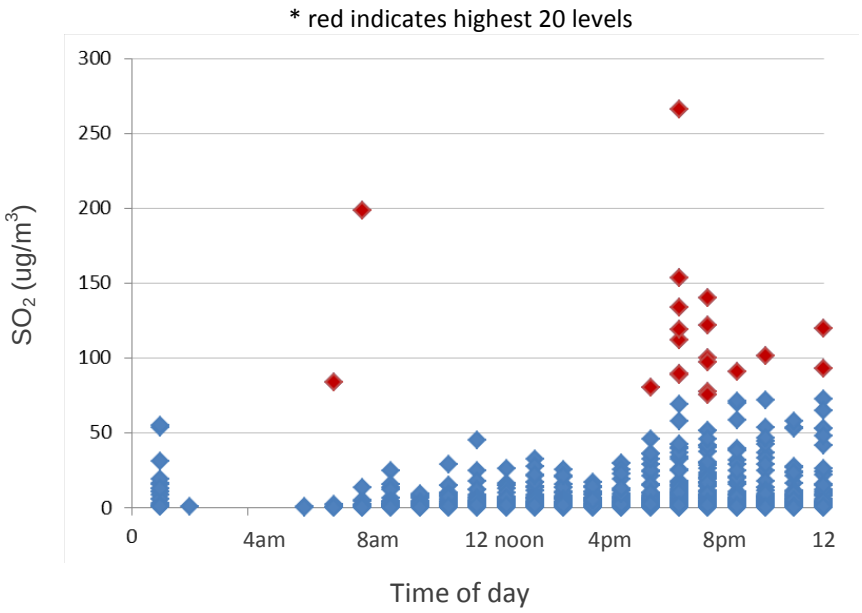
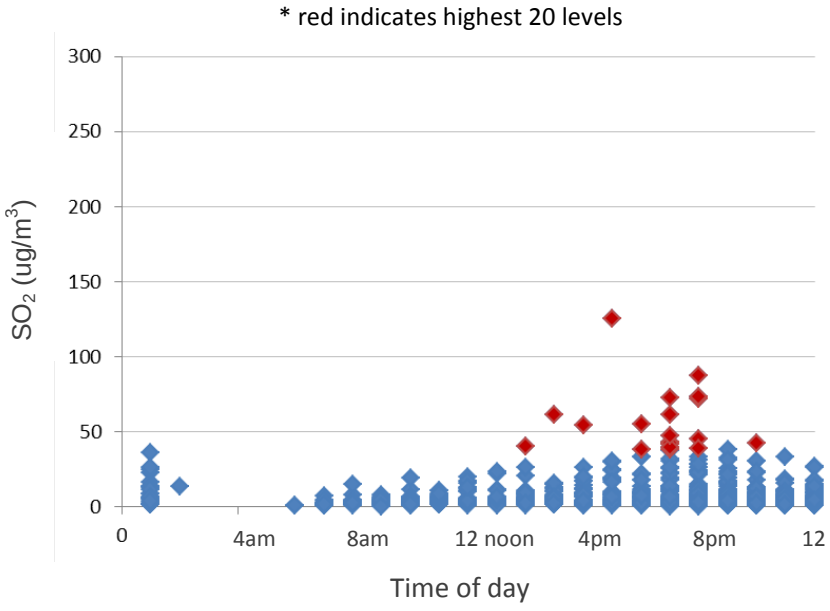


Figure 6. Hourly SO_2 levels by time of day when cruise ships present – Topaz 2012



Elevated levels of SO_2 were recorded at various times of day, but more often in the early evenings when most cruise ships arrive.

Figure 7. Hourly SO_2 levels by wind direction at Ogden Point when cruise ships present– Erie 2012

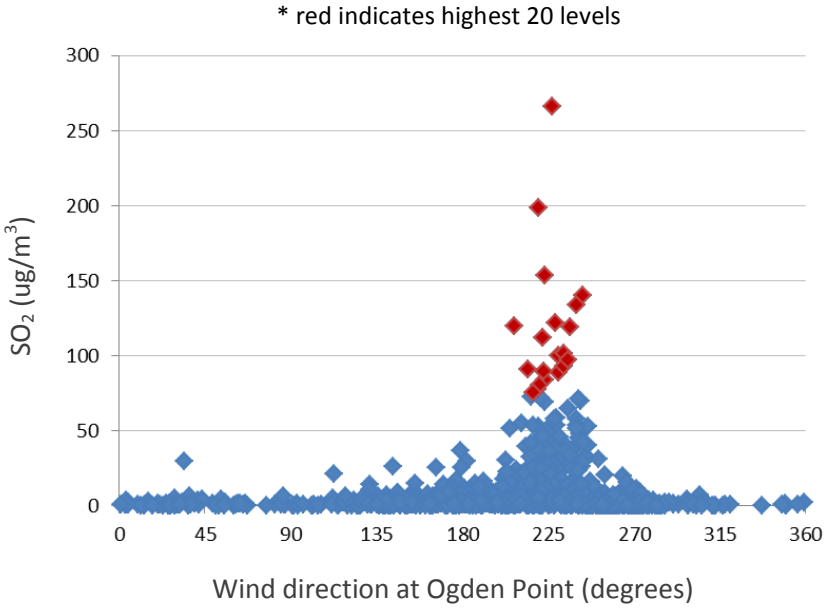
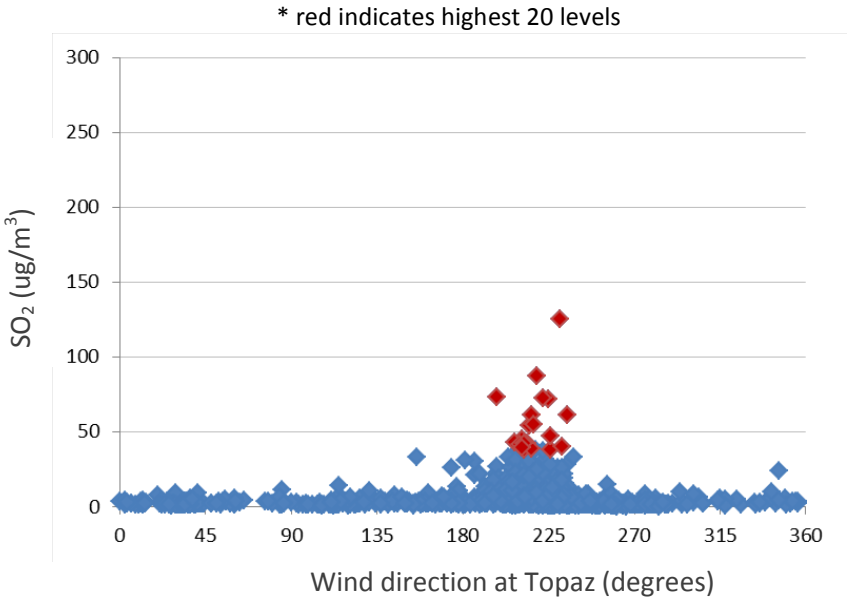


Figure 8. Hourly SO_2 levels by wind direction at Topaz when cruise ships present – Topaz 2012



Elevated levels of SO_2 at both Erie and Topaz stations occur when winds generally are blowing from the Ogden Point Terminal toward the stations (approximately from 200 to 250 degrees).

Figure 9. Hourly SO_2 levels by number of cruise ships present – Erie 2012

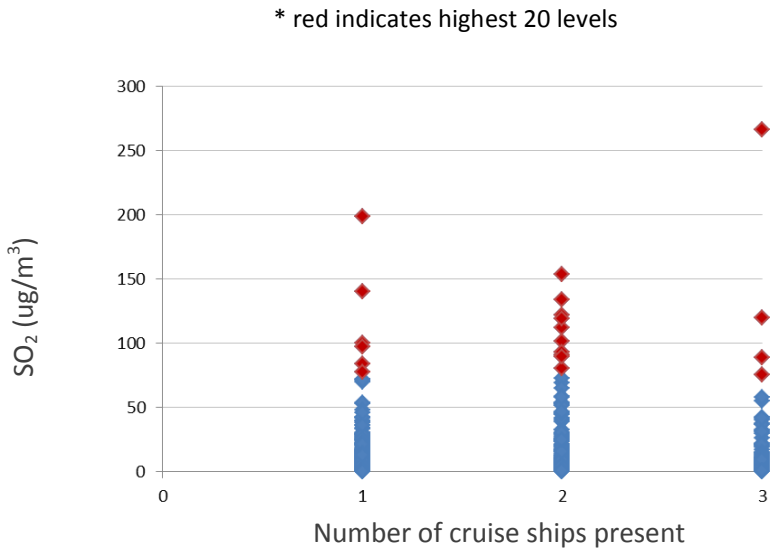
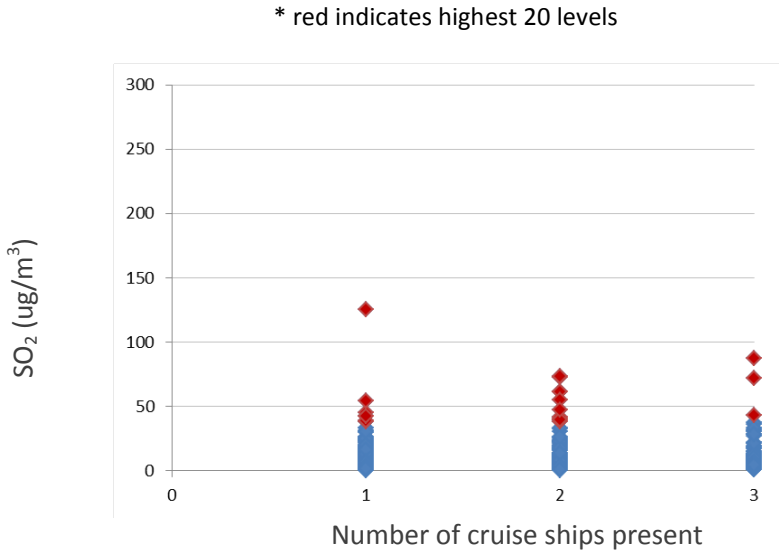


Figure 10. Hourly SO_2 levels by number of cruise ships present – Topaz 2012



Elevated hourly levels of SO_2 at Erie and Topaz stations are not obviously related to the number of cruise ships present. Prior to August 1st, this lack of relationship may be due to differences in the types of fuels used or the age and efficiency of ship engines. For example, the emissions of one ship using higher sulfur fuel or with older less efficient engines might be higher than the combined emission of two ships burning lower sulfur fuel with newer more efficient engines. It may also be that winds were not always blowing toward the monitoring stations when more ships were present, and peak levels associated with every cruise ship arrival and departure may not be reflected in the available data. See Appendix B for an analysis of the hourly average SO_2 versus number of ships present considering only data when wind direction was from 200 to 250 degrees (blowing from the terminals toward Erie station).

Figure 11. Hourly SO_2 levels by wind speed at Ogden Point when cruise ships present – Erie 2012

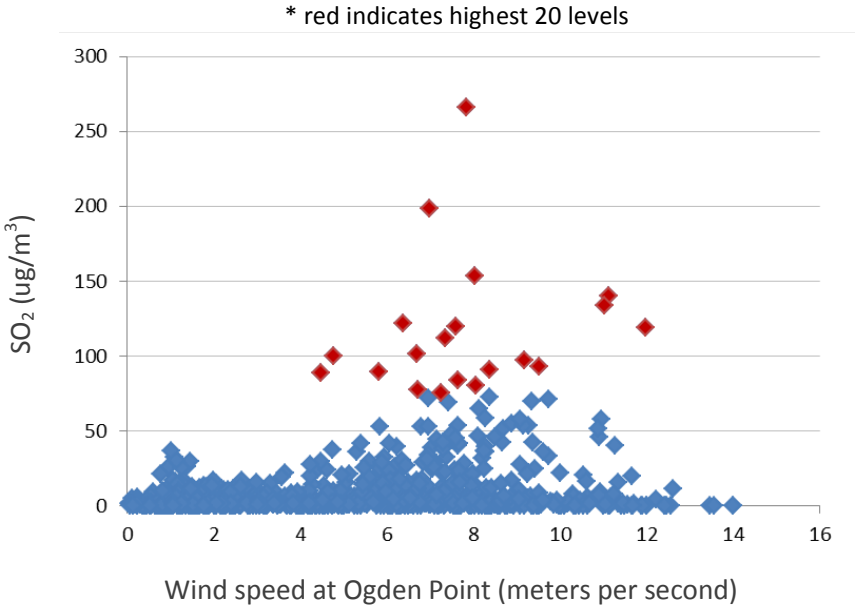
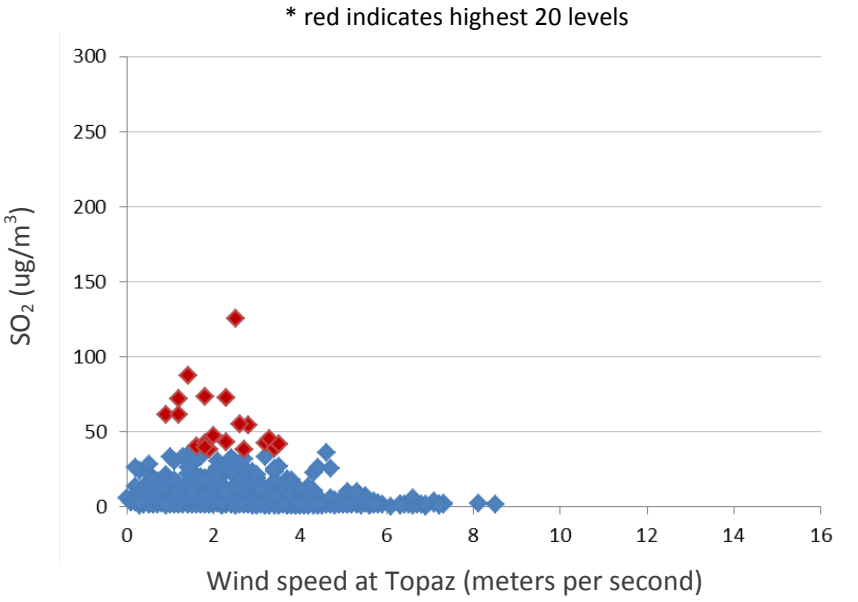


Figure 12. Hourly SO_2 levels by wind speed at Topaz when cruise ships present – Topaz 2012



Elevated hourly levels of SO_2 at Erie and Topaz stations are not obviously related to wind speed. See Appendix C for analysis of hourly average SO_2 versus wind speed considering only data when wind direction was from 200 to 250 degrees (blowing from the terminals toward Erie station).

Figure 13. Wind speed and direction at Ogden Point during highest forty 10 minute averages at Erie and Topaz Stations – 2012

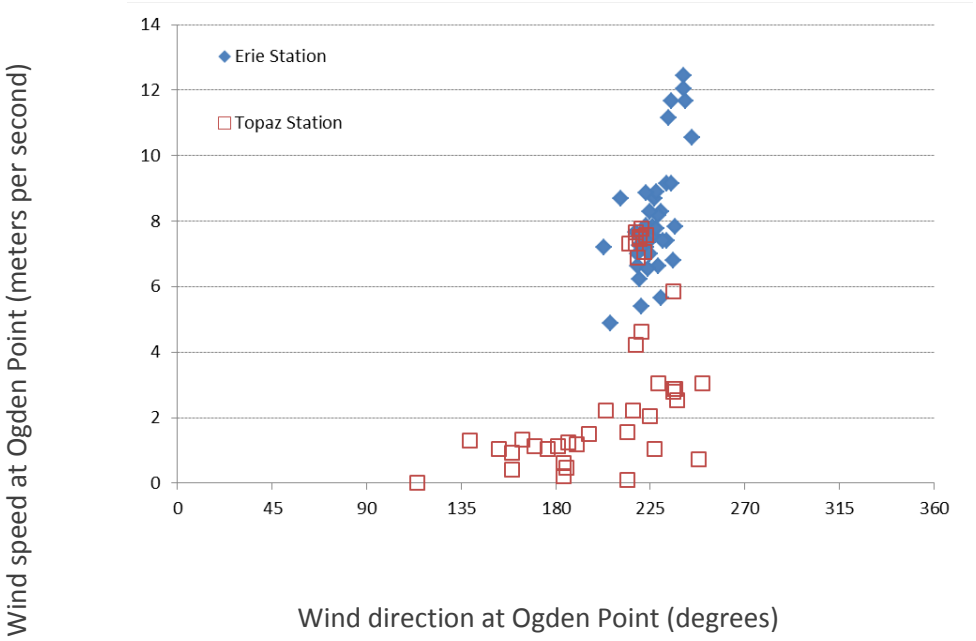
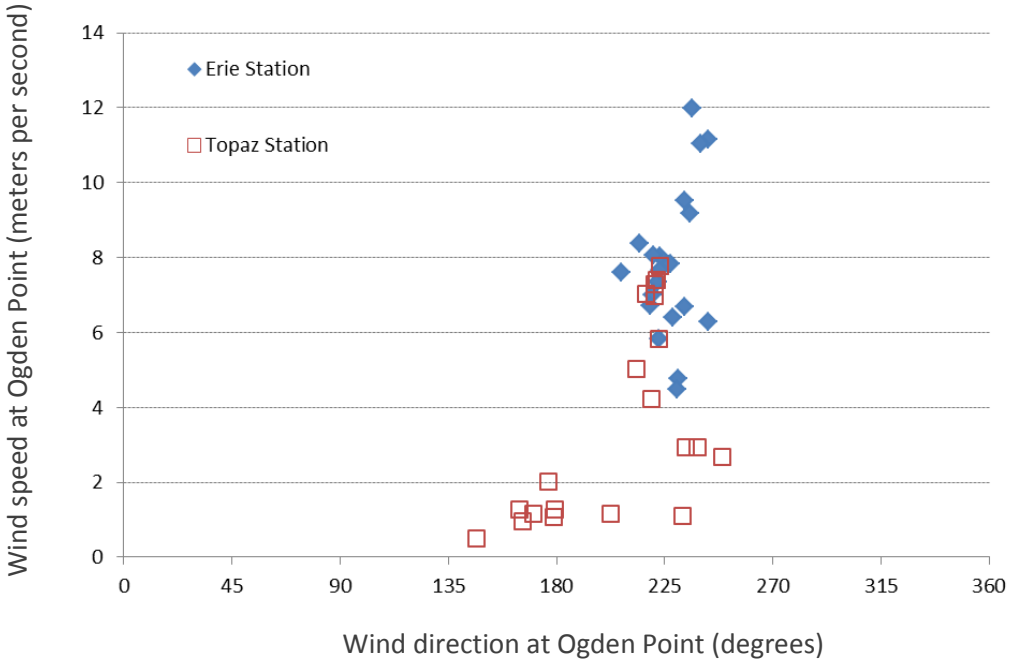


Figure 14. Wind speed and direction at Ogden Point during highest twenty 1 hour averages at Erie and Topaz Stations – 2012



Elevated 10 minute and hourly levels of SO_2 are more likely at Erie station when wind speeds at Ogden Point are above 6 m/s, and are more likely at Topaz station when wind speeds at Ogden Point are below 6 m/s.

5. Trends and comparisons

The number of cruise ships visiting Victoria has risen relatively steadily since 2006; as has the number of hours with cruise ships in port (Table 16).

Table 16. Number of cruise ships visiting and hours with cruise ships present – 2006 to 2012

	2006	2007	2008	2009	2010	2011	2012
Number of cruise ships visiting	179	161	201	217	215	209	222
Hours with cruise ships	962 (19%)	816 (16%)	982 (19%)	1188 (23%)	1160 (23%)	1165 (23%)	1136 (22%)

5.1 Topaz 2006 to 2012

The maximum 10 minute average level recorded at Topaz station was higher in 2012 (269 $\mu g/m^3$) than in 2011 (124 $\mu g/m^3$) (Figure 15). In total, nine 10-minute intervals in 2012 were higher than the maximum recorded in 2011.

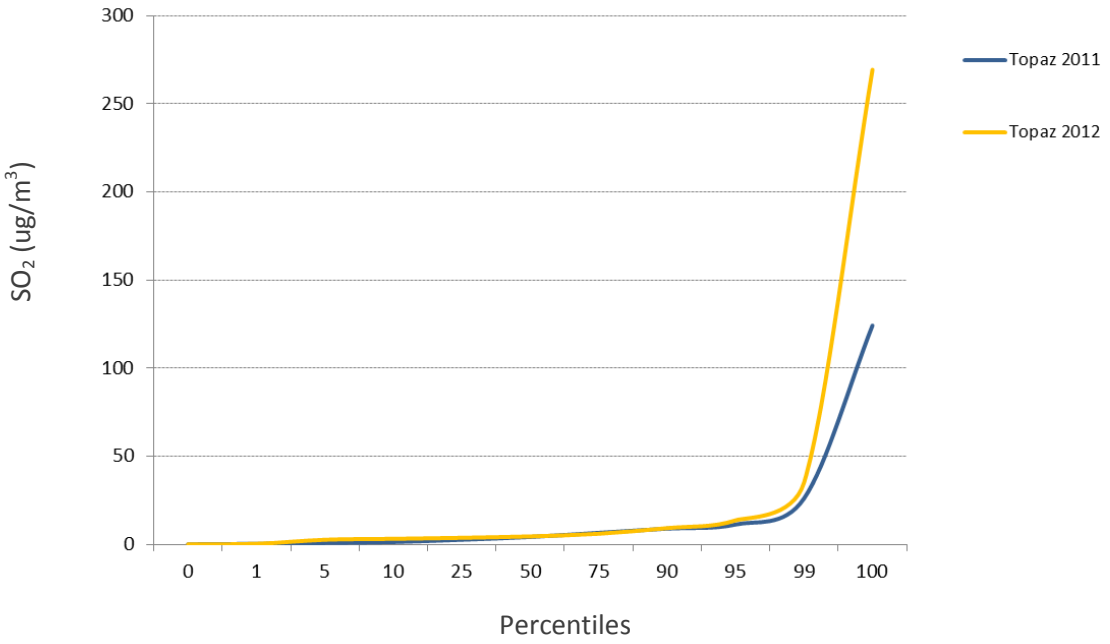
When comparing the highest 25 percent of 1 hour average levels from Topaz station in 2006 to 2012 when cruise ships were present (data at and above the 75th percentile), levels were highest in 2009, followed by 2008 and 2012 (Figure 16), and the lowest in 2011. Levels below the 75th percentile were similar in all years.

The diurnal pattern at Topaz in 2012 was similar to but generally higher than that recorded in 2011, and shows the third highest peak level (2006 – 2012) associated with cruise ship arrivals (Figure 17). For hours without cruise ships present, average hourly levels at Topaz site typically were less than 5 $\mu g/m^3$ in all years (Figure 18). Factors that may contribute to these differences include:

- Average temperatures - during hours with cruise ships, temperatures were highest during June and July of 2009, the year when the highest SO_2 levels were recorded, but were lowest during the same period in 2008 which is not the year of lowest SO_2 levels (Figures 19 and 20). 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 21), but do not appear to relate to higher or lower SO_2 levels.
- Wind speed and direction – these were similar at Topaz from 2007 to 2011 during hours with cruise ships; however Topaz station was more frequently downwind of the Ogden Point terminal in 2012 than in any other year, based on wind direction recorded at Topaz station (Figure 24).

Given these analyses, 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.

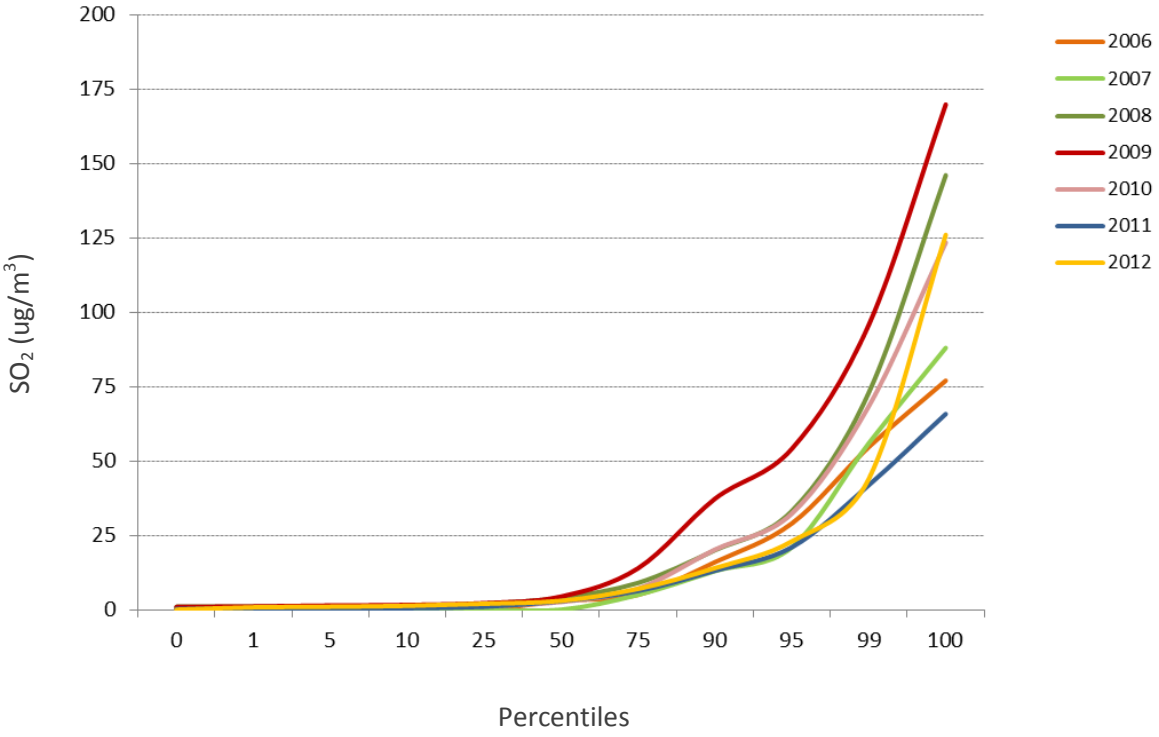
Figure 15. Percentiles of 10-minute SO_2 levels Topaz 2011 to 2012



SO_2 levels measured at Topaz Site ($\mu g/m^3$)

Percentile	2011	2012
0	0	0
1	<1	<1
5	1	3
10	1	3
25	3	4
50	4	5
75	7	6
90	9	9
95	11	14
99	26	35
100	124	269

Figure 16. Percentiles of hourly SO_2 levels for hours with cruise ships – Topaz 2006 to 2012



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

Percentile	2006	2007	2008	2009	2010	2011	2012
minimum	0	0	1	1	0	< 1	0
1	0	0	1	1	0	< 1	1
5	0	0	1	1	< 1	< 1	1
10	0	0	1	2	1	< 1	1
25	0	0	2	1	1	1	2
50	3	0	4	4	3	3	3
75	5	5	9	14	7	6	7
90	16	13	20	37	20	13	14
95	29	21	33	54	32	21	23
99	55	56	73	96	68	42	44
maximum	77	88	146	170	123	66	126

Figure 17. Diurnal SO_2 levels on days with cruise ships – Topaz 2006 to 2012

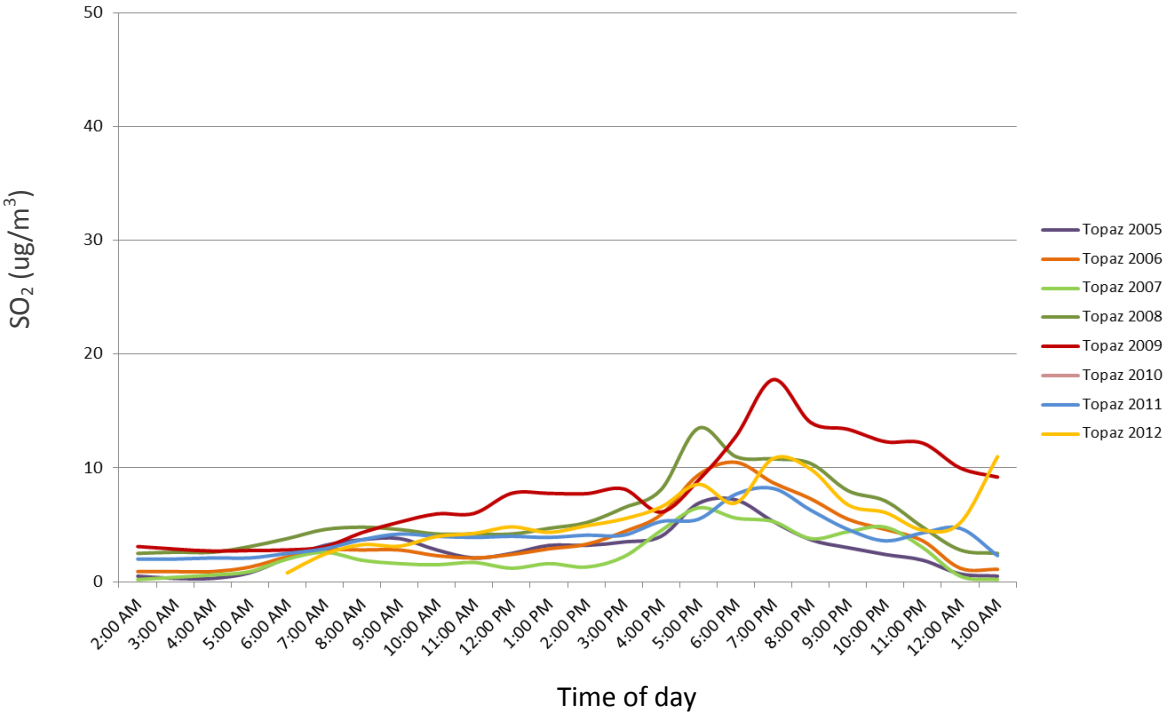


Figure 18. Diurnal SO_2 levels on days without cruise ships – Topaz 2006 to 2012

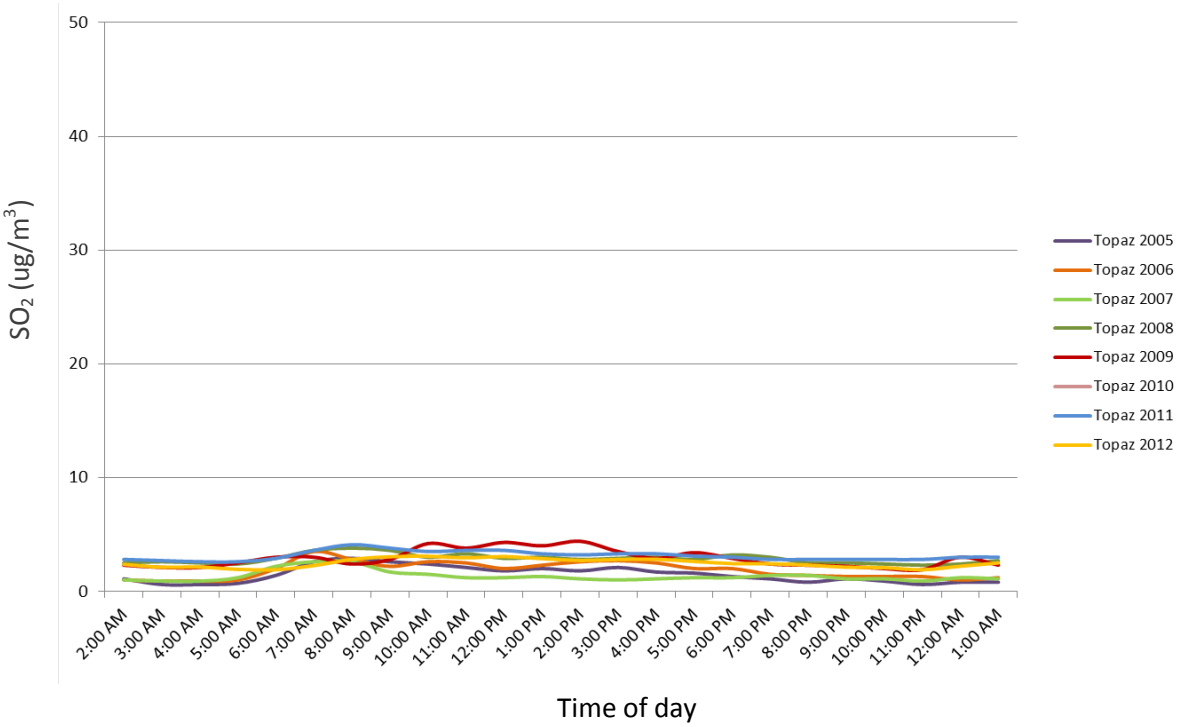
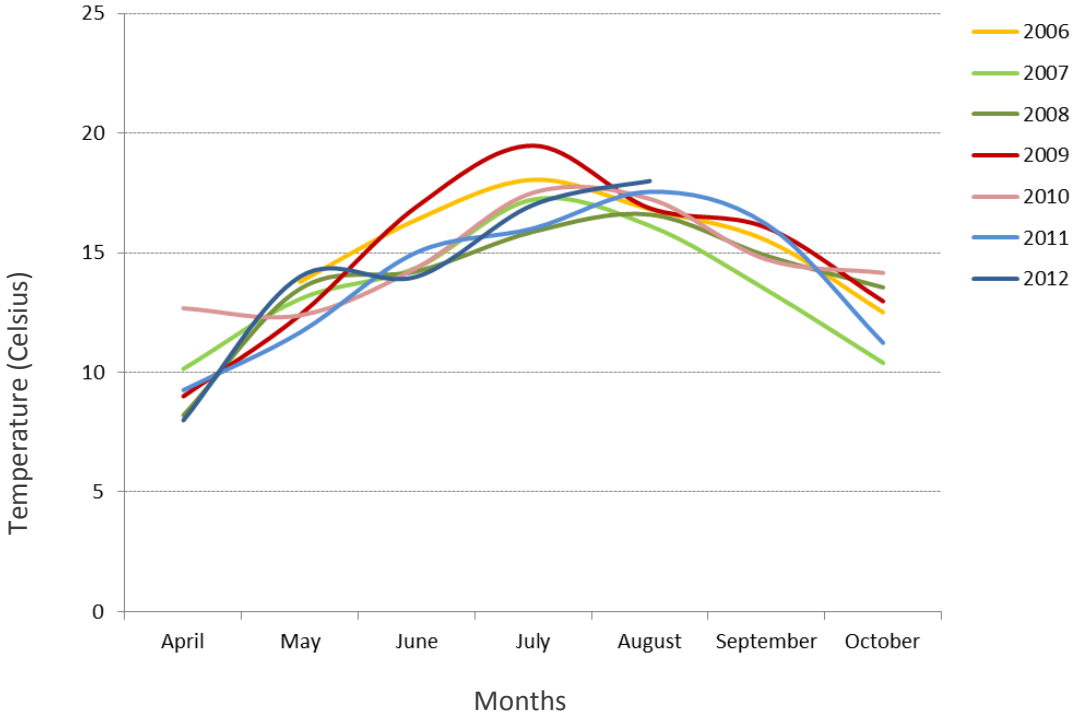


Figure 19. Average hourly temperature for hours with cruise ships – Topaz 2006 to 2012

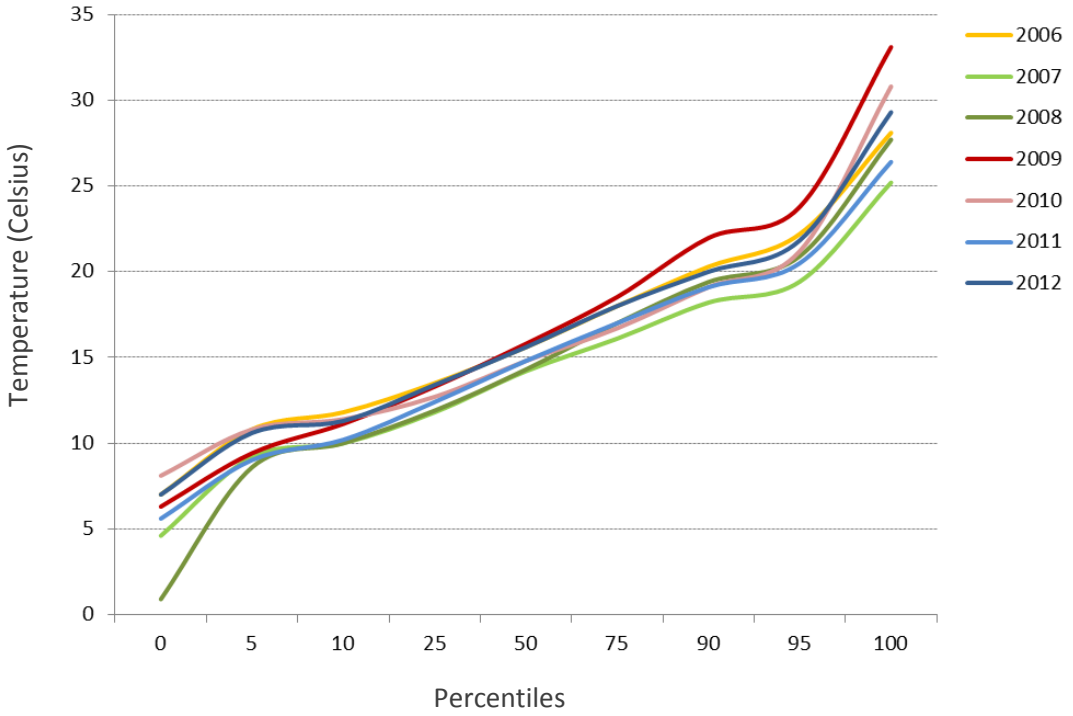


Temperature recorded at Topaz Site (Celsius)

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
2012	8	14	14	17	18	--	--

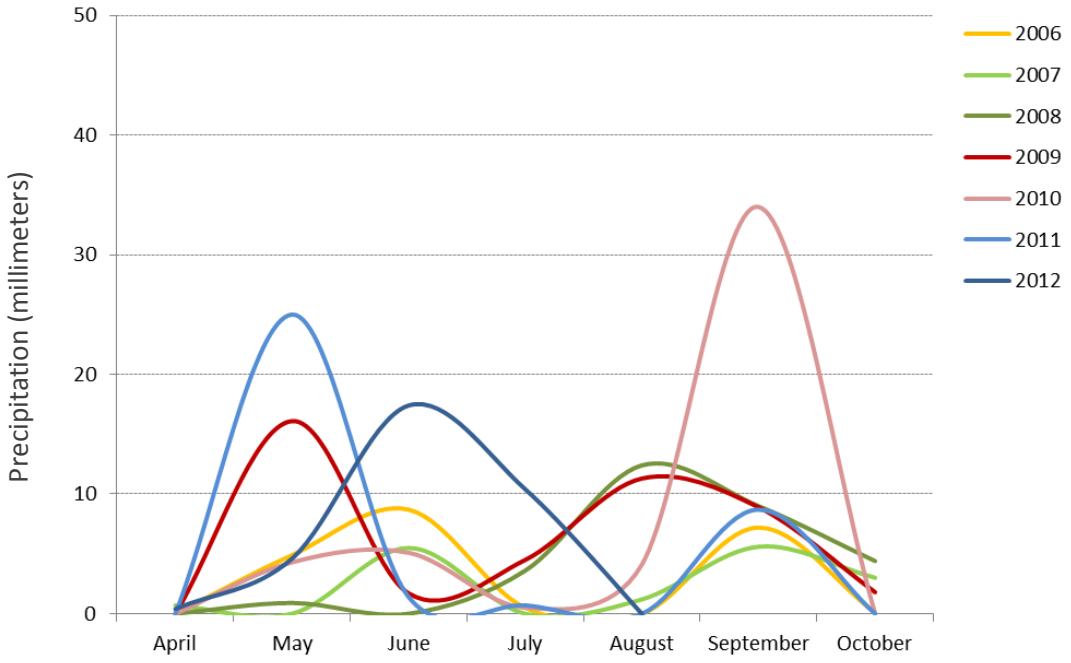
* Data for only 101 out of 184 hourly intervals (55%) were available for September 2012.

Figure 20. Percentiles of average temperature for hours with cruise ships – Topaz 2006 to 2012



Temperature recorded at Topaz Site (Celsius)							
Percentile	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
0	7	5	1	6	8	6	7
5	11	9	9	9	11	9	11
10	12	10	10	11	11	10	11
25	14	12	12	13	13	12	13
50	16	14	14	16	15	15	16
75	18	16	17	19	17	17	18
90	20	18	19	22	19	19	20
95	22	19	21	24	21	21	22
100	28	25	28	33	31	26	29

Figure 21. Total monthly precipitation for hours with cruise ships – Topaz 2006 to 2012



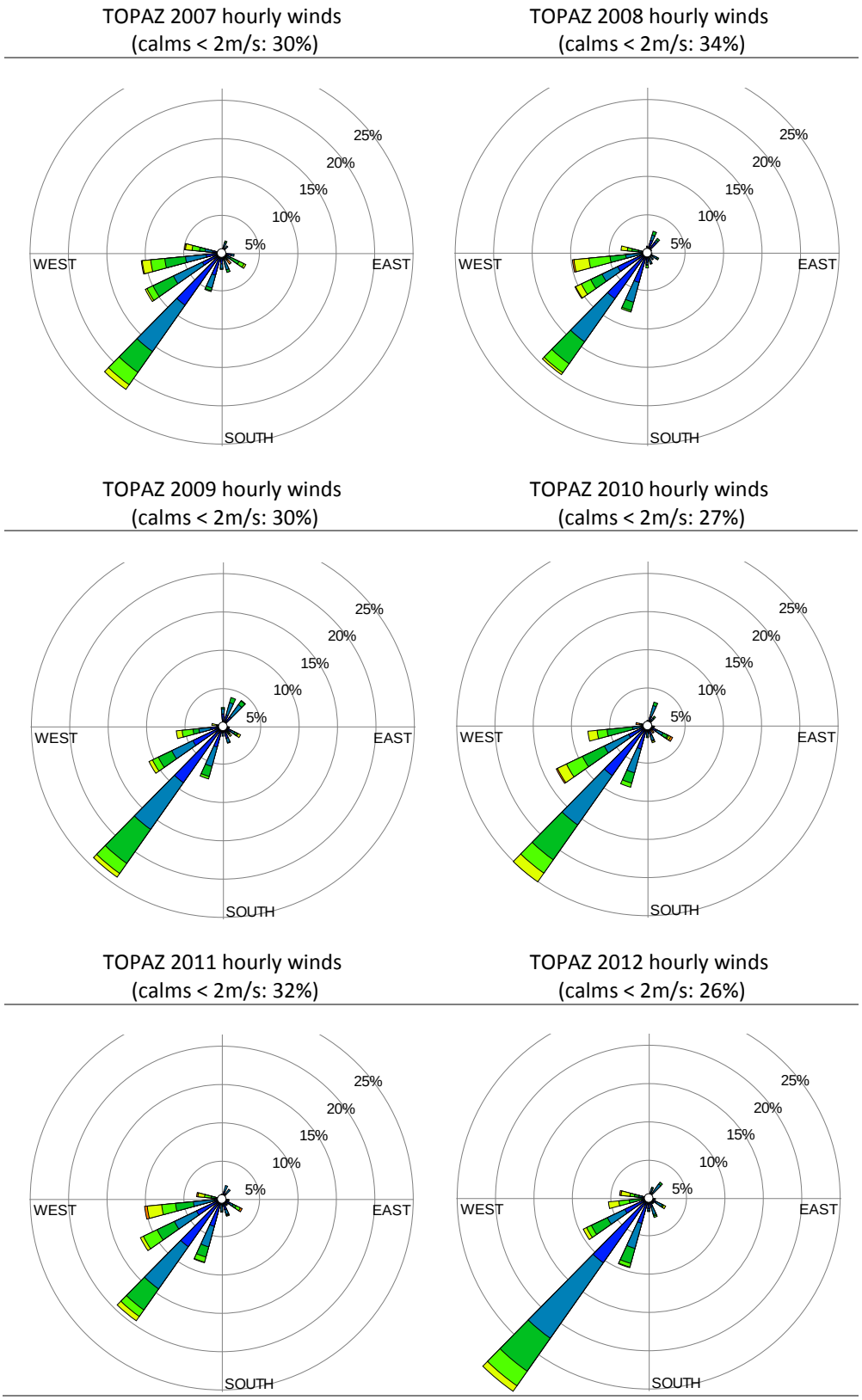
Total monthly precipitation recorded at Topaz (millimeters)

	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
2012	0.4	4.6	17.4	10.4	0	--	--

* Data for only 101 out of 184 hourly intervals (55%) were available for September. No measurable precipitation was recorded from August through to October 13th of 2012 at the nearby Esquimalt station.[16]

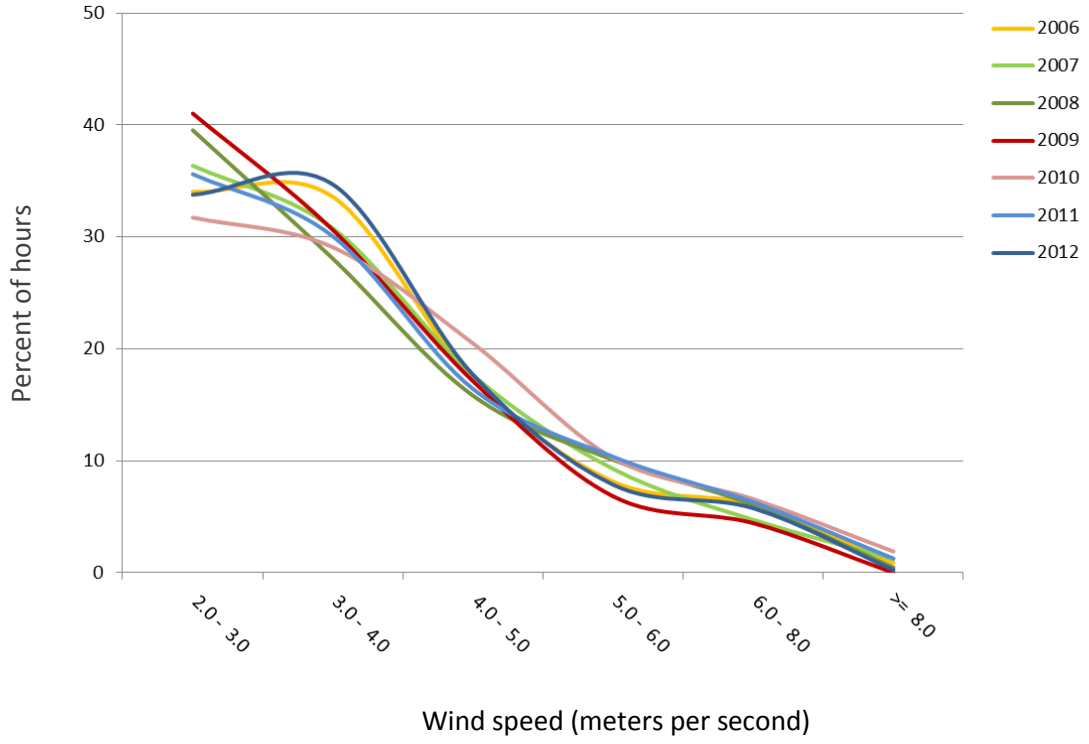
[16] Personal communication, Earle Plain, BC Ministry of Environment, April 16, 2013.

Figure 22. Wind speed and direction for hours with cruise ships - Topaz 2007 to 2012



Note: Wind rose for 2006 was omitted to maintain single page graphic

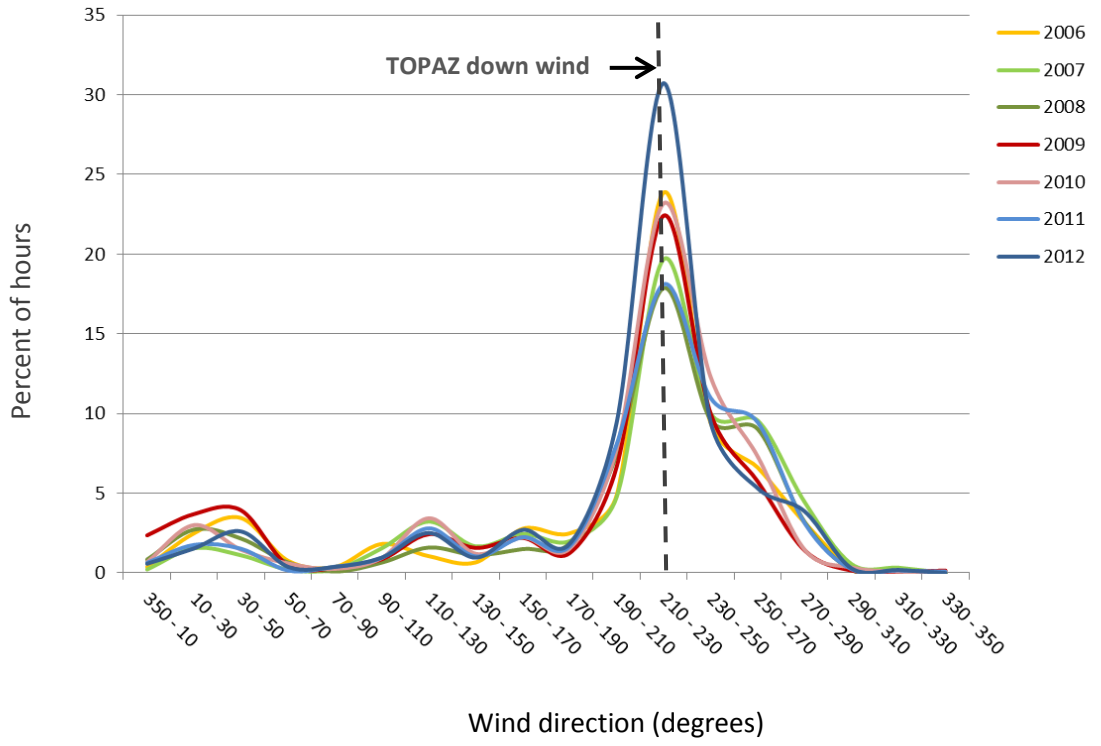
Figure 23. Percent of time by wind speed for hours with cruise ships - Topaz 2006 to 2012



Percent of hours in each wind speed class (m/s)
Topaz Station during hours with cruise ships

Speed	2006	2007	2008	2009	2010	2011	2012
2.0 - 3.0	34	36	40	41	32	36	34
3.0 - 4.0	34	31	28	31	29	30	35
4.0 - 5.0	17	18	16	17	21	16	18
5.0 - 6.0	8	9	10	7	10	10	8
6.0 - 8.0	6	5	6	4	7	6	6
>= 8.0	1	1	1	0	2	1	<1

Figure 24. Percent of time by wind direction for hours with cruise ships - Topaz 2006 to 2012



Percent of hours in each wind direction class (degrees)
Topaz Station during hours with cruise ships

Directions	2006	2007	2008	2009	2010	2011	2012
350 - 10	<1	<1	<1	2.4	<1	<1	<1
10 - 30	2.5	1.6	2.7	3.7	3.0	1.8	1.5
30 - 50	3.5	1.1	2.2	3.9	1.5	1.5	2.6
50 - 70	<1	<1	<1	<1	<1	<1	<1
70 - 90	<1	<1	<1	<1	<1	<1	<1
90 - 110	1.8	1.6	<1	<1	<1	1.0	1.0
110 - 130	1.1	3.2	1.6	2.4	3.4	2.8	2.5
130 - 150	<1	1.7	1.1	1.6	1.2	1.0	1.0
150 - 170	2.8	2.4	1.5	2.2	2.2	2.2	2.7
170 - 190	2.5	2.0	1.9	1.3	1.5	1.7	1.8
190 - 210	4.9	4.8	7.4	6.7	7.8	8.1	9.5
210 - 230	23.9	19.7	17.9	22.4	23.2	18.1	30.7
230 - 250	9.4	10.0	9.6	10.0	12.3	11.0	9.5
250 - 270	6.6	9.6	9.0	5.7	7.3	9.5	5.3
270 - 290	3.2	4.4	3.2	1.4	1.5	3.1	3.9
290 - 310	<1	<1	<1	<1	<1	<1	<1
310 - 330	<1	<1	<1	<1	<1	<1	<1
330 - 350	0	0	0	<1	<1	<1	0
Calms (<2m/s)	27.2	27.1	31.5	27.7	24.9	29.9	26.2

5.2 MAML 2009 and Erie 2011 - 2012

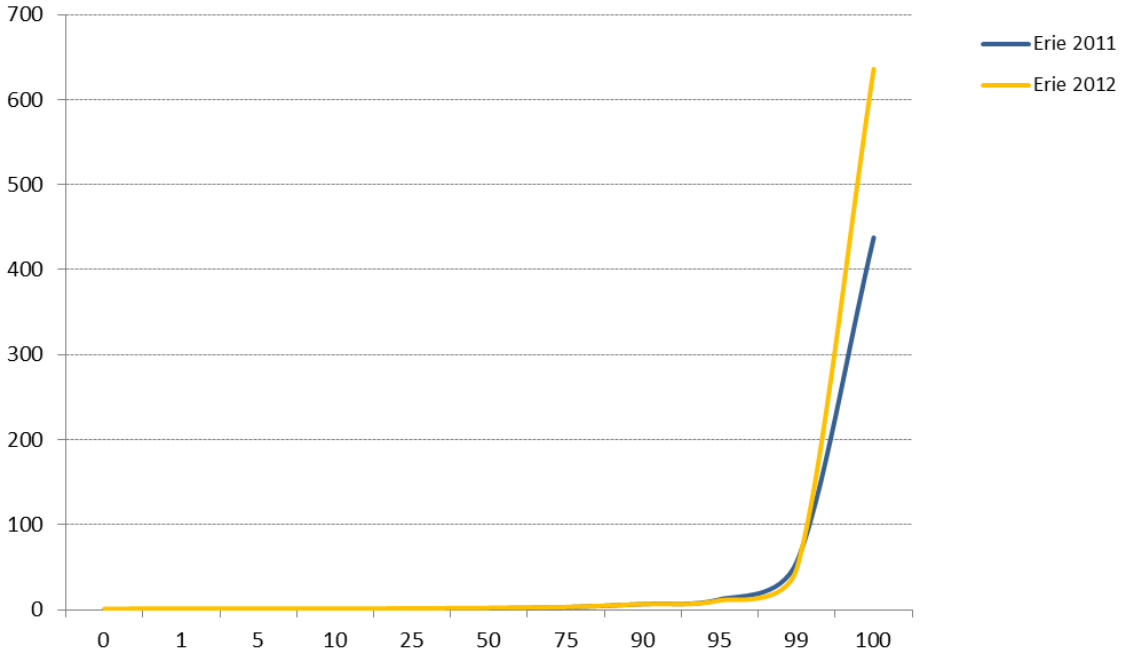
The maximum 10 minute average level recorded at Erie station was higher in 2012 (636 μg/m^3) than in 2011 (438 μg/m^3) (Figure 15), but only the single 10 minute average interval during which the maximum occurred in 2012 was higher than the maximum in 2011.

Hourly average SO_2 levels at and above the 75th percentile measured at the Erie site in 2012 when cruise ships were present were similar to those in 2011, and markedly lower than those measured at the MAML site in 2009 (Figure 26). In 2011 and 2012, 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 27). When cruise ships were not present, average hourly SO_2 levels were similar in 2011 and 2012 (less than 10 μg/m^3), but still lower than in 2009 (Figure 28).

Factors that may contribute to these differences include wind speed and direction. Wind roses for 2009, 2011 and 2012 were relatively similar during hours with cruise ships (Figure 29), although the MAML site (2009) was directly downwind of the Ogden Point terminal approximately 15 percent of the time, while Erie station was directly downwind approximately 13 percent of the time in 2011 and 17 percent of the time in 2012 (Figure 30). Higher maximum levels were recorded in 2009 and 2012 when the monitoring stations were directly downwind more frequently; however, the distributions of measured levels at Erie Station are very similar in 2011 and 2012, other than the highest recorded level. This suggests that the amount of time directly downwind may not have enough of an effect to account for the large difference in levels measured in 2009 at MAML in comparison to those measured at Erie station.

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

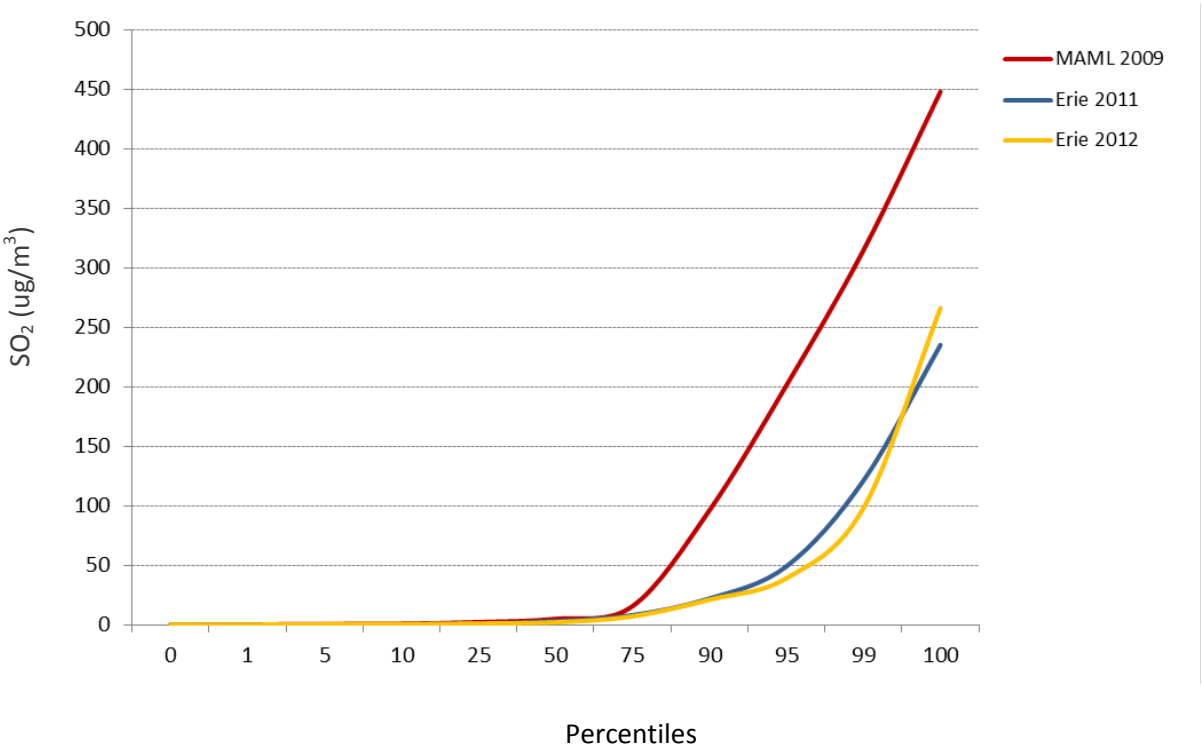
Figure 25. Percentiles of 10-minute average SO_2 levels – Erie 2011 - 2012



SO_2 levels measured at Erie Site (µg/m^3)

Percentile	2011	2012
0	0	1
1	<1	1
5	<1	1
10	<1	1
25	1	2
50	2	2
75	3	3
90	7	7
95	12	11
99	57	49
100	438	636

Figure 26. 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) during hours with cruise ships

Percentile	MAML 2009	Erie 2011	Erie 2012
0	0	<1	0
1	<1	<1	0
5	<1	<1	<1
10	1	<1	<1
25	2	1	1
50	5	3	2
75	16	8	7
90	96	22	21
95	201	49	38
99	315	121	97
100	448	235	266

Figure 27. Diurnal SO_2 levels on days with cruise ships – Erie and MAML

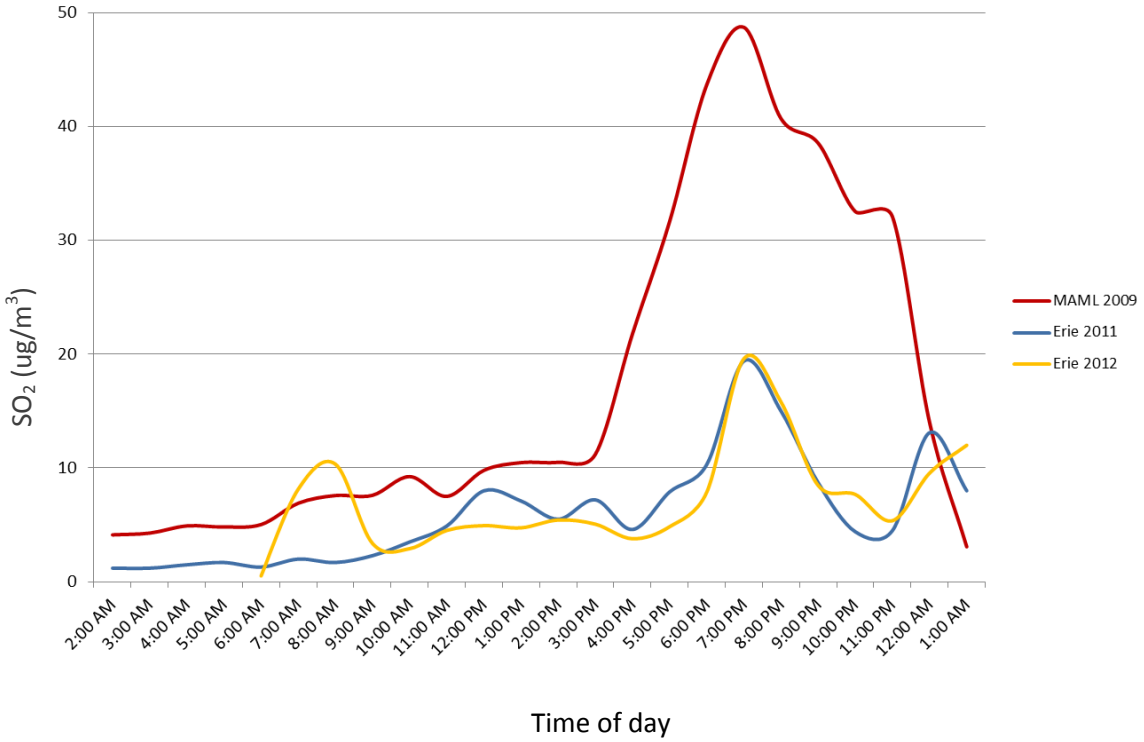


Figure 28. Diurnal SO_2 levels on days without cruise ships – Erie and MAML

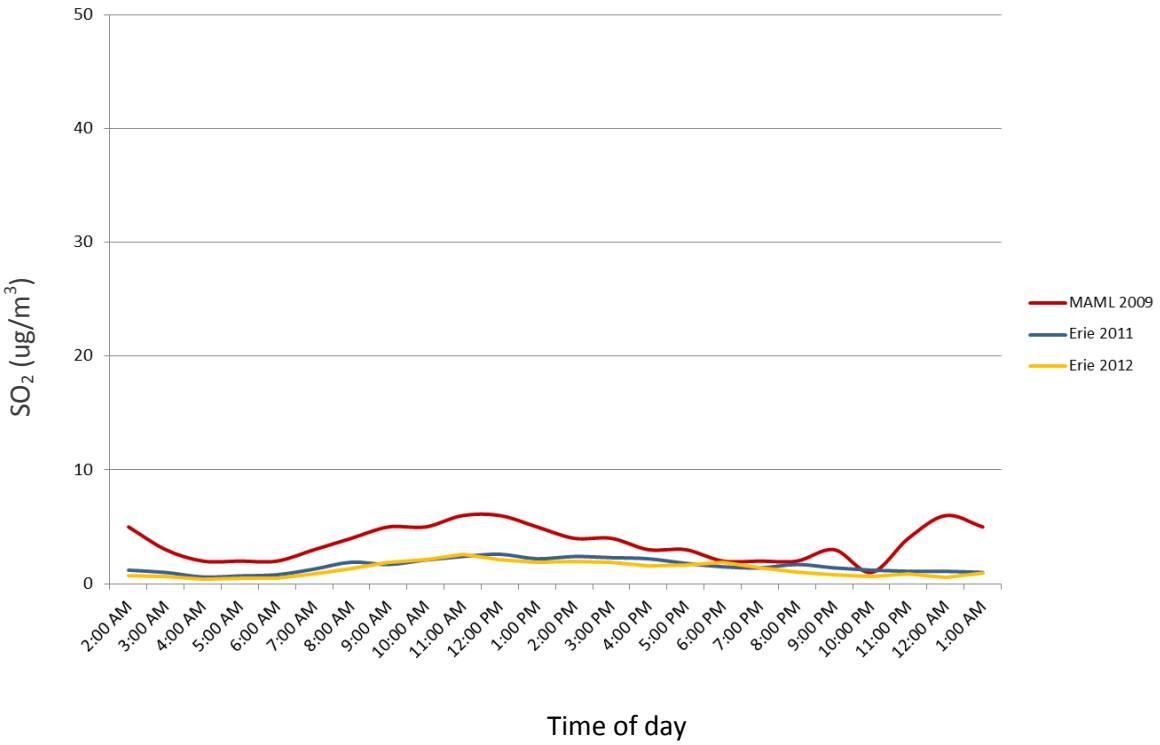
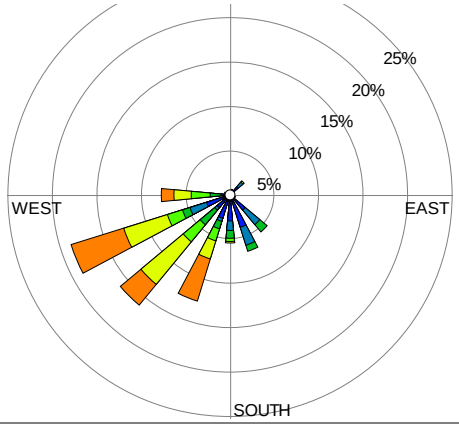
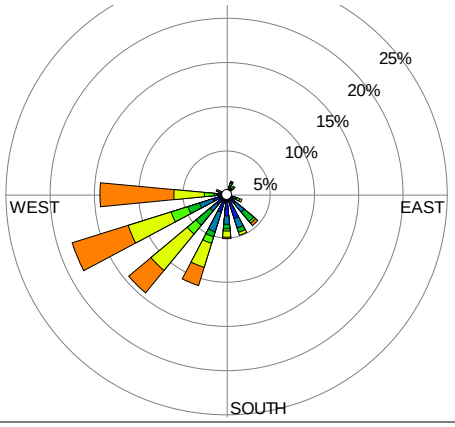


Figure 29. Wind speed and direction at Ogden Point – hours with cruise ships in 2009 - 2012

MAML 2009
OGDEN POINT hourly winds
May 30th to August 22nd
(calms < 2m/s: 22%)



ERIE 2011
OGDEN POINT hourly winds
April 16th to October 5th
(calms < 2m/s: 20%)



ERIE 2012
OGDEN POINT hourly winds
April 1st to September 30th
(calms < 2m/s: 22%)

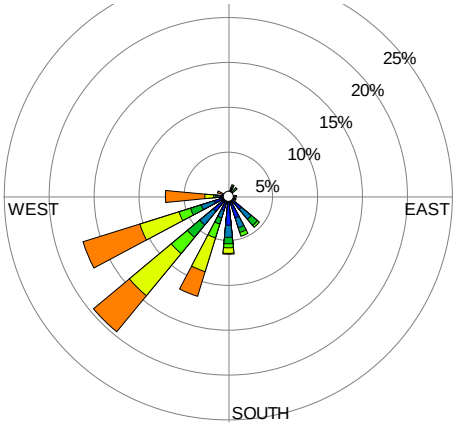
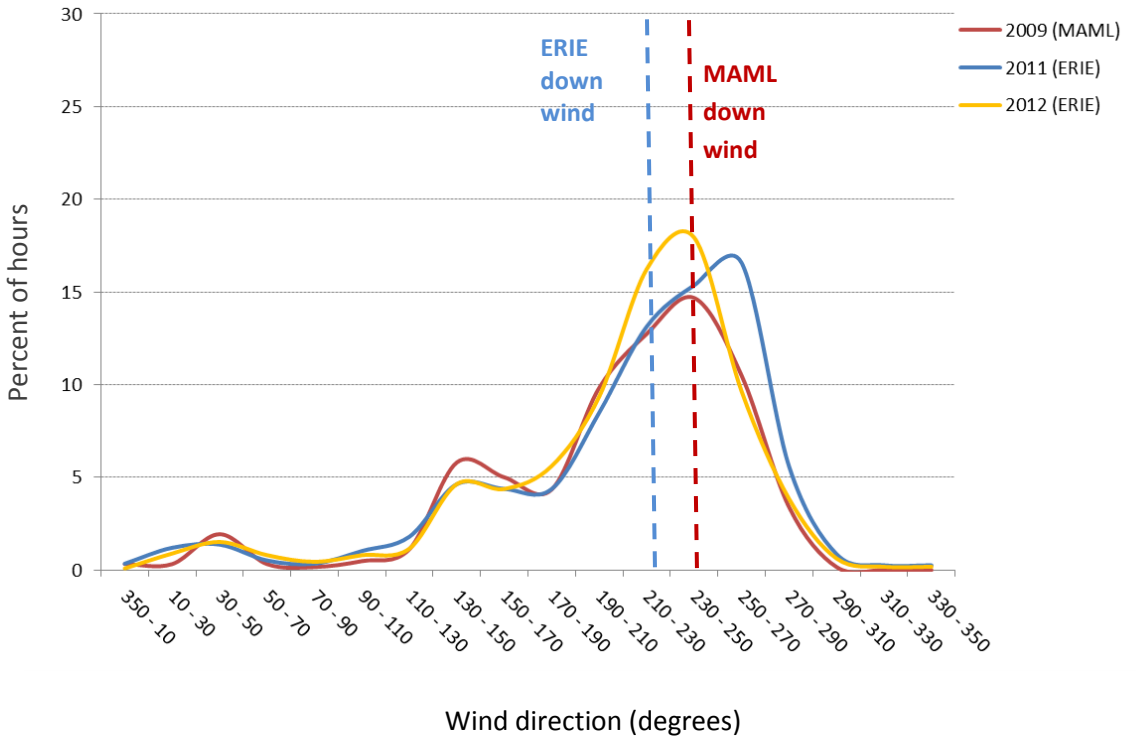


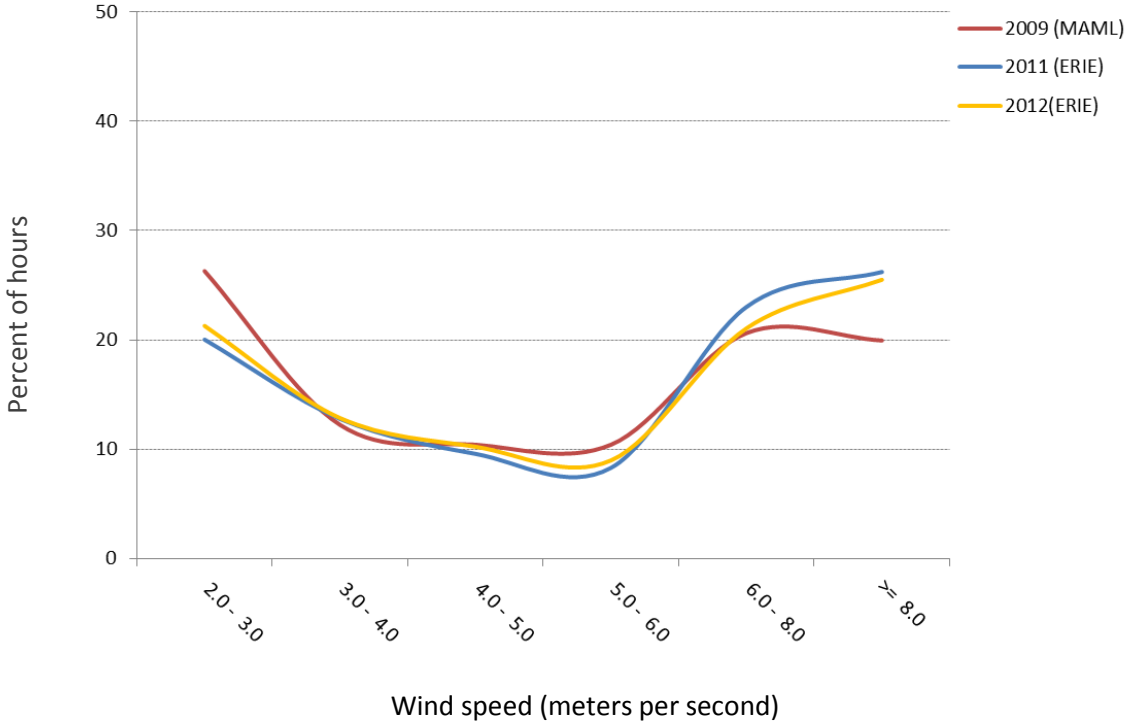
Figure 30. Percent of time by wind direction for hours with cruise ships – Erie and MAML



Percent of hours in each wind direction class (degrees)
Ogden Point during hours with cruise ships

Direction	2011 (ERIE)	2009 (MAML)	2012 (ERIE)
350 - 10	<1	<1	<1
10 - 30	1.2	<1	0.9
30 - 50	1.4	1.9	1.5
50 - 70	<1	<1	<1
70 - 90	<1	<1	<1
90 - 110	1.0	<1	<1
110 - 130	1.8	1.1	1.2
130 - 150	4.6	5.8	4.6
150 - 170	4.4	5.0	4.4
170 - 190	4.4	4.4	5.6
190 - 210	8.5	9.8	9.4
210 - 230	13.1	12.7	16.2
230 - 250	15.4	14.7	17.9
250 - 270	16.6	10.5	9.6
270 - 290	5.6	3.4	3.8
290 - 310	<1	<1	0.6
310 - 330	<1	0	<1
330 - 350	<1	0	<1
Calms (< 2 m/s)	20	20	22

Figure 31. Percent of time by wind speed for hours with cruise ships – Erie and MAML



Percent of hours in each wind speed class (m/s)
Ogden Point during hours with cruise ships

Speed	2009	2011	2012
2.0 - 3.0	20	26	21
3.0 - 4.0	13	12	13
4.0 - 5.0	10	10	10
5.0 - 6.0	8	10	9
6.0 - 8.0	23	21	21
>= 8.0	26	20	26

5.3 Comparison of measured levels pre- and post-ECA sulfur content reduction regulation

The regulated reduction in fuel sulfur content from 3.5 percent to 1 percent came into effect August 1st, 2012. A preliminary comparison of measured levels was conducted but is limited by the relatively short period of data. Future analyses should compare Erie station data from 2011 and 2012 (up to July 31st) with data from 2012 (from August 1st onward) and 2013 when available.

In general:

- The distribution of 10 minute average levels on days with cruise ships was higher before regulation from the 95th percentile upward at Erie station in comparison to after regulation, while at Topaz station, distribution levels were actually slightly higher at the lower percentiles, and only slightly lower at the upper percentiles post-regulation (Table 17). Post-regulation, the distribution of levels at Erie Station was very similar to the distribution of levels at Topaz Station (Figure 32).

- The distribution of 1 hour average levels during hours with cruise ships was higher before regulation from the 75th percentile upward at Erie station in comparison to after regulation. At Topaz station, distribution levels pre- and post-regulation were very similar, being slightly lower or the same up to the 97th percentile before regulation, then higher from the 98th percentile upward when compared to the post-regulation distribution levels (Table 18). Post-regulation, the distribution of levels at Erie Station was more similar to both the pre- and post-regulation distributions at Topaz Station (Figure 33).

- The distribution of 24 hour average levels at Erie Station was always higher before regulation in comparison to the distribution of levels post-regulation, with the exception of the minimum, while at Topaz Station, the distribution of levels pre- and post-regulation were essentially the same (Table 18 and Figure 34). Post-regulation, the distribution of levels at Erie Station was similar to both the pre- and post-regulation distributions at Topaz Station (Figure 34).

Although no WHO, Canadian, BC, or local guidelines for SO_2 levels were exceeded after the sulfur content reduction regulation came into force on August 1st (Tables 19, 20 and 21), elevated levels did occur:

- Five of the top forty 10 minute average levels (155 to 182 $\mu g/m^3$) were recorded at Erie Station post-regulation (Table 22). The maximum 10 minute average level recorded at Erie Station on days without cruise ships for the entire season was 59 $\mu g/m^3$.

- Thirteen of the top forty 10 minute average levels (69 to 133 $\mu g/m^3$) recorded at Topaz station occurred post-regulation, including two in the top ten for the season (Table 22). The maximum

10 minute average level recorded at Topaz Station on days without cruise ships for the entire season was 45 μg/m^3.

- Three of the top twenty 1 hour average levels (97 to 134 μg/m^3) were recorded at Erie Station post-regulation, including two in the top ten for the season (Table 23). The maximum 1 hour average level recorded at Erie Station on hours without cruise ships for the entire season was 34 μg/m^3.

- Five of the top twenty 1 hour average levels (40 to 88 μg/m^3) recorded at Topaz station occurred post-regulation, including three in the seasonal top ten (Table 23). The maximum 1 hour average level recorded at Topaz Station on hours without cruise ships for the entire season was 21 μg/m^3.

- Three of the top ten 24 hour average levels for the entire season occurred post-regulation at both Erie (12 to 14 μg/m^3) and Topaz (10 to 12 μg/m^3) stations (Table 24). The maximum 24 hour average levels recorded at Erie and Topaz Stations on days without cruise ships during the entire season were 7 μg/m^3 and 6 μg/m^3 respectively.

While it appears that measured SO_2 levels have generally decreased post-regulation, the period on record is not yet long enough to establish this as an ongoing trend. The occurrence of elevated levels post-regulation well above the maximums measured when cruise ships were not present suggests either:

- the ships associated with elevated levels post-regulation were already burning fuel with 1 percent or lower sulfur content, in which case substantial differences in peak measured levels pre- and post-regulation may be limited;

or:

- one or more of the ships associated with elevated levels post-regulation were not yet complying with the regulation.

Going forward, it will be important to confirm the sulfur content of the fuel used by each cruise ship to fully understand the causes of elevated levels and the expected benefit to local air quality post-regulation.

Finally, wind speeds and directions during hours with cruise ships nearby or in port were generally similar pre- and post-regulation (Figure 35), although a higher percentage of calm conditions (winds < 2 m/s) were observed after August 1st at both Ogden Point (33% after versus 15% before) and at Topaz Station (38% after versus 21% before). While meteorology has a role in the creating differences in the observed levels, the magnitude of its effect is unknown.

Table 17. Distribution of 10-minute SO_2 levels on Days with Cruise Ships - Pre-ECA and Post-ECA 2012

	10-minute* (ug/m^3)			
	PRE		POST	
Percentile	**Erie**	**Topaz**	Erie	Topaz
5	**1**	**0**	1	4
25	**2**	**0**	2	4
50	**2**	**3**	2	5
75	**4**	**5**	4	7
90	**10**	**8**	7	11
95	**20**	**14**	13	15
96	**24**	**17**	17	17
97	**32**	**21**	22	20
98	**47**	**26**	34	25
99	**89**	**38**	62	34
100	**636**	**269**	182	133
Total intervals	**17,568**	**17,568**	8,784	8,784
Total with valid data	**16,445**	**16,729**	8,439	8,044
Percent with valid data	**94**	**95**	96	92

*0.5 ppb (1.3 ug/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 ug/m^3 and should be considered a 'worst case scenario'.

Figure 32. Percentiles of 10 minute SO_2 levels for hours with cruise ships pre- and post-ECA 2012

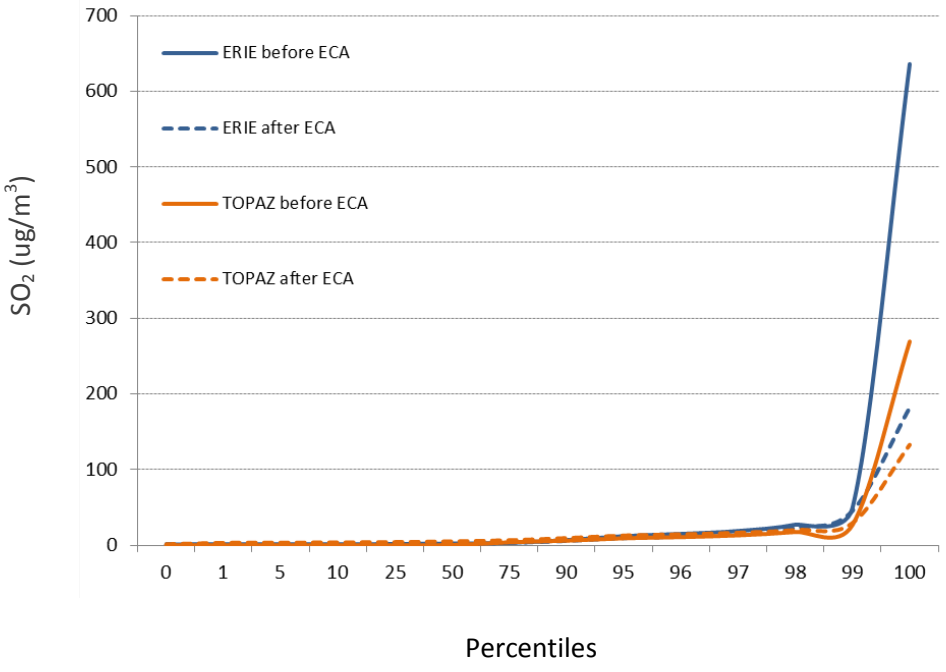


Table 18. Distribution of SO_2 levels during hours with cruise ships (1 hour and 24 hour) - Pre-ECA and Post-ECA 2012

	1 hour (ug/m^3)				24 hour (ug/m^3)			
	PRE		POST		**PRE**		POST	
Percentile	**Erie**	**Topaz**	Erie	Topaz	**Erie**	**Topaz**	Erie	Topaz
5	**<1**	**1**	<1	1	**1**	**2**	1	2
25	**1**	**2**	1	2	**2**	**2**	1	2
50	**2**	**3**	2	4	**4**	**3**	2	4
75	**7**	**7**	5	7	**7**	**5**	4	5
90	**21**	**14**	15	14	**11**	**9**	7	6
95	**38**	**23**	36	23	**22**	**10**	12	10
96	**43**	**26**	42	26	**23**	**11**	13	10
97	**53**	**30**	46	30	**25**	**11**	13	11
98	**71**	**37**	50	33	**26**	**12**	14	11
99	**97**	**44**	64	39	**34**	**12**	14	11
100	**266**	**126**	134	88	**44**	**12**	14	12
Total intervals with cruise ships	717	717	419	419	64	64	43	43
Total with valid data	697	679	404	403	60	64	41	43
Percent with valid data	97	95	96	96	94	100	95	100

Figure 33. Percentiles of hourly SO_2 levels for hours with cruise ships pre- and post-ECA 2012

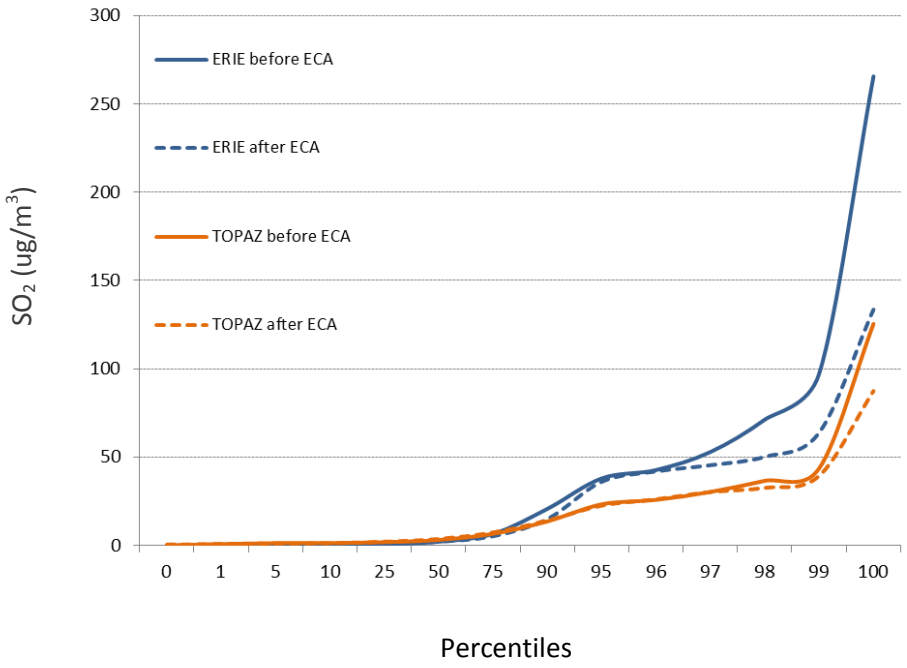


Figure 34. Percentiles of 24 hour SO_2 levels for hours with cruise ships pre- and post-ECA 2012

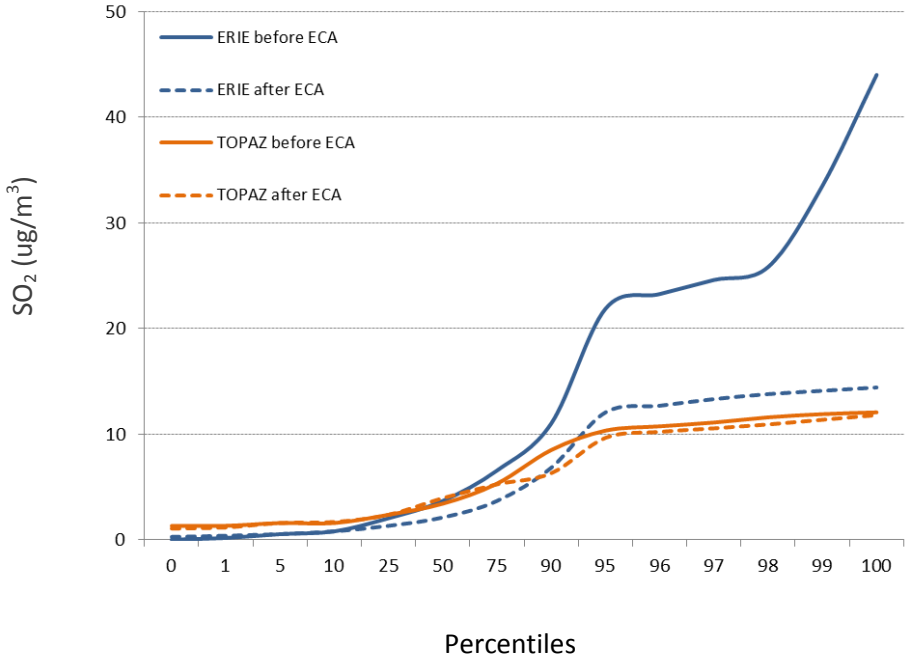


Table 19. 10 minute average levels at or above guidelines – Pre and Post ECA 2012

Guideline	Level (ug/m^3)	Erie Station Pre	Topaz Station Pre	Erie Station Post	Topaz Station Post
World Health Organization	500	1 (0.004%)	0	0	0

Table 20. 1 hour average levels with cruise ships at or above guidelines – Pre and Post ECA 2012

Guideline	Level (ug/m^3)	Erie Pre	Topaz Pre	Erie Post	Topaz Post
VIHA health risk guide - good	<=92	674 (99%)	661 (99%)	400 (99%)	402 (100%)
Moderate	93 - 197	8 (1%)	1 (<1%)	3 (<1%)	0
Unhealthy for sensitive groups	198 - 485	2 (<1%)	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 21. 24 hour average levels on cruise days at or above guidelines – Pre and Post ECA 2012

Guideline	Level (ug/m^3)	Erie Pre	Topaz Pre	Erie Post	Topaz Post
World Health Organization	20	4 (7%)	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 22. Elevated 10 minute average levels– Post-ECA 2012*

Date	Time	SO_2 (ug/m^3)	Ships present or nearby during peak levels	First Line	Last Line	Activity +/- 1 hour
ERIE						
08/13/2012	19:30	182	Carnival Spirit	19:14	23:38	Arrival
08/23/2012	11:10	161	Rhapsody of the Seas	8:13	17:44	At dock
09/01/2012	18:00	160	Norwegian Pearl	17:41	23:59	Arrival
	18:10	155	Star Princess	18:07	23:50	Arrival
09/08/2012	18:20	171	Norwegian Pearl	17:40	23:39	Arrival
			Star Princess	18:12	23:54	Arrival
TOPAZ						
08/11/2012	18:50	87	Norwegian Pearl	17:43	23:29	At Dock
	19:00	96				
	19:10	94				
	19:20	**128**	Star Princess	18:16	23:58	Arrival & At Dock
	19:30	71				
08/17/2012	18:40	71	Norwegian Jewel	13:56	21:20	At Dock
	19:20	69				
	19:30	75	Golden Princess	18:06	23:50	Arrival & At Dock
	19:40	103				
	19:50	**133**	Westerdam	18:30	0:00	Arrival & At Dock
	20:00	97				
08/25/2012	18:40	96	Norwegian Pearl	17:40	23:29	Arrival & At Dock
	18:50	78	Star Princess	18:11	23:50	Arrival

(*selected from top 40 events April1 – Sept 30)

Table 23. Elevated 1 hour average levels – Post-ECA 2012*

Date	Time	SO_2 (ug/m^3)*	Ships present or nearby during peak levels	First Line	Last Line	Activity +/- 1 hour
ERIE						
08/13/2012	20:00	97	Carnival Spirit	19:14	23:38	Arrival
09/01/2012	19:00	**119**	Norwegian Pearl	17:41	23:59	At Dock
			Star Princess	18:07	23:50	Arrival
09/08/2012	19:00	**134**	Norwegian Pearl	17:40	23:39	At Dock
			Star Princess	18:12	23:54	Arrival
TOPAZ						
08/05/2012	19:00	43	Disney Wonder	18:11	23:02	Arrival
08/11/2012	19:00	40	Norwegian Pearl	17:43	23:29	At Dock
	20:00	**73**	Star Princess	18:16	23:58	Arrival
08/17/2012	20:00	**88**	Golden Princess	18:06	23:50	At Dock
			Westerdam	18:30	0:00	At Dock
08/25/2012	19:00	**47**	Norwegian Pearl	17:40	23:29	At Dock
			Star Princess	18:11	23:50	Arrival

(*selected from top 20 events April1 – Sept 30)

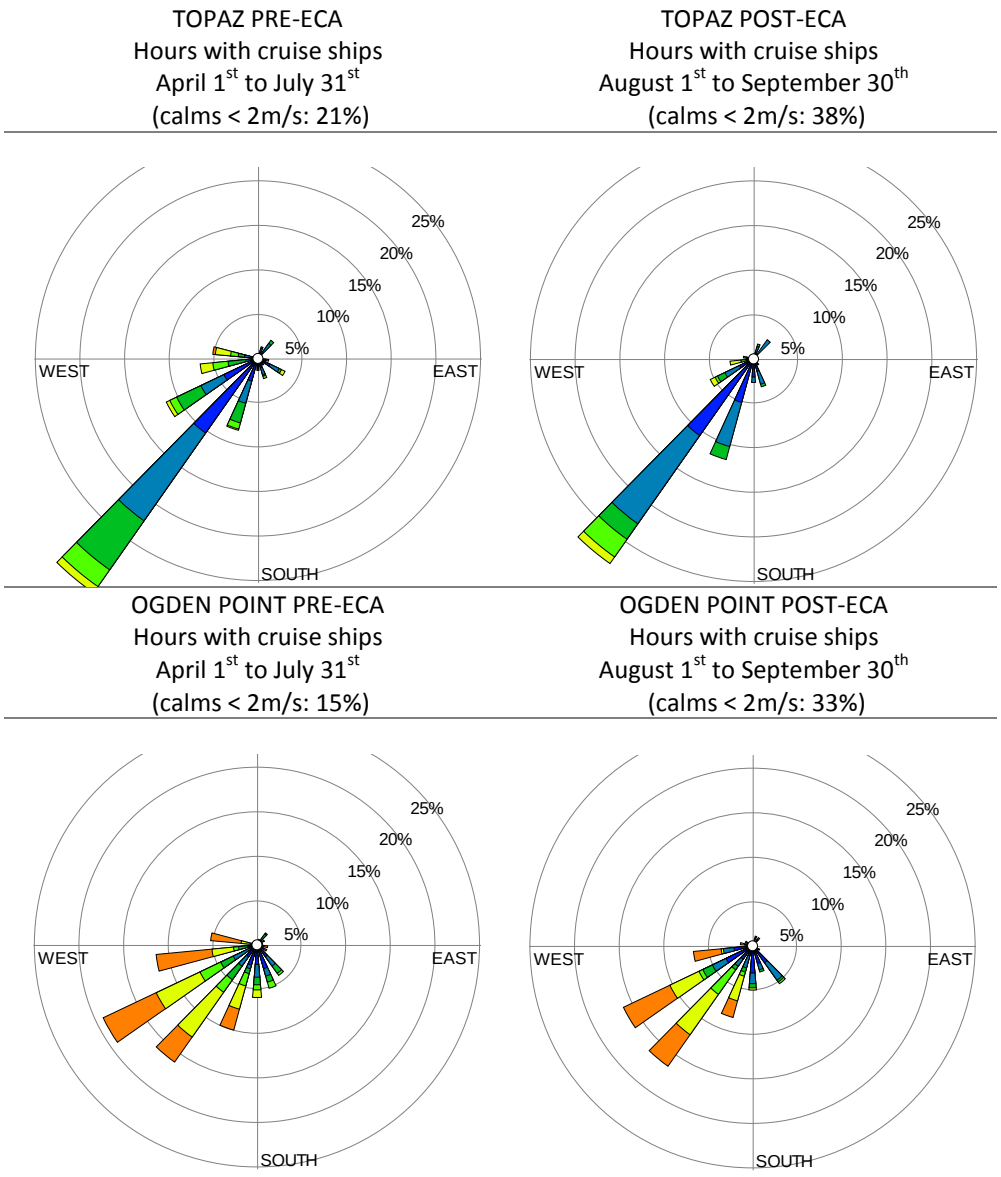
Table 24. Elevated 24 hour average levels – Post-ECA 2012*

Date	SO_2 (ug/m^3)*	Ships present or nearby during peak levels	First Line	Last Line
ERIE				
08/13/2012	14.4	Carnival Spirit	19:14	23:38
09/01/2012	12.1	Norwegian Pearl	17:41	23:59
		Star Princess	18:07	23:50
		Oosterdam	20:08	23:28
09/20/2012	13.6	Amsterdam	11:55	22:48
		Celebrity Infinity	17:13	23:35
TOPAZ				
08/05/2012	10.7	Disney Wonder	18:11	23:02
08/11/2012	10.0	Norwegian Pearl	17:43	23:29
		Star Princess	18:16	23:58
		Oosterdam	20:41	23:46
08/17/2012	11.8	Norwegian Jewel	13:56	21:20
		Golden Princess	18:06	23:50
		Westerdam	18:30	0:00

*selected from top 10 events April1 – Sept 30

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.

Figure 35. Wind speed and direction pre and post ECA – hours with cruise ships - 2012



Appendix A. Vancouver Island Health Authority health guidelines for ambient sulfur dioxide

Sulphur Dioxide Concentration (ppb*)	Air Quality	At-Risk Populations**	General Population
0 - 35 Good	Air quality is satisfactory, SO2 concentrations pose little or no risk	Enjoy your usual outdoor activities. Follow Dr's advice for exercise regime and condition management.	No need to modify usual outdoor activities.
36 - 75 Moderate	There may be a moderate health risk for a very small number of people who are unusually sensitive to SO2.	A small number of persons with asthma who are very sensitive to SO2 may experience symptoms. Follow Dr's advice for managing condition.	No need to modify usual outdoor activities.
76 - 185 Unhealthy for Sensitive Groups	Members of sensitive groups may experience health effects. The general public is not likely to be affected.	Increasing likelihood of respiratory symptoms such as chest tightness and breathing discomfort in people with asthma. People with asthma should consider limiting outdoor exertion or reschedule when SO2 concentrations are lower. Follow Dr's advice for managing condition.	No need to modify usual outdoor activities unless you experience symptoms of cough or wheeze when exercising.
more than 185 Unhealthy	Everyone may begin to experience health effects; members of sensitive groups may experience more serious health effects.	Children, the elderly, asthmatics and people with heart and lung disease should limit exertion outdoors or reschedule when SO2 concentrations are lower. Follow Dr's advice for managing condition.	At elevated SO2 concentrations, chest tightness and wheezing can occur, even with very brief exposures (minutes) in healthy people without asthma. Reschedule outdoor activity when SO2 levels are lower.

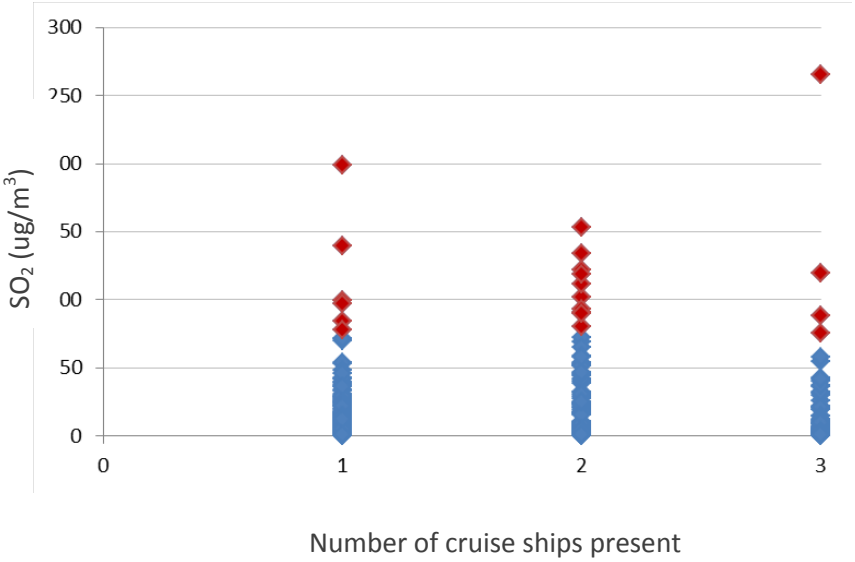
**ppb = parts per billion*
*** At risk populations include exercising asthmatics. At higher concentrations, children, the elderly and people with chronic heart and lung conditions may experience symptoms of shortness of breath and chest tightness.*

Source: http://www.viha.ca/mho/james_bay_sulphur_dioxide_monitoring.htm

Appendix B. Additional analysis of hourly SO_2 levels and number of ships present considering wind direction.

The following supplemental figure shows hourly average SO_2 levels at Erie station by number of ships present, using data when winds were from 200 to 250 degrees only (SSW, SW and WSW).

Figure S1. Average hourly SO_2 level by number of cruise ships present when winds from 200 to 250 degrees - Erie 2012



In addition, the overall average of hourly SO_2 levels when cruise ships were present was calculated for all hours, and for those when the wind was only blowing from 200 to 250 degrees:

	Average of all hourly SO_2 readings ($\mu g/m^3$)	
Number of ships	All wind directions	Winds from 200 to 250 degrees
1	6	10
2	14	22
3	11	19

Based on these analyses, it is reasonable to conclude that hourly average SO_2 levels do not increase systematically based on the number of cruise ships present. This may differ for 10-minute average SO_2 levels.

Appendix C. Additional analysis of hourly SO_2 levels and wind speed considering wind direction.

The following supplemental figures show hourly average SO_2 levels at Erie station by wind speed using all data (Figure S2), and using data only when winds were blowing from 200 to 250 degrees (Figure S3). A trend line and associated R^2 statistic are included for each figure.

Figure S2. Average hourly SO_2 level by wind speed - Erie 2012

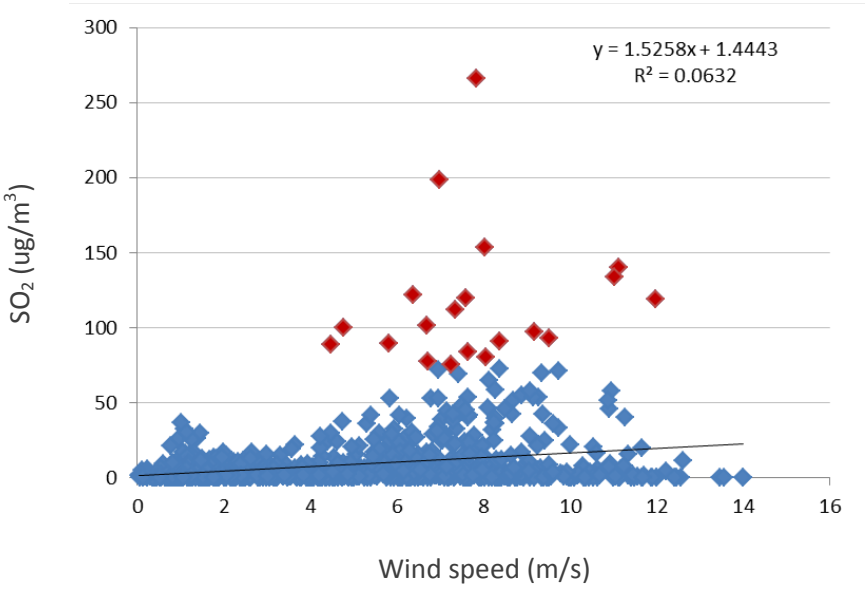
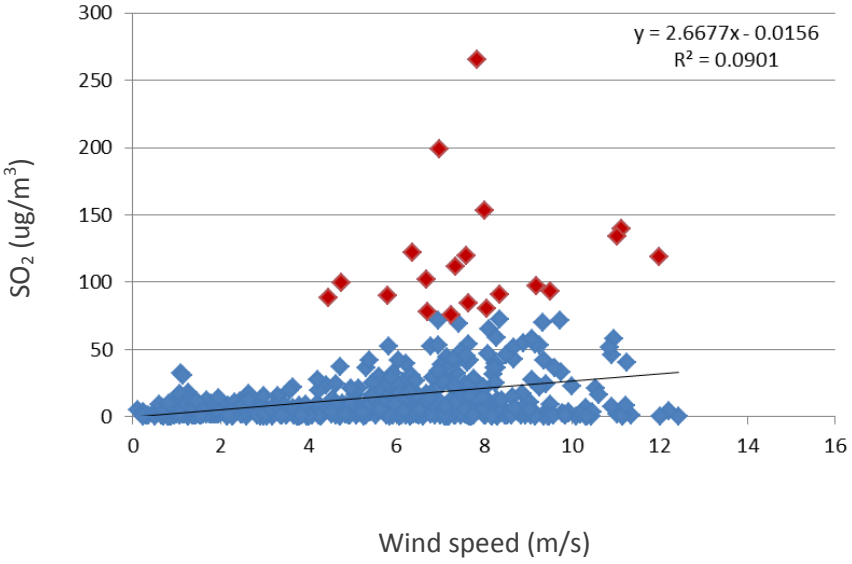


Figure S3. Average hourly SO_2 level by wind speed when winds from 200 to 250 degrees - Erie 2012



R^2 refers to the fraction of variance. In this case, it is the square of the correlation coefficient between hourly average SO_2 levels at Erie station and wind speed at Ogden Point. R^2 typically ranges from 0 (no linear relationship is present, values are randomly related) to 1.0 (an exact linear relationship is present, and given the value of one variable, it is possible to accurately predict the value of the other).

Another way to interpret R^2 is as the amount of variation explained. In this case, the R^2 value of 0.06 shown in Figure S2 means that 6 percent of the variation in hourly average SO_2 levels at Erie station is explained by wind speed at Ogden Point. When considering data when winds were blowing only from 200 to 250 degrees (Figure S3), this increases to approximately 10 percent of the variation explained.

Based on these analyses, it is reasonable to conclude that there is a very weak linear relationship between hourly average SO_2 levels at Erie station and wind speed using either all data (R^2 = 0.06), or those restricted to wind directions from 200 to 250 degrees only (R^2 0.09). This may differ for 10-minute average SO_2 levels.