Sulphur Dioxide (SO_2) Objective Literature Review

Prepared for:

Metro Vancouver
Air Quality Policy & Management Division
4330 Kingsway
Burnaby, BC V5H 4G8

Prepared by:
Bohdan W. Hrebenyk, M.Sc.
Harriet A. Phillips, Ph.D.
Katherine J. Woolhouse, M.Sc.
Malcolm A. Smith, P.Eng.

SENES Consultants
1338 West Broadway, Suite 303
Vancouver, B.C. V6H 1A6

23 December 2013

TABLE OF CONTENTS

Page No.

LIST OF TABLES

Page No.

LIST OF FIGURES

Page No.

GLOSSARY OF ACRONYMS AND ABBREVIATIONS

Abbreviations	
AAQO	Ambient Air Quality Objectives (Metro Vancouver)
AQI	Air Quality Index
AQO	Air Quality Objectives (British Columbia)
B.C.	British Columbia
CAAQS	Canadian Ambient Air Quality Standards
CASAC	Clean Air Scientific Advisory Committee; U.S. Congressionally-chartered body of independent scientific advisors charged with giving advice to the U.S. EPA
CRD	Capital Regional District in British Columbia
EU	European Union
NAAQO	National Ambient Air Quality Objectives (Canada)
NAAQS	National Ambient Air Quality Standards (United States)
PCO	Pollution Control Objectives (British Columbia)
U.S. EPA	United States Environmental Protection Agency
VIHA	Vancouver Island Health Authority in British Columbia
WHO	World Health Organization
Contaminants	
DMS	Dimethyl Sulphide
DMSP	Diemthylsulphoniopropionate
H_2S	Hydrogen Sulphide
NO_2	Nitrogen Dioxide
O_3	Ozone
$PM_{2.5}$	Fine particulate matter with a mean diameter $\leq$2.5 microns
SO_2	Sulphur Dioxide
SOx	Sulphur Oxides
Units of Measure	
mol/m^3	mols per cubic metre(unit of concentration in water)
nM	nanomols
nmol/litre	nanomols per litre
µg/m^3	micrograms per cubic metre (unit of concentration in air)
µg S/m^2	micrograms of Sulphur per square metre (unit emissions to air)
ppb	parts per billion (unit of concentration)
ppm	parts per million (unit of concentration)

1.0 INTRODUCTION

The Provincial Government of British Columbia has the authority to delegate primary responsibility for air quality management to regional or municipal jurisdictions. In 1972, the Provincial Government delegated authority for air quality management to the Greater Vancouver Regional District (GVRD). As part of the Air Quality Management Plan (AQMP) within its jurisdiction, the GVRD (Metro Vancouver) established a set of Ambient Air Quality Objectives (AAQO) that are used in policy planning, permitting of air contaminant emission sources and overall air quality management. The current set of AAQO for sulphur dioxide (SO_2)[1] was updated by Metro Vancouver in 2005 and includes:

450 $\mu g/m^3$	(174 ppb)	1-hour average
125 $\mu g/m^3$	(48 ppb)	24-hour rolling average
30 $\mu g/m^3$	(12 ppb)	annual average

These objectives remained unchanged in Metro Vancouver's 2011 Integrated Air Quality and Greenhouse Gas Management Plan.

SENES Consultants was retained to complete a literature review in support of Metro Vancouver's efforts to review the AAQO for SO_2. The scope of work for the project consisted of the following tasks:

1. a review and summary of established ambient air quality criteria in other jurisdictions in North America, Europe, Australia, New Zealand, etc.;
2. a review of recent SO_2 human health science assessments;
3. a review of recent SO_2 ecosystem health science; and
4. a review of sulphur emissions from natural environments which can contribute to ambient SO_2 concentrations.

This report provides a summary of the information gathered as part of this literature review.

It should be noted that information on SO_2 concentrations as presented in the literature is often presented either as parts per billion (ppb), parts per million (ppm) and/or micrograms per cubic metre ($\mu g/m^3$). Conversion rates between ppb and $\mu g/m^3$ vary slightly between published sources and regulatory jurisdictions. Consequently, wherever authors have provided concentration data in units of both ppb (or ppm) and $\mu g/m^3$, the author's conversion rates have

[1] http://public.metrovancouver.org/about/publications/Publications/IntegratedAirQualityGreenhouseGasManagementPlan-October2011.pdf

been reported as given in the publication. Where authors have provided concentrations only in ppb (or ppm), concentrations in ppb were multiplied by a factor of 2.66 to convert to $\mu g/m^3$, based on the conversion rate listed in Bates and Caton (2002) and which is consistent with the conversion factor used by the World Health Organization (WHO 2006).

