

**Analysis of the SO₂ levels
measured at the
Erie St. monitoring site
during the
2011 cruise ship season**

July 2012



James Bay Neighbourhood Association

www.jbna.org

Analysis of the SO₂ levels measured at the Erie St. monitoring site during the 2011 Cruise Ship season (up to October 5th)

Key Points

- The wind direction is mainly from the WSW (25%), SW (21%) and W (18%).
- The single SO₂ monitoring site is at Daniels Electronics located at 43 Erie St. This site is in the SW wind sector.
- The recorded SO₂ levels for both the averages and the maxima are many times higher when ships are in port.
- The recorded SO₂ levels drop off sharply when the wind is not from the SW.
- The wind direction often fluctuates significantly during a one hour period. Only for 36% of the time that the 1-hour wind direction was from the SW were all six 10-minute averages also from the SW.
- The recorded SO₂ levels increase at higher wind speeds. The highest SO₂ measurements were recorded at Erie St. for wind speeds ≥ 15 knots.
- The wind was only totally (i.e., all six measurements) from the SW ≥ 15 knots for 17 of the 926 hours that ships were in port. These were the wind conditions when the highest 1-hour average SO₂ measurement of 89.6 ppb was recorded.
- When the wind direction was from the SW (with at least 4 of the 10 minute measurements also from the SW) and the speed was ≥ 10 knots the SO₂ level exceeded 35 ppb for 18% of the time that ships were in port.
- Additional monitoring stations are required to determine the full extent of the SO₂ levels experienced by the James Bay, Inner Harbour and the Songhees communities.

How representative are the Erie St. SO₂ measurements?

The measurements are, of course, totally representative of the conditions at the Erie St. location.

However, for this analysis “representative” is defined to mean “have SO₂ values closest to those of the actual ship emissions” i.e., the Erie St. location is more representative than the more distant Topaz. However, the Erie St. site, although a good location, would only by chance be the most appropriate single location in James Bay. Additional monitoring sites are required to determine which areas of James Bay, the Inner Harbour and the Songhees are most affected and have the highest levels of SO₂.

Methodology

This analysis is based on available data for:

- 10-minute average wind speed and direction as measured at Ogden Point
- Cruise Ship scheduled arrival and departure times
- Both the 10-minute and 1-hour average SO₂ levels measured at the Erie St. site

The wind direction is very variable and can change significantly over a one hour period. As a result over a one hour period the SO₂ levels measured at the Erie St. site, in the SW sector, will often be “diluted” by lesser measurements due to winds from other directions not reaching the monitor. In order to reduce this effect some of the “1-hour average” charts will be labelled with “4/6”. In these cases, the charts only include results when at least four of the 10-minute wind measurements were in the same direction as the 1-hour average (see Appendix 1).

The tables and graphs in this report will use three methods for presenting the data:

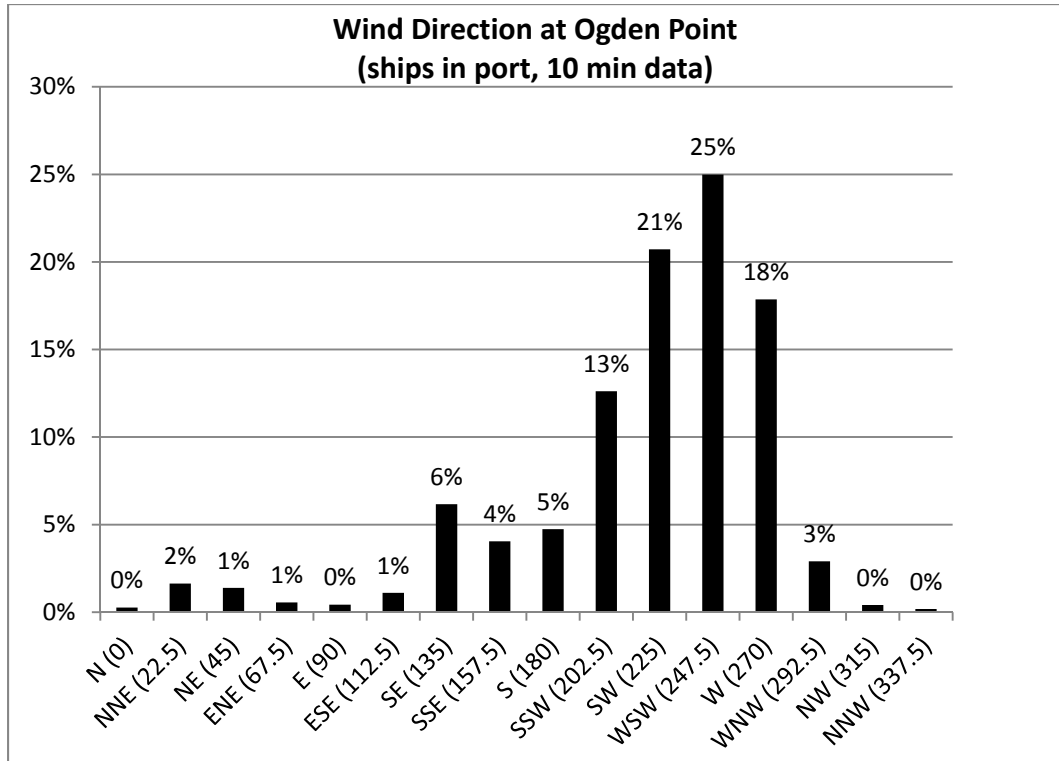
- **“1-hour average”** – Used when a comparison with the Vancouver Island Health Authority (VIHA) SO₂ 1-hr exposure guidelines is useful; e.g., when looking at actual SO₂ levels detected at the Erie site
- **“10-minute average”** – used when a larger dataset will provide more accurate information and a comparison with health standards is not required; e.g., when calculating the % of the time the wind is from a SW direction.
- **“Top 12.5%”** – used for identifying “best”, “worst” or “most”; e.g., when identifying which ships were in port when the highest 12.5% of SO₂ levels were detected. 12.5% was chosen since this was the point at which the 1-hour average measurements (SW, 4/6) exceeded 35 ppb This method is described in Appendix 2

Each table and chart is labelled with the method used.

The Erie St. site is in the SW sector (213.75° to 236.25°). Its actual location relative to the cruise ship will vary between 215° and 230° depending on which pier is in use.

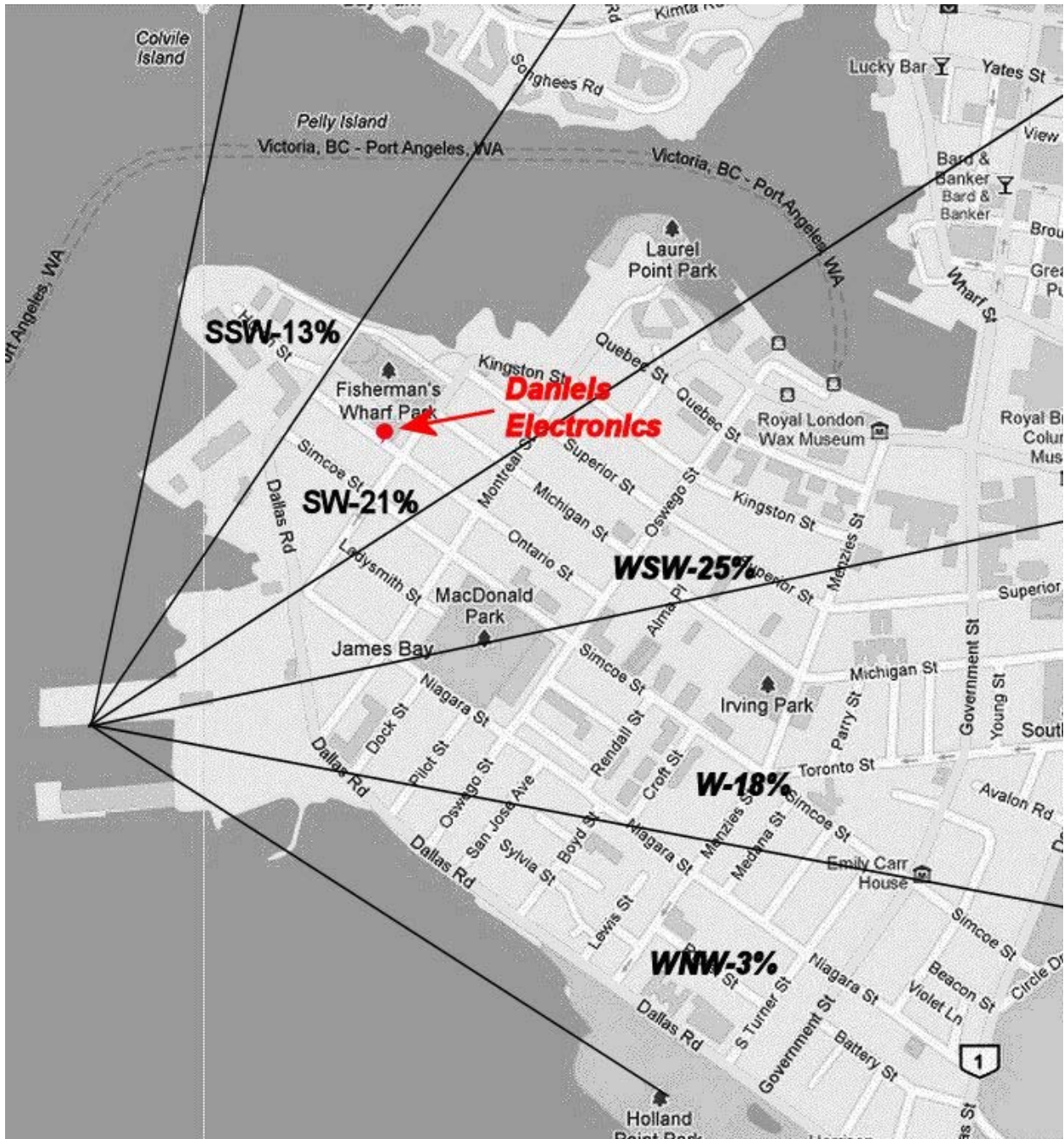
Wind Direction

The frequency of wind direction in each of 16 sectors (N, NNE, NE, ENE, E etc), when cruise ships are in port, is shown in the chart below:



The Erie St. monitoring site is at a wind direction, from Ogden Point, of approximately 215°-230°; i.e., it will most accurately capture Ogden Point data when the winds are from the SW. This occurred 21% of the times that the cruise ships have been docked.

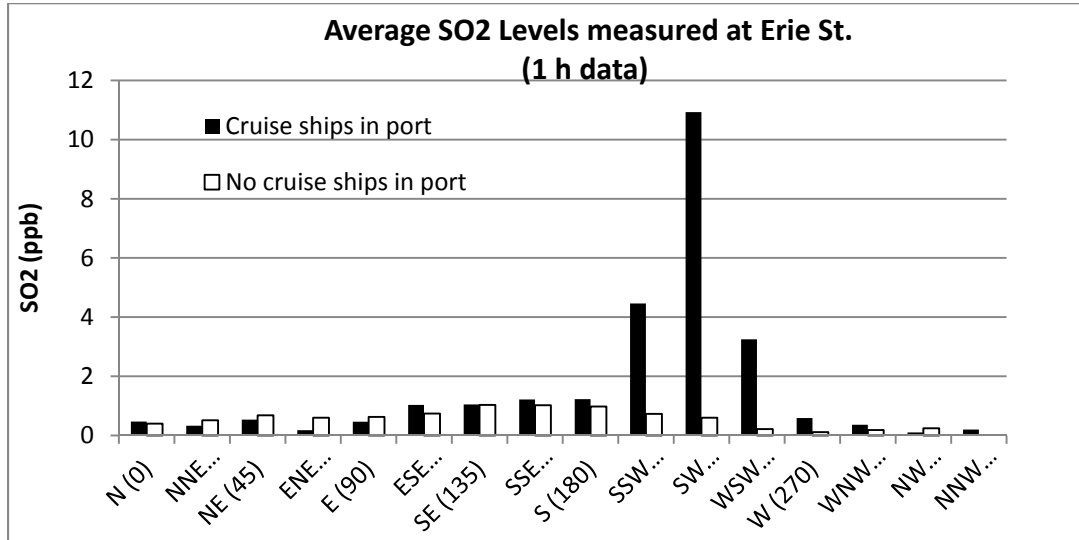
Wind directions in James Bay (as measured at Ogden Point)



The wind direction from Pier A at Ogden Point and the direction frequency have been superimposed on the above James Bay map. The location of the Erie St. SO₂ monitoring station is also indicated.

Average and Maximum SO₂ levels measured at Erie St.

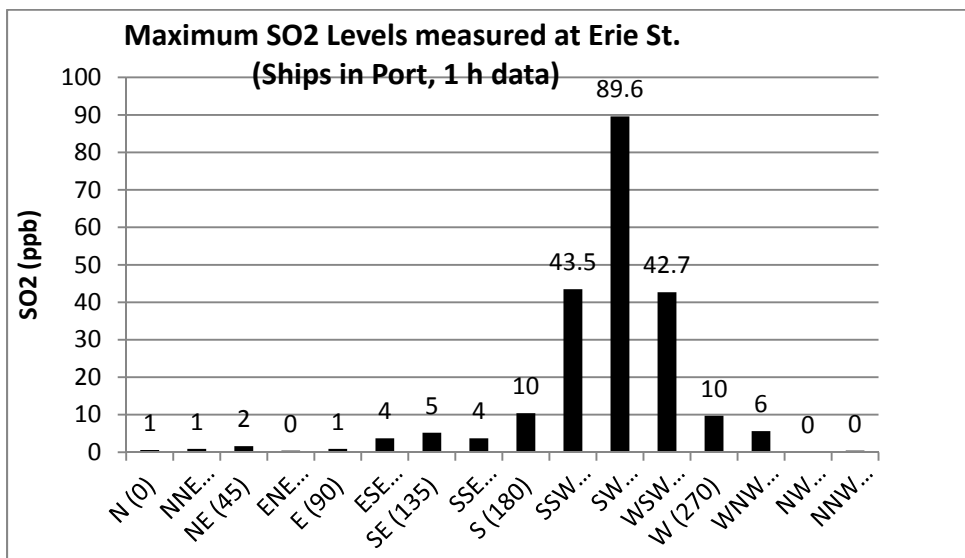
a) Average SO₂



Of note for the “average” readings are:

- The obvious increase in SO₂ levels when the ships are in port.
- The narrow wind direction range in which the Erie St. monitor will capture relevant data; essentially, only in the SSW, SW and WSW sectors, with only diffused measurements being recorded in the outer 2 sectors.

b) Maximum SO₂



Of note for the “maximum” measurements are:

- Same comments as above regarding wind direction and the effect of cruise ships.
- The maximum 1-hour SO₂ level recorded, at Erie St., during the 2011 season was 89.6 ppb. (June 9th, 4-5 pm),
- These are single location measurements. The actual ground level maximum may be higher and may occur either closer to, or further from, Ogden Point depending on wind speed and meteorological conditions. If closer, the maximum may be significantly higher due to a less dispersed plume.

The Vancouver Island Health Authority publishes the following SO₂ Health Risk Guide on its website - http://www.viha.ca/mho/air_quality_index.htm

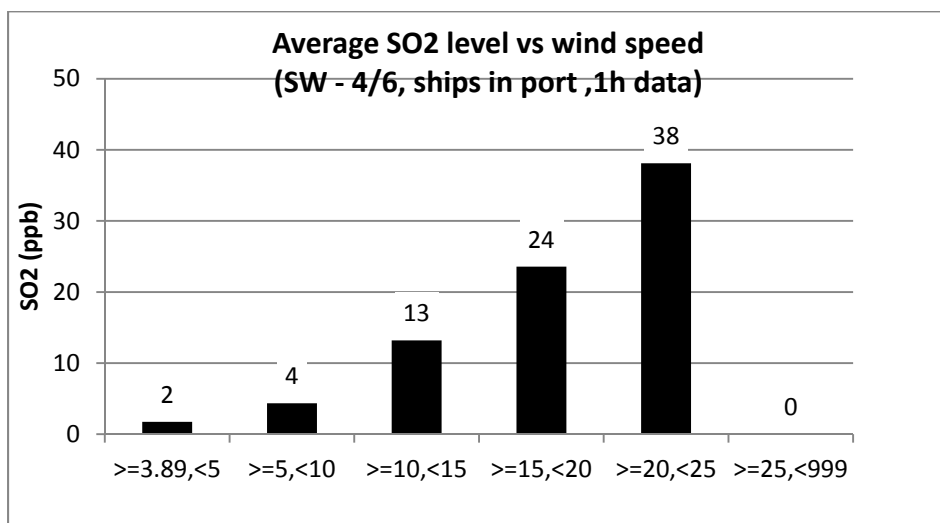
>35 ppb - small number of persons with asthma who are very sensitive to SO₂ may experience symptoms. Follow Dr's advice for managing condition.

>75 ppb - 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.

> 185 ppb - 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.

Effect of wind speed

Wind speed, in addition to wind direction, may also impact the ability of the Erie St. monitor to record representative SO₂ levels.



This chart suggests that:

- There is a relationship between wind velocity and the SO₂ levels detected at the Erie St. site
- The monitor records the highest levels of SO₂ when the wind is from the SW and the speed ≥15 knots.

Note that since the wind speed only exceeded 20 knots for 2 hours during which a cruise ship was in port the average measurement of 38 ppb should be discounted.

	Wind Speed in knots (SW - 4/6, ships in port ,1h data)						120
	≥3.89	≥5	≥10	≥15	≥20	≥25	
	<5	<10	<15	<20	<25	<999	
# of measurements	6	31	54	27	2	0	
%	5%	26%	45%	23%	2%	0%	
Avg SO ₂	2	4	13	24	38	0	
Max SO ₂	5	26	85	90	60	0	
# ≥35	0	0	7	7	1	0	
% of total	0%	0%	13%	26%	50%	0%	
# ≥75	0	0	1	1	0	0	
% of total	0%	0%	2%	4%	0%	0%	

Total Ship in port measurements	926	
Total ≥ 10 knots	83	9%

With wind from the SW and speeds ≥10 knots the SO₂ levels measured at Erie St. exceeded 35 ppb (the level at which those most sensitive to SO₂ may experience symptoms) for (7+7+1)/(54+27+2) = 18% of the time that ships were in port.

Appendix 3 includes a more in depth discussion of wind speed vs. SO₂ levels and also uses both the “10-minute” and “12.5%” methods to illustrate a possible wind speed vs. SO₂ level relationship.

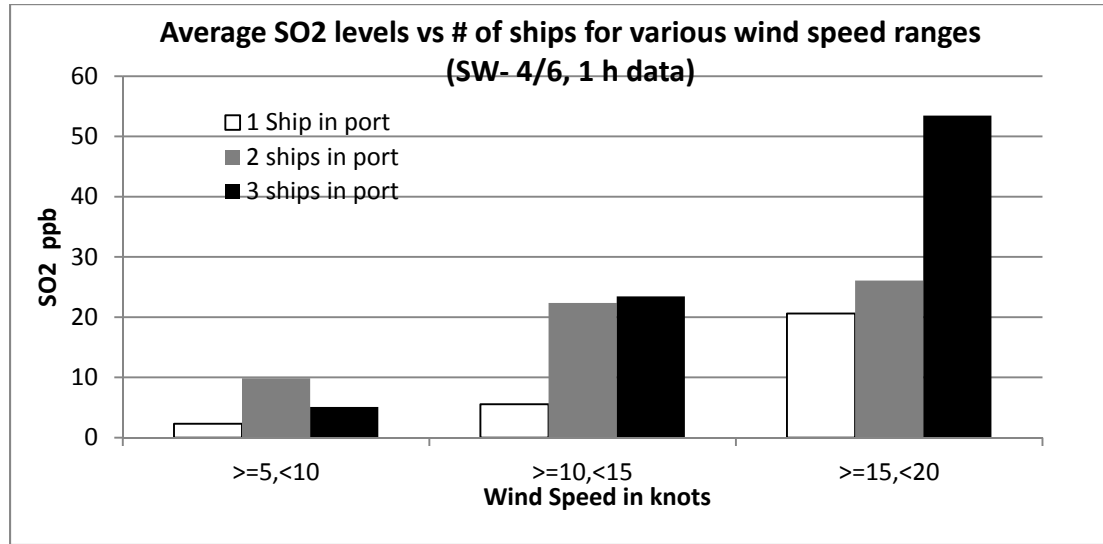
The above analysis has indicated that of the 926 hourly measurements:

- 183 were for SW “1-hour average” winds
- 120 of these had at least 4 of 6 of the 10-minute winds also from the SW
- 83 of these were at wind speeds ≥10 knots
- 51 of these had all 6 of the 10-minute winds from the SW

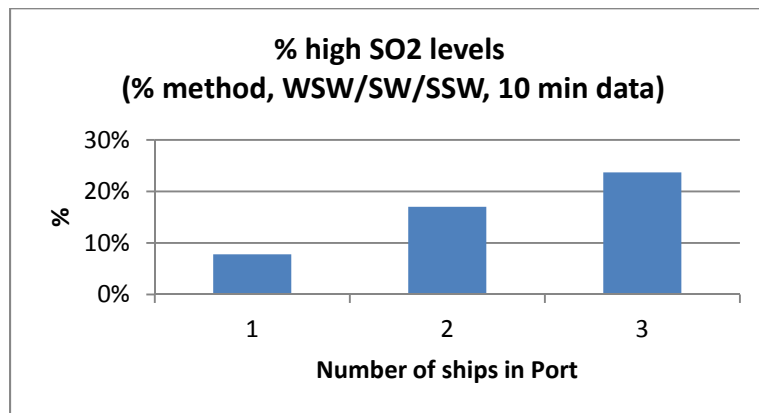
The highest 1-hour SO₂ measurement of the year (89.6 ppb) was recorded when the wind conditions were from the SW (6 of 6) and with a wind speed ≥ 15 knots. These conditions occurred for 2% (17/926) of the time that ships were in port.

Effect of number of ships in port

1-hour data



Top 12.5% data (using 10-minute counts)



10-min counts SSW/SW/WSW			
Ships in Port	All	Top 12.5% SO ₂	% in top
1	1644	128	8%
2	887	151	17%
3	325	77	24%
4	1	1	100%
	2857	357	12.5%

Both the “1-hour data” and the “top 12.5%, 10-minute” charts show the expected relationship between measured SO₂ levels and the number of ships in port.

Ships in port vs. Measured SO₂ levels

10-min counts SSW/SW/WSW			
ShipNames	All Visits	# in top 12.5% SO ₂	% high SO ₂
Carnival Spirit, Crystal Symphony	53	14	26%
Crystal Symphony	304	62	20%
Norwegian Pearl, Oosterdam, Sapphire Princess	280	57	20%
Amsterdam, Celebrity Infinity	193	38	20%
Golden Princess, Westerdam	344	59	17%
Amsterdam, Rhapsody Of The Seas	120	20	17%
Arcadia	76	10	13%
Norwegian Pearl, Oosterdam	49	5	10%
Sea Princess	209	14	7%
Carnival Spirit	270	17	6%
Westerdam	80	4	5%
Rhapsody Of The Seas	292	11	4%
Celebrity Infinity	116	2	2%
Regatta	91	0	0%

This chart uses the “top 12.5%” method to rank those ships which were in port when the wind was from the SSW, SW or WSW for at least 40 10-minute periods. There is strong indication that some ships are significantly higher SO₂ emitters than others.

The highest 1-hour average SO₂ measurement this year of 89.6 ppb occurred when the Amsterdam, Celebrity Infinity and Rhapsody of the Seas were in port. This combination of ships appeared for a total of 31 x 10 minutes while the wind was in a SSW, SW, and WSW direction. Of these 14 or 45% were in the top 12.5% of SO₂ measurements and likely > 35 ppb.

Conclusions

For the 2011 cruise ship season, the single Erie St. monitoring station captured a relatively low percentage of data which was representative of actual ship emissions.

Wind speed, wind direction and distance from Ogden Point are key parameters in determining the location where the SO₂ level will be most severe at any one time. With wind speeds greater than 10 knots there is an indication that SO₂ levels will likely exceed 35 ppb, in the direction of the wind and at about 1km from Ogden Point, for at least 18% of the time that ships are in port. Locations nearer to or further from Ogden Point may experience higher levels.

Additional monitoring stations are required to:

- Determine the effect of distance and wind speed on the SO₂ measurements. Sites located closer to, or further from, Ogden Point may record higher SO₂ concentrations.
- Create a model which will estimate the actual maximum SO₂ levels within the James Bay, Inner Harbour & the Songhees communities.
- Identify those ships which are responsible for high SO₂ emissions or, hopefully and more positively, encourage cruise companies to minimize their environmental impact and take pride in contributing to a greener Victoria.

Appendix 1 – Wind Averaging

The 1-hour wind direction average is not a simple arithmetic average; for example, the average of a wind at 350° and another at 10° is 0° not $(10+350)/2 = 180°$. A vector method must therefore be used for wind direction calculations.

However, the wind direction is very variable over a one hour period and, in the SW direction, only for 36% of the results were all six 10-minute measurements in the same direction as the 1-hour vector average direction. The table below shows how many of the “10-minute” wind directions match the “1-hour vector average” direction:

	SSW	SW	WSW	W
0	7%	1%	1%	0%
1	4%	4%	6%	5%
2	12%	16%	12%	5%
3	14%	13%	13%	11%
4	17%	16%	15%	17%
5	21%	14%	13%	15%
6	25%	36%	41%	47%

In this report, many of the charts include only the results where at least 4 out of 6 of the 10-minute measurements are in the same direction as the 1-hour vector average. For the SW direction this occurs $16+14+36 = 66%$ of the time. Although this will result in a lower representative value of actual ship SO₂ emissions it will provide a larger dataset.

Appendix 2 - Using “data counts” to further analyse the data

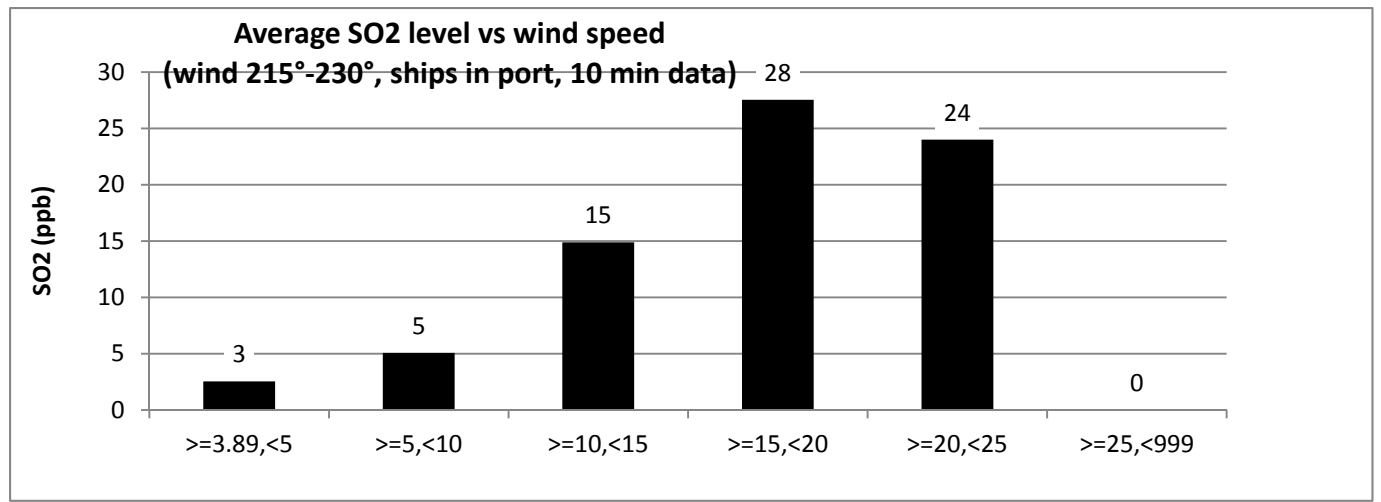
- The 1-hourly SO₂ measurements exceeded 35 ppb for 15 of the 120 (4 of 6) measurements for SW winds. This is 12.5% of the total.
- A larger dataset can be obtained by combining the top 12.5% of the SO₂ measurements for the SSW, SW and WSW directions. It is likely that the measurements within this dataset will also correspond to SO₂ levels greater than 35 ppb
- This data can then be compared with all the measurements for the SSW, SW and WSW wind directions to identify relationships i.e., there was a total of 36 measurements at 7pm and, of these, 7 were in the top 12.5%; this leads to a reasonable assumption that 19% ($=7/36$) of the ship emissions between 6 and 7 pm would result in a SO₂ level in excess of 35 ppb at a location at a similar distance from Ogden Point. A much larger data set is obtained with the 10-minute data

Appendix 3 – Effect of wind speed

The 1-hour graph indicated a relationship between wind speed and SO₂ level but was based on a limited number of results. The following section will look at the relationship in two additional ways:

10-minute results

These charts show the 10-minute data with a narrower wind direction range (215° to 230°) than the 1-hour chart included in the body of the report.



These results are very similar to the 1-hour results with the exception of the ≥20 knots range where there is a slightly larger dataset (18 vs. 2).

Air Speed in knots for 215 to 230 wind direction - cruise season - ships in port							
	>=3.89	>=5	>=10	>=15	>=20	>=25	
	<5	<10	<15	<20	<25	<999	
# of measurements	48	224	312	128	18	0	730
%	7%	31%	43%	18%	2%	0%	
Avg SO2	3	5	15	28	24	0	
Max SO2	22	83	140	167	107	0	
# >=35	0	7	42	34	3	0	
% of total	0%	3%	13%	27%	17%	0%	
# >=75	0	1	14	11	2	0	
% of total	0%	0%	4%	9%	11%	0%	

Total Ship in port measurements	4898	
Total >= 10 knots	458	9%

Top 12.5% method

SW, 10 min data, 1 ship		
	Average Speed	Count
Top 12.5%	15.1	82
Bottom 87.5%	10.7	571

This table looks at the 653 out of 730 10-minute measurements where there was both one ship in port and the wind was from the SW. One ship, rather than all ships, was chosen to remove one variable, number of ships, from the speed vs. SO₂ level relationship.

The results were sorted in order of descending SO₂ values and the average speed calculated for the top 12.5% (≥ 35 ppb) and also for the remainder.

The higher average speed associated with the higher SO₂ values indicates a relationship between wind speed and the level of SO₂ detected at the Erie St. site.

Wind Speed/Measured SO₂ Level Correlation

The correlation table, for the 10-minute data, wind direction 215°-230°, ships in port, showing the r values is:

	<i>Speed</i>	<i>SO₂</i>	<i>ShipCount</i>
Speed	1.00		
SO ₂	0.35	1.00	
ShipCount	0.05	0.29	1.00

The r value between wind speed and SO₂ is 0.35 giving an r² value of 0.12 (and increases to 0.37/0.14 if results are restricted to one ship in port). This is similar to, but higher than, the r value for the SO₂ / Number of ships relationship where, intuitively, a relationship is expected (and is shown to be the case in this report). Many factors influence the correlation and these will inevitably result in a reduced r² value. They include:

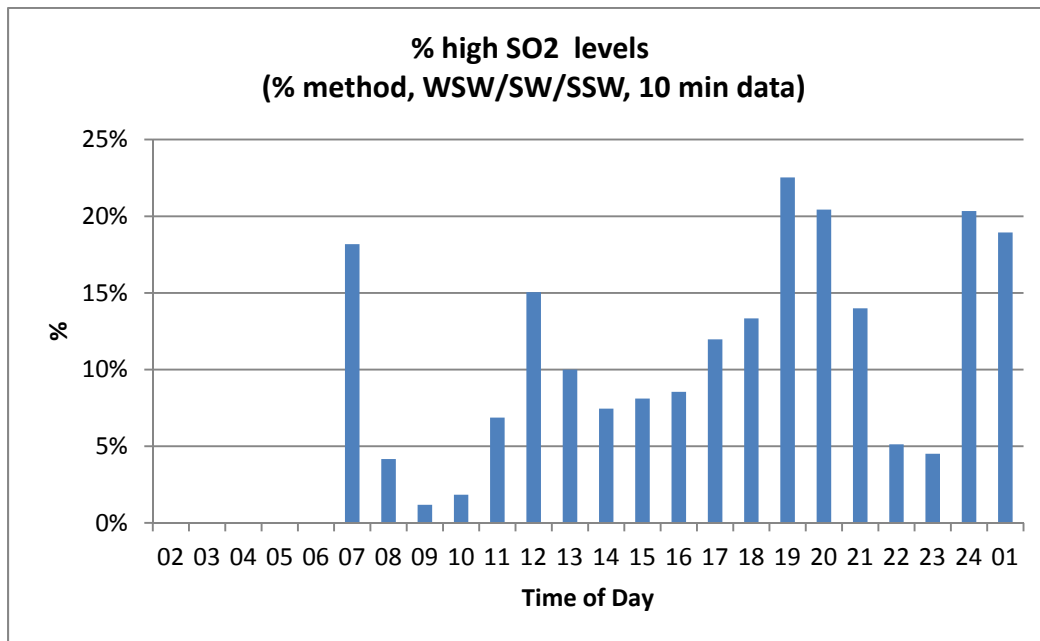
- The number of ships in port
- Some ships emit SO₂ at higher levels than others.
- Higher SO₂ levels are emitted during arriving/leaving than at other times.
- The SO₂ detection is very sensitive to wind direction. Measurements made when the wind is directly towards the Erie St. site will be more relevant than those in the outer range.
- Lower wind speed will take longer to reach Erie St. site and have less of a time match with the SO₂ measurements.
- Data are based on scheduled rather than actual arrivals/departures.

Appendix 4 - Other Charts

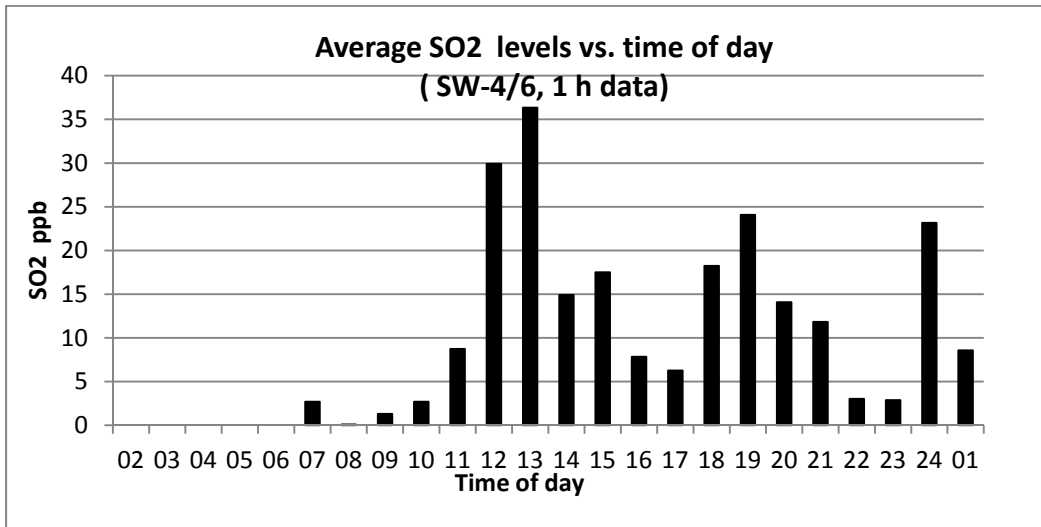
The following charts will be useful for:

- Comparing ship numbers and wind conditions for different years
- Determining the most appropriate locations/times for additional monitoring – assuming each season and year are similar!

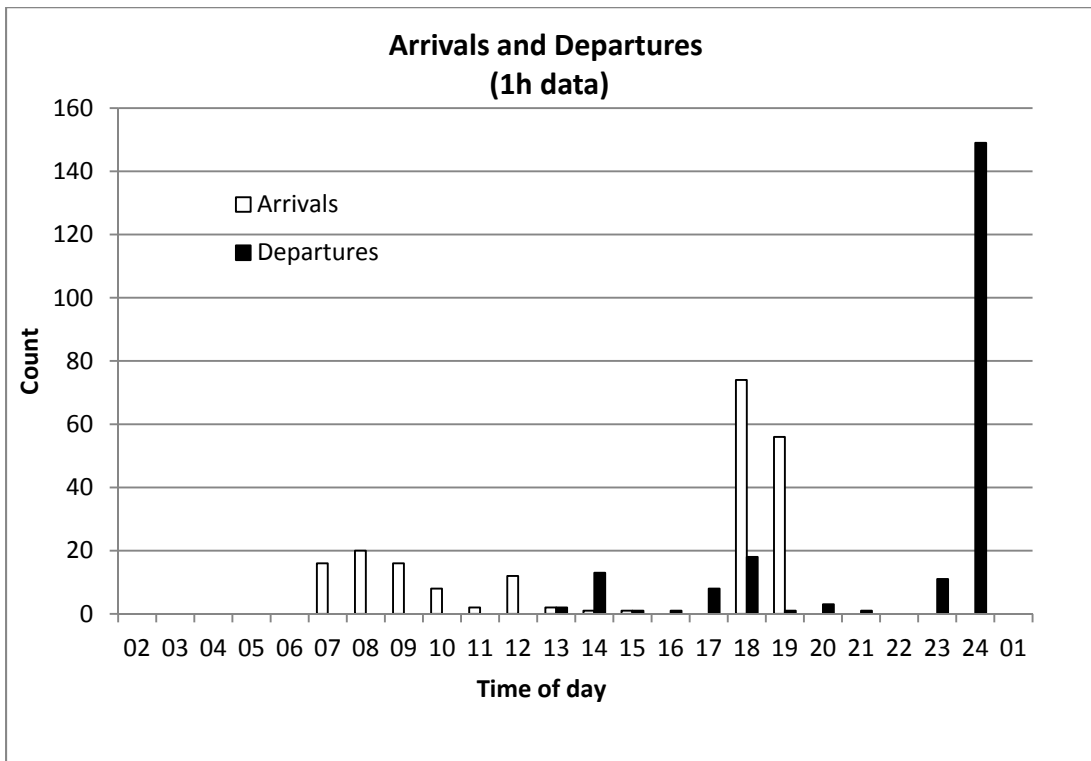
Ship related charts:



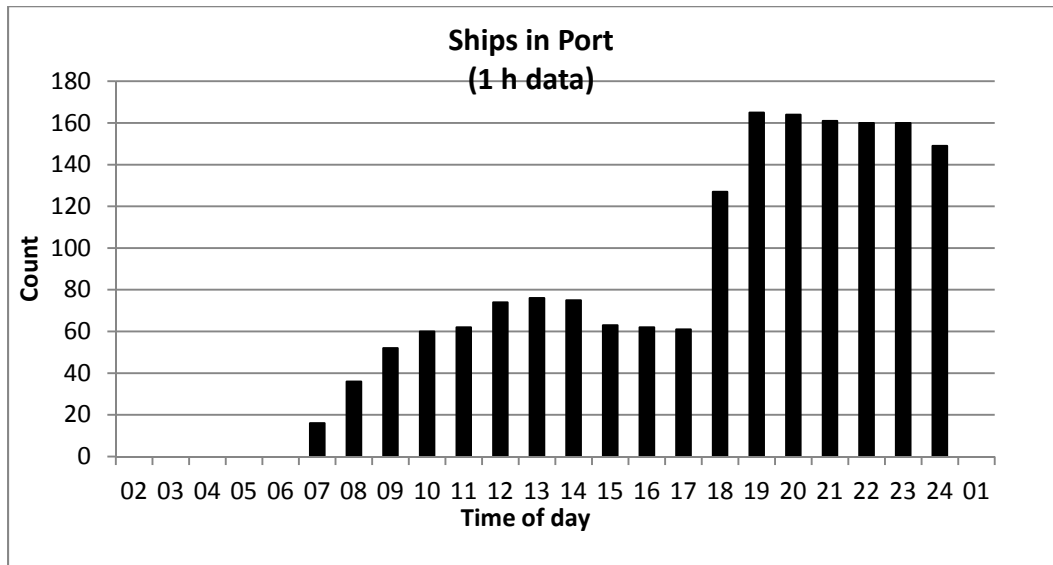
Apart from the 7 am data, which had a low number of results, the above chart is similar to that of the average SO₂ level chart for SW winds only:



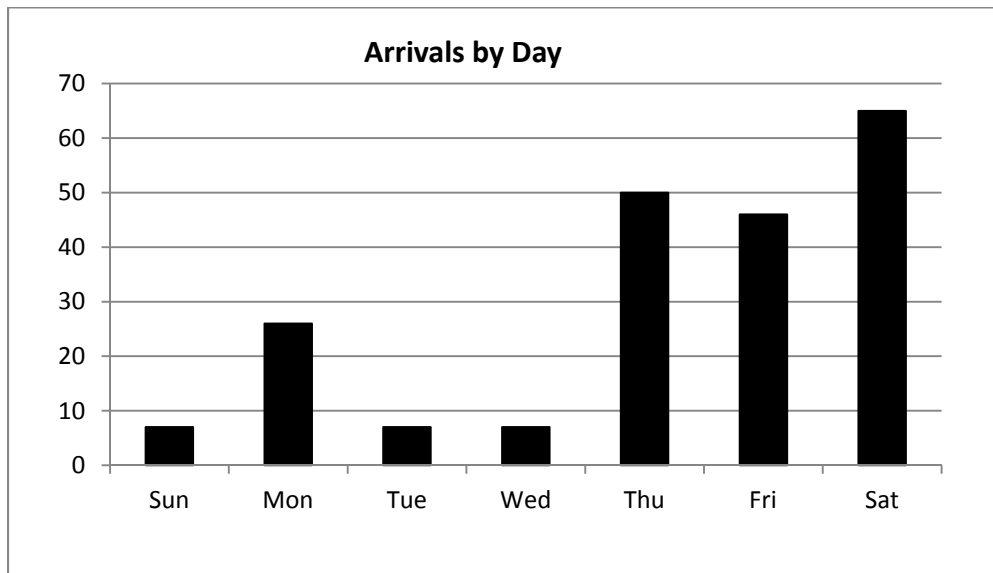
Note that the average SO₂ level for the 12-1pm period (15 1-h periods meeting the SW, 4 of 6 criterion) exceeded the 35 ppb threshold.



Ships in Port vs. Time of Day

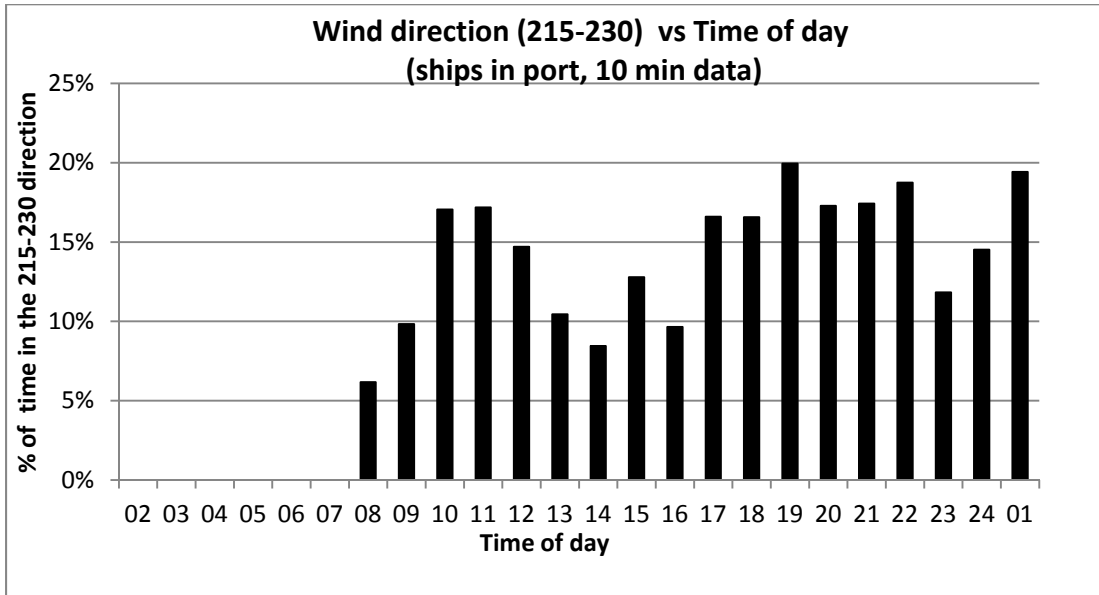


Arrivals vs. Day of Week

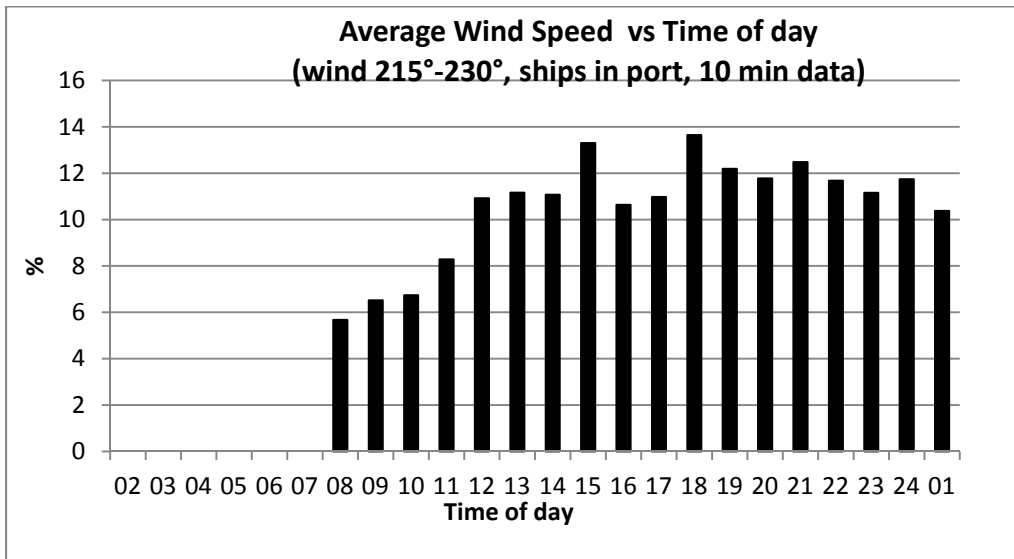


Wind related charts:

Wind Direction vs. Time of Day



Wind Speed vs. Time of Day



Wind Direction vs. Month

		Wind Direction by Month (ships in port, 10 min data)			
		SSW	SW	WSW	W
Apr		7%	23%	30%	5%
May		12%	15%	18%	15%
Jun		12%	13%	27%	30%
Jul		7%	29%	30%	22%
Aug		20%	32%	25%	7%
Sep		12%	17%	27%	14%
Oct*		12%	18%	24%	0%
ALL		13%	21%	25%	18%

*There were very few ships in October – hence the 0% for West winds.

Wind Speed vs. Wind Direction

Wind Speeds with Ships in Port vs. Direction (ships in port, 10 min data)										
SPEED	Overall		winds from SSW		winds from SW		winds from WSW		winds from W	
	results	%	results	%	results	%	results	%	results	%
>=3.89,<5	553	11%	64	10%	64	6%	62	5%	38	4%
>=5,<10	1473	30%	199	32%	304	30%	269	22%	87	10%
>=10,<15	1511	31%	212	34%	438	43%	425	35%	267	31%
>=15,<20	1002	20%	114	18%	186	18%	355	29%	302	35%
>=20,<25	313	6%	29	5%	23	2%	107	9%	145	17%
>=25,<999	46	1%	0	0%	0	0%	6	0%	36	4%
	4898		618		1015		1224		875	
	100%		13%		21%		25%		18%	

Appendix 4 - Data Sources

1) Wind Speed & Direction

- Obtained from the GVHA website: <http://www.victoriaharbour.org/weather.php>
- These measurements are at 10 minute intervals and are used to create hourly averages, i.e., the wind measurements used for “10 am” is the average of all the 10-minute measurements between 9 am and 10 am.
- Only data associated with average wind speeds > 2m/s (3.9 knots) have been included in this report. At wind speeds <2m/s eddying occurs and the measured direction may not be accurate.

2) SO₂ data

- Raw hourly data has been supplied by the BC Ministry of Environment.
- A “10am” measurement is the average of the measurements between 9am and 10am.
- 1 hour has been added to all the times during the cruise ship season to account for DST.
- Where the SO₂ measurements indicated “calib”, “zero”, “<samp>” or “RS232” an average of adjacent measurements has been used.
- Note that the measurements on the BC Government website - <http://www.bcairquality.ca/readings/index.html> - have already been corrected to local time and for calibration errors.

3) Ship arrivals and departures

- The ship times were obtained from the GVHA website <http://www.victoriacruise.ca/page/cruise-schedule>
- For ship arrivals and departures the following are examples of the times used for linking the ship times to the **hourly** SO₂ and Wind data:

Arrival	Leave	Data Link (arrival)	Data link (departure)
1 pm	11:59 pm	1 pm	1 am next day
7:30 pm	11:59 pm	7 pm	1 am next day

Thus, in general, 0 hours have been deducted from the arrival times (30 minutes in the case of arrivals on the half hour) and 1 hour has been added to departure times. This ensures the correlation of ship arrival and departure emissions with the SO₂ data (A 7am measurement is for the 6am to 7am period).

For the **10-minute results** - 30 minutes have been deducted from the arrival time and 30 minutes added to the departure times.

- 2 ships with extended stays, Oosterdam and Norwegian Star on September 25th, have been excluded from the analysis.