2.0 JURISDICTIONAL REVIEW

This section provides a review and summary of SO_2 air quality standards, objectives and guidelines (collectively referred to as criteria) in place in various jurisdictions throughout the world. In general, jurisdictions develop either standards, which represent maximum allowable (i.e., not to exceed) ground level SO_2 concentrations that can be applied in an industrial area, or objectives, which represent general ambient concentrations that a jurisdiction would like to attain.

Standards and objectives can also be expressed in tiers as desirable, acceptable and tolerable levels of ambient SO_2 concentrations, which is the approach taken by Environment Canada, or expressed in tiers based on surrounding land uses, which is the approach taken by a number of countries such as India and China. The WHO has also developed tiers, which are expressed as interim targets and targets that jurisdictions can adopt as they work towards reducing overall SO_2 emission rates.

Jurisdictions also have different standards or objectives for different averaging periods, typically 1-hour, 24-hour and annual. Some jurisdictions also consider shorter term periods (4, 10, 15 or 20-minutes) or mid-range periods (3-hour, 8-hour or 30-days), while some apply criteria over several months during the winter period. SO_2 standards and objectives are typically established to protect human health and/or ecosystems.

2.1 METHODOLOGY

Available information on existing air quality management criteria (i.e., standards, guidelines, objectives, targets, etc.) used in other jurisdictions was compiled through a search of internet web sites for various jurisdictions and agencies. Information was obtained from:

- Environment Canada;
- Canadian Provinces, specifically British Columbia, Alberta, Saskatchewan, Manitoba, Ontario, Quebec, Nova Scotia, New Brunswick, Prince Edward Island and Newfoundland;
- U.S. Environmental Protection Agency (U.S. EPA), as well as the California Air Resources Board;
- World Health Organization (WHO);
- European Union (EU), as well as from the United Kingdom (UK);
- Asian jurisdictions, specifically from the Clean Air Initiative for Asian Cities Center;
- Individual countries such as Australia, New Zealand, Sweden, Switzerland, the UK, Mexico, South Africa, Saudi Arabia, Tanzania, Argentina, Brazil, Belize, Chile,

Dominican Republic, Jamaica, Nicaragua, Peru, Trinidad and Tobago, China & Hong Kong, and India.

Different jurisdictions have developed different procedures to establish standards and objectives for ambient SO_2 concentrations, but all have the same common elements – review of pollution effects literature, review of what other jurisdictions have set as an objective or standard, and some assessment of the economic implications of a particular objective or standard. Typically, a scientific panel is established which looks at all of the data and makes a recommendation to government on the level of objective or standard and its implications to public health, the environment and the economy.

A paper assessing global ambient air quality standards for SO_2 was also reviewed. Vahlsing and Smith (2011) reviewed 24-hour average national SO_2 standards by sending surveys to 153 countries. The surveys covered three broad topics: 1) background information on standards; 2) awareness of the WHO guidelines and their role in determining standards; and 3) the standard setting process, specifically the evidence-base used to establish or revise standards. In a number of cases, additional information on criteria in specific countries was checked via internet searches for more recent information on air quality standards.

2.2 CANADIAN JURISDICTIONS

2.2.1 Federal, Provincial and Territorial Criteria

In Canada, air quality regulations are primarily enforced at the provincial level, and air quality standards, guidelines and objectives are most often based on time-averaged, ground-level ambient air concentrations. National Ambient Air Quality Objectives (NAAQO) were first established in the 1970s. NAAQO is a three-tiered system defined as Maximum Tolerable, Maximum Acceptable and Maximum Desirable. Each level has a specific concentration for an individual air contaminant, with one or more averaging periods.

In addition to NAAQO concentration-based SO_2 criteria, Canadian provinces also have their own permitting or approval systems in place. In general, provincial permits will contain ambient air concentration limits and/or stack emission limits, monitoring requirements, and operating and maintenance requirements. Ambient levels are typically set considering the impact of concentration levels on the general public and ecosystems.

The status of air quality criteria in British Columbia is defined in the update to the provinces ambient air quality objectives issued in August 2013:

> *"The province of B.C. uses a suite of ambient air quality criteria that have been developed provincially and nationally to inform decisions on the management of air contaminants. These include Provincial Air Quality Objectives (AQOs), the former Pollution Control Objectives (PCOs), National Ambient Air Quality Objectives (NAAQOs) and Canadian Ambient Air Quality Standards (CAAQS). Metro Vancouver has also established air quality objectives that apply within the Metro Vancouver area.*
>
> *For any particular averaging period, a range of air quality criteria may exist (e.g. Levels A, B and C), reflecting the different conditions under which criteria may be applied. In the case of PCOs, these may also differ across source sectors."*

Table 2-1 lists the relationship between the NAAQO tiers and the B.C. Level A, B and C tiers for specific industry sectors, as defined in the most recent update of the provincial AAQO.

Table 2-2 summarizes the review of SO_2 standards in Canadian jurisdictions. As outlined in the table, all provinces have adopted 1-hour, 24-hour and annual standards in the range of either the Canadian desirable or acceptable standards. Some key differences among the criteria used by various provinces are:

- Manitoba is the only other province that has adopted a tiered approach to air quality criteria which follows from the NAAQO levels;
- Quebec is the only province that has adopted criteria for SO_2 concentrations averaged for less than 1 hour;
- British Columbia and Newfoundland have 3-hour criteria; and
- Alberta has a 30-day standard.

In general, acceptable levels represent criteria applied in industrial areas and desirable levels represent criteria applied to residential areas, although in practice the desirable levels may also be used even in remote locations if there are concerns about emissions from a particular facility.

Table 2-1 Description of B.C. PCO and NAAQO Levels[2]

PCO	B.C. Level A	B.C. Level B	B.C. Level C
Forest Products Industry 1977	Desirable goals for all discharges and will generally apply to all new discharges, and to existing installations whose discharges are significantly altered in quantity or quality	Intended as acceptable interim objectives for all other discharges and will be reviewed periodically by the Direction of Pollution Control	
Chemical & Petroleum Industries 1974	For new and proposed discharges, and within the limits of the best practicable technology, to existing discharges by planned staged improvements for these operations	Intermediate objective for all existing discharges to reach within a period of time specified by the Director, and as an immediate objective for existing discharges which may be increased in quantity or altered in quality as a result of process expansion or modification	Immediate objective for all existing chemical and petroleum industries to reach within a minimum technically feasible period of time
Food-processing, Agriculturally-oriented & other miscellaneous industries	Intended to provide adequate long-term protection	Not defined	Intended to provide adequate short-term protection of the environment
PCO	**Lower Range**	**Upper Range**	
Mining, Smelting & related industries 1979	Defined for discharges as applying to sensitive environmental situations	Defined for discharges as applying to where it can be shown that unacceptably deleterious changes will not follow	
NAAQO	**Maximum Desirable**	**Maximum Acceptable**	**Maximum Tolerable**
	Long-term goal for air quality and provides a basis for an anti-degradation policy for unpolluted parts of the country and for the continuing development of pollution control technology	Intended to provide adequate protection against effects on soil, water vegetation, materials, animals, visibility, and personal comfort and well-being	Time-based concentrations of air contaminants beyond which, owing to a diminishing margin of safety, an appropriate action is required without delay to protect the health of the general population

[2] http://www.bcairquality.ca/reports/pdfs/aqotable.pdf

Table 2-2 Summary of Federal/Provincial/Territorial SO_2 Criteria in Canada

Jurisdiction	SO_2 Concentration (µg/m³) Time Averaging Period						Comments
	4-min	1-hr	3-hr	24-hr	30-day	Annual	
Canada		450		150		30	Maximum Desirable
		900		300		60	Maximum Acceptable
				800			Maximum Tolerable
British Columbia		450	375	160		25	Level A or Lower
		900	665	260		50	Level B or Upper
		900		360		80	Level C
Alberta		450		125	30	20	
Saskatchewan		450		150		30	
Manitoba		450		150		30	Maximum Desirable
		900		300		60	Maximum Acceptable
				800			Maximum Tolerable
Ontario		690		275		55	
Quebec	1,050			288		52	
Nova Scotia		900		300		60	
New Brunswick		900		300		60	
Prince Edward Island		900		300		60	
Newfoundland		900	600	300		60	
Yukon		450		150		30	
Northwest Territories		450		150		30	

Some of the effects of SO_2 above or below the three Federal objective levels are summarised in Table 2-3, as defined by Environment Canada in 1991. The Air Quality Index for the Province of Ontario considers SO_2 concentrations less than 690 µg/m³ (1-hour average) as being protective of both human health and vegetation, although the Ministry of Environment[3] also notes that concentrations greater than 465 µg/m³ may cause some vegetation damage in combination with ground-level ozone. The AQI assumes that only concentrations greater than 5,520 µg/m³ result in increasing sensitivity for asthmatics and people with bronchitis. By comparison, the Province of Quebec uses a value of 200 ppb (~530 µg/m³) (4-minute average) for the AQI in the rest of the province[4] and an objective of 1050 µg/m³. No other provincial or

[3] http://www.airqualityontario.com/science/pollutants/sulphur.php
[4] http://www.iqa.mddefp.gouv.qc.ca/contenu/calcul_en.htm

territorial jurisdictions in Canada were identified that base air quality management or public communications about air quality on criteria less than a 1-hour average.

Table 2-3 Relationships Between SO_2 NAAQO for Health & Environmental Effects
(Source: Environment Canada 1991)

Good Range (0-Max. Desirable)	Fair Range (Max. Desirable-Max. Acceptable)	Poor Range (Max. Acceptable - Max. Tolerable)	Very Poor Range* (over the Max. Tolerable)
0-450 µg/m^3 (1-hr) 0-150 µg/m^3 (24-hr) 0-30 µg/m^3 (annual)	450-900 µg/m^3 (1-hr) 150-300 µg/m^3 (24-hr) 30-60 µg/m^3 (annual)	>900 µg/m^3 (1-hr) 300-800 µg/m^3 (24-hr) >60 µg/m^3 (annual)	>800 µg/m^3 (24-hr)
no effects	increasing injury to species of vegetation	odorous; increasing vegetation damage and sensitivity	increasing sensitivity of patients with asthma and bronchitis

*The upper limit of the very poor range is not defined. At extremely high levels, symptoms would be worse than those listed.

Updated standards for air quality are currently under discussion at the federal/provincial government levels, and the Canadian Council of Ministers of the Environment (CCME) announced in 2012 the introduction of a new, comprehensive Air Quality Management System (AQMS). The primary objective of the AQMS will be to protect human health and the environment through continuous improvement of air quality within a framework that allows air quality management actions to become increasingly more stringent as air quality deteriorates and approaches the new ambient air quality standards defined under the AQMS. New Canadian Ambient Air Quality Standards (CAAQS) have been introduced for fine particulate matter ($PM_{2.5}$) and ground-level ozone (O_3), and work has been initiated on new CAAQS for SO_2 and nitrogen dioxide (NO_2). The CAAQS for SO_2 and NO_2 would take effect in 2020 and 2025 and will consist of three related parts:

- one or more numerical values;
- the averaging time of each numerical value; and
- the statistical form of the numerical values.

A final report to the multi-stakeholder CAAQS Working Group is expected to be completed by October 2014, with on-going Working Group consultations to be completed by December 2015.

2.2.2 Regional and Municipal Criteria

In addition to the federal and provincial criteria, a number of regional and municipal governments have adopted ambient air quality objectives, guidelines or indicators that are used either for air quality management or to assist in communicating information about air quality to the general public.

As previously noted, Metro Vancouver adopted new SO_2 AAQO of 450 µg/m^3 (1-hour average), 125 µg/m^3 (24-hour rolling average) and 30 µg/m^3 (annual average) in 2005 which are used for policy planning, permitting of air contaminant emission sources and overall air quality management within Metro Vancouver's jurisdiction. In addition, following a study of potential health effects from the air contaminant emissions of the Chevron oil refinery in Burnaby which was completed in 2002, Metro Vancouver amended the air emissions permit for the refinery in 2008 (Permit GVA0117) to include triggers for reducing SO_2 emissions, based on observed SO_2 concentrations recorded at four monitoring stations located within a 2 km radius of the refinery. A sulphur oxides (SOx) Curtailment Event (SCE) is defined in the plant's operating permit as a time period when the SO_2 concentration at any of the four stations exceeds 190 ppb (10-minute rolling average), equivalent to the WHO guideline level of 500 µg/m^3 (10-minute average) (see Section 2.3.1).

In 2004, the Capital Regional District (CRD) in Victoria also developed a 24-hour SO_2 average air quality guideline which could be used to report on air quality in a more meaningful way to the general public, as well as to assist the CRD in interpreting trends in air pollutant concentrations. The CRD SO_2 guideline of 125 µg/m^3 was based on the WHO guidelines for Europe that were established in 2000 (WHO 2000).

A health risk guide for residents of the James Bay neighbourhood in Victoria issued by the Vancouver Island Health Authority (VIHA)[5] listed 1-hour average SO_2 concentrations less than 35 ppb (<95 µg/m^3) as posing little or no risk to human health, concentrations of 36-75 ppb (approximately 95-200 µg/m^3) as posing a moderate risk for a very small number of people who are unusually sensitive to SO_2, concentrations 76-185 ppb (~200-490 µg/m^3) as being unhealthy for sensitive groups (e.g., asthmatics), but not to the general public, and concentrations greater than 490 µg/m^3 as levels at which everyone may begin to experience health effects and at which members of sensitive groups may experience more serious health effects.

[5] http://www.viha.ca/mho/james_bay_sulphur_dioxide_monitoring.htm

Montreal's Air Quality Index (AQI), which is used to define poor air quality, was also established in 2004 and uses the WHO SO_2 guideline of 500 µg/m^3 (10-minute average) (Gagnon et al. 2007).

The Capital Region in Alberta, which comprises 25 municipalities around Edmonton, adopted an air quality management framework which includes a set of tiered 'trigger levels' for management actions if concentrations of NO_2, SO_2, $PM_{2.5}$ and O_3 exceed specified levels (Alberta Environment and Sustainable Resource Development 2012). The trigger levels are set below the ambient air quality objectives for the province and are intended to induce mitigative measures that would prevent contaminant concentrations from reaching or exceeding the objective levels. The trigger levels are not intended to replace the Alberta Ambient Air Quality Objectives. Instead, the framework will be used to supplement the evaluation of the annual and hourly data by using the triggers to help select management actions that can be taken to reduce the likelihood of reaching the annual and hourly Alberta objective levels.

The Capital Region (Edmonton) trigger levels for SO_2 are defined for both annual average hourly average concentrations as listed in Table 2-5. Under this framework, mitigative measures would begin to be investigated if hourly concentrations at the 99th percentile exceed 76 µg/m^3 or annual average concentrations exceed 13 µg/m^3, while emission reductions would begin to be required if hourly concentrations exceed 76 µg/m^3 and annual average concentrations exceed 20 µg/m^3.

Table 2-4 Capital Region (Edmonton) Triggers for SO_2 Investigation

Levels	**Upper Range of Hourly Data** (µg/m^3) Based on 99th percentile	**Annual Average Concentrations** (µg/m^3)
Level 1	Avoid or minimize degradation wherever reasonable or possible	
Trigger into Level 2	37	8
Level 2	Early indication of emerging air quality issues, time to react and plan	
Trigger into Level 3	76	13
Level 3	Identify pressures and implement management actions required to prevent *Alberta Ambient Air Quality Objectives* being reached	
Trigger into Level 4	113	20
Level 4 (not a limit)	Investigation required to understand and manage localized emissions	Emission reductions required, with mandatory compliance and approval implications

2.3 INTERNATIONAL JURISDICTIONS

The Vahlsing and Smith (2011) global study determined that 79% of respondents (76 of 96 respondents) have a 24-hour SO_2 criterion, although the current review has identified a total of 79 countries that use a 24-hour criterion. The study by Vahlsing and Smith also determined that criteria were typically established based on air quality monitoring data and a review of criteria from other jurisdictions and/or the WHO. For the current review of international jurisdictions, additional information on criteria in Asia was derived from the Clean Air Initiative for Asian Cities Center (2010) and Patdu (2012).

Table 2-5 summarizes the review of SO_2 criteria in international jurisdictions. For the 28 member states of the EU, only those countries whose criteria differ from the EU directives are listed separately (e.g., the United Kingdom, Sweden, Switzerland). Similarly, Hong Kong is listed separately from China because Hong Kong’s criteria differ from those used in the rest of China, and California is identified separately from the U.S. EPA NAAQS.

As outlined in the table, the WHO and jurisdictions in China, Bhutan and Belize use tiered criteria. It is also worth noting that the European Union, United Kingdom, Hong Kong, Australia, New Zealand, the U.S. EPA NAAQS, Mexico, India (Ministry of Environment and Forests 2013), Brazil, South Africa (Government Gazette 2009) and Saudi Arabia (Presidency of Meteorology and Environment 2012) allow for a number of exceedances per year of their respective standards. Consequently, the numerical values of the criteria alone do not indicate the precise stringency with which those criteria are applied. The degree of success in achievement of the adopted criteria in each jurisdiction is also not considered in Table 2-5.

Table 2-5 Summary of SO_2 Criteria in International Jurisdictions

Jurisdiction	SO_2 Concentration (µg/m³) Time Averaging Period					Comments
	10-min	**15-20 min**	**1-hr**	**24-hr**	**Annual**	
World Health Organization	500			20		Human health protection
				50		Interim Target for human health
				100	20 10	Annual average guideline for vegetation protection; also applies October 1st to March 31st; lower annual value applies to protection for lichens
				125		Interim Target for human health
European Union			350	125	20	Permitted exceedances per year: 24 (1-hr) and 3 (24-hr)
United Kingdom		266	350	125	20	Permitted exceedances per year: 35 (15-min), 24 (1-hr) and 3 (24-hr) Annual limit also applies for October 1st to March 31st
Switzerland[6]				100	30	
Sweden			350	125	5	Interim annual target adopted in 2000 to be achieved by all municipalities by 2005
U.S. National Ambient Air Quality Standards			196			3-year average of the annual 99th percentile of the 1-hour daily maximum concentration; secondary standard 1330 µg/m³ (3-hr)
California			655	105		
Mexico				345	80	Permitted exceedances 1 day per year (24-hr)
Australia			570	230	60	Permitted exceedances 1 day per year for both 1-hr & 24-hr
New Zealand			350 570			9 exceedances per year 0 exceedances per year

[6] http://www.admin.ch/opc/fr/classified-compilation/19850321/index.html

Jurisdiction	SO_2 Concentration (μg/m^3) Time Averaging Period					Comments
	10-min	15-20 min	1-hr	24-hr	Annual	
Argentina			850	367	79	Secondary standard of 1309 μg/m^3 (3-hr)
Brazil[7]				365	80	Primary standard for human health; 1 exceedance per year (24-hr)
				100	40	Secondary standard for human health, flora/fauna, materials; 1 exceedance per year (24-hr)
Belize[8]				120		Industrial & mixed use
				80		Rural & residential areas
				30		Sensitive areas
Chile[9]				250	80	
Dominican Republic[10]			200	150	100	
Jamaica[11]			700	365	80	
Nicaragua[12]				365	80	
Peru[13]				365	80	
Trinidad & Tobago[14]	500			125	50	120 μg/m^3 (8-hr)
Russian Federation		500		50		Short-term exposure limit based on 20-minute average
China[15]			150	50	20	Specially Protected Areas
			500	150	60	Residential Areas
			700	250	100	Special Industrial Areas
			150	50	20	Specially Protected Areas - by 2016
			500	150	60	Residential/industrial & mixed use areas - by 2016
Hong Kong			800	350	80	Permitted exceedances per year: 3 (1-hr) and 1 (24-hr)
				125		Proposed objective; 3 exceedances per year

[7] http://transportpolicy.net/index.php?title=Brazil:_Air_Quality_Standards#Technical_Standards
[8] http://faolex.fao.org/docs/pdf/blz50555.pdf
[9] http://www.temasactuales.com/laws_policies/legislation_Chile.html
[10] http://www.temasactuales.com/assets/pdf/gratis/Calidad%20del%20Aire.pdf
[11] http://www.nepa.gov.jm/standards/air_quality_standards_regulations.pdf
[12] http://www.temasactuales.com/laws_policies/legislation_Nicaragua.html
[13] http://www.temasactuales.com/laws_policies/legislation_Peru.html
[14] Republic of Trinidad and Tobago (2001)
[15] http://cleanairinitiative.org/portal/node/8163

Jurisdiction	SO_2 Concentration (µg/m^3)					Comments
	Time Averaging Period					
	10-min	15-20 min	1-hr	24-hr	Annual	
India[16]				80	20	Ecologically Sensitive Areas; 98th percentile
				80	50	Industrial, Residential, Rural and Other Areas; 98th percentile
Bangladesh				366	78	
Bhutan				120	80	Industrial land use
				80	60	Mixed use
				30	15	Sensitive areas
Cambodia			500	300	100	
Indonesia			900	260	60	
Laos			780	300	100	
Malaysia			350	105		
Mongolia				20	10	
Nepal				70	50	
Pakistan				120	80	Effective 1 January 2012
Japan			265	105		
Philippines				180	80	
South Korea			392	131	52	
Singapore			196	365	80	Current
				50	15	Targets for 2020
				20		Long term target
Sri Lanka			200	80		
Taiwan			654	78		
Thailand			780	300	100	
Vietnam			350	125	50	
Egypt[17]			350	150	60	
Mauritius			350	200	50	
Saudi Arabia			730	365	80	Permitted exceedances per year: 2 (1-hr) and 1 (24-hr)
South Africa	500		350	125	50	Permitted exceedances per year: 526 (10-minute), 88 (1-hr) and 4 (24-hr)
Tanzania	500			100	40-60	

Table 2-6 lists the countries for which information was only available for 24-hour average criteria based on Vahlsing and Smith (2011). These countries may have also adopted 1-hour or

[16] Ministry of Environment and Forests (2013)

[17] Loeb (2001)

annual average criteria, but there was insufficient time available to research all of these countries' regulatory requirements for this report.

Table 2-6 Summary of 24-hour Average SO_2 Criteria in Other Jurisdictions
(Source: Vahlsing and Smith 2011)

Country	SO_2 Concentration (µg/m³)	Country	SO_2 Concentration (µg/m³)
Belarus	200	Ghana	100
Bolivia	365	Israel	280
Botswana	300	Moldova	50
Colombia	250	Turkey	150
Costa Rica	365	Venezuela	365
Ecuador	350	Serbia	150
El Salvador	365	Zambia	125
Ethiopia	365		

2.3.1 Criteria for <u><</u>20 minutes Average Concentrations

As indicated in Table 2-5, only three countries (South Africa, Tanzania and Trinidad and Tobago) have adopted the WHO SO_2 guideline value of 500 µg/m^3 (10-minute average), but South Africa applies its standard as a 99th percentile (i.e., allowing 526 exceedances per year). The Russian Federation has adopted a short-term exposure limit of 500 µg/m^3 averaged over 20 minutes. New Zealand had previously adopted a criterion identical to the WHO guideline in 1994, but has discontinued using this level as an official regulatory standard. Nevertheless, 10-minute average concentrations may still be considered and addressed as part of the permitting process for specific industrial discharges.[18] Similarly, the National Environment Protection Council in Australia (2004) conducted a review of the practicality of adopting the WHO guideline value as a National Environmental Protection Measure (NEPM) for air quality and concluded that there was no need to do so as part of the national standards because such issues could better be addressed on a case-by-case basis at the permitting level for specific industrial SO_2 emission sources.

The United Kingdom has adopted a SO_2 15-minute average criterion of 266 µg/m^3, with an allowance for 35 exceedances of the criterion in a one-year period. In addition, 15-minute average concentrations less than 266 µg/m^3 are considered to be representative of 'Good' air quality for the Daily Air Quality Index, and concentrations in the range of 266-531 µg/m^3 are

[18] http://www.mfe.govt.nz/publications/air/air-quality-tech-report-43/html/page7.html

representative of 'Moderate' air quality during which adults and children with lung problems, and adults with heart problems, are advised to reduce strenuous physical activity, particularly outdoors. If 15-minute average SO_2 concentrations rise to between 530 and 1063 µg/m^3, adults and children with lung problems, and adults with heart problems, are advised to reduce strenuous physical exertion, particularly outdoors, and people with asthma may find it necessary to use inhalers to relieve symptoms. Air pollution is considered to be 'Very High' if the 15-minute average SO_2 concentration exceeds 1064 µg/m^3.

The State of Hawaii, which frequently has to deal with elevated concentrations of SO_2 from volcanic eruptions, issues air quality advisories for SO_2 concentrations which are based on 15-minute averages[19]. Similar to the air quality index in the United Kingdom, SO_2 concentrations less than 100 ppb (~265 µg/m^3) are considered to represent 'Good' air quality with no expected health effects for most members of the general public, except highly sensitive individuals. Concentrations greater than 210 ppb (~558 µg/m^3) are considered to be 'Unhealthy for Sensitive Groups', while concentrations greater than 1001 ppb (~2687 µg/m^3) are considered 'Unhealthy', and individuals experiencing health effects are advised to leave the area.

2.3.2 Criteria for 1-hour Average Concentrations

There are a broad range of values that have been adopted internationally for 1-hour average SO_2 criteria. The most stringent level is 150 µg/m^3 adopted by China for specially protected areas, while the least stringent levels are 900 µg/m^3 for Indonesia (i.e., at the current Maximum Acceptable level in Canada), 780-850 µg/m^3 for Argentina, Laos, Thailand and Honk-Kong, 730 µg/m^3 in Saudi Arabia. The current criterion for special industrial areas in China is 700 µg/m^3, but the country has announced the adoption of a new criterion of 500 µg/m^3 for residential, industrial and mixed use areas beginning in 2016. Taiwan and California's standards are only slightly lower at 655 µg/m^3. The new National Ambient Air Quality Standard (NAAQS) in the United States of 196 µg/m^3 adopted in 2010 is lower than the limit value of 350 µg/m^3 adopted by the EU and several other countries (i.e., Malaysia, Vietnam, Egypt and Mauritius), but the NAAQS is calculated as the 99th percentile averaged over 3 consecutive years, while the EU allows up to 35 exceedances of the limit value in a one year period. Therefore, while the NAAQS and EU criteria are numerically much lower than those in Southeast Asia and in industrial areas of China, they are much closer in their practical application. South Africa has adopted a guideline value of 350 µg/m^3 as a 99th percentile (i.e., allowing up to 88 exceedances of the standard per year) while Sri Lanka uses a level of 200 µg/m^3, only slightly less stringent than China's value for sensitive areas.

[19] http://www.hiso2index.info/assets/FinalSO2Exposurelevels.pdf

It should also be noted that the European Union has also adopted a 1-hour average Alert Level of 500 µg/m^3 that applies to SO_2 measurements over three consecutive hours at locations representative of air quality over at least 100 km or an entire air zone or agglomeration, whichever is the smaller.[20]

2.3.3 Criteria for 3-hour and 8-hour Average Concentrations

Two countries have adopted air quality criteria for intermediate averaging periods $\leq$24-hours. Buenos Aires in Argentina[21] uses a 3-hour average level of 1309 µg/m^3, while Trinidad and Tobago uses an 8-hour average of 120 µg/m^3. The rationale for the use of these intermediate averaging periods was not identified in this review.

In 1971, the U.S. EPA adopted a secondary NAAQS standard of 1330 µg/m^3 (3-hour average) which was retained at the time of the most recent NAAQS review in 2010. Secondary NAAQS are intended to protect public welfare, including protection against visibility impairment, damage to animals, crops, vegetation, and buildings.

2.3.4 Criteria for 24-hour Average Concentrations

Most countries in the world have adopted a 24-hour average SO_2 criterion, but there is no consistency in the levels chosen by various jurisdictions and values range from 20 µg/m^3 to 365 µg/m^3. Mongolia is the only country to have adopted the WHO guideline value of 20 µg/m^3. Only three countries (China, the Russian Federation and Moldova) have adopted the WHO Interim Guideline of 50 µg/m^3, but China's criterion only applies in sensitive areas while the criterion for all other areas of China is 150 µg/m^3 beginning in 2016. Similar to China, Bhutan uses a 24-hour average concentration of 30 µg/m^3 for sensitive areas. Singapore has adopted 50 µg/m^3 as a target level for achievement by 2020, with a long term goal of attaining the WHO guideline of 20 µg/m^3. Belize uses a tiered approach ranging from 120 µg/m^3 for industrial and mixed use areas, to 80 µg/m^3 for rural and residential areas, and 30 µg/m^3 for environmentally sensitive areas.

Nepal, India, Sri Lanka, Argentina and Switzerland use criteria in the range of 70-80 µg/m^3, while South Africa, Japan, Ghana and Malaysia use 100-105 µg/m^3 and Brazil has a secondary standard of 100 µg/m^3 for the protection of human health, flora and fauna and materials damage. The latter values are consistent with the WHO guideline of 100 µg/m^3 for vegetation protection. The adoption by the 28 member states of the European Union of the limit value of 125 µg/m^3

[20] http://www.scribd.com/doc/176290911/EEA-Report-9-2013-Air-Quality-in-Europe-1

[21] http://www.buenosaires.gob.ar/areas/med_ambiente/pol_ambiental/archivos/relada/decreto_198GCBA2006.pdf

provides the largest geographic area of consistency in the international community. Other countries to have adopted the WHO interim guideline of 125 µg/m^3 include South Africa (98.9th percentile with 4 allowable exceedances per year), Trinidad and Tobago, and Vietnam, while Hong Kong has proposed adopting this level and would allow 3 exceedances per year.

The previous U.S. NAAQS of 365 µg/m^3 was revoked in 2010 when the new 1-hour average NAAQS was introduced. The former NAAQS level appears to represent the upper limit for national 24-hour average SO_2 regulatory criteria, and many of the countries around the world that adopted this level were likely following the U.S. EPA lead by adopting the same level for their own criteria.

2.3.5 Criteria for Annual Average Concentrations

As with the criteria for 24-hour averages, the criteria chosen by various countries for annual average SO_2 concentrations also vary over a wide range. The most stringent criterion of 5 µg/m^3 was adopted by Sweden in 2000 (Sweden Ministry of Environment 2001) as an interim target level to be achieved in municipalities by 2005. The least stringent annual average criteria are 100 µg/m^3 in China, Thailand, Cambodia, Laos and the Dominican Republic, although China's annual average criterion will be reduced to 60 µg/m^3 in residential and industrial areas beginning in 2016. Therefore, there is a 20 fold difference between the most stringent (5 µg/m^3 in Sweden) and least stringent criteria (100 µg/m^3 in Southeast Asian countries) for annual average concentrations, similar to the range in concentrations for 24-hour averages.

The WHO (2006) determined that an annual average guideline level was unnecessary for the protection of human health because compliance with the 24-hour average concentration of 20 µg/m^3 would ensure that low annual average SO_2 concentrations would be achieved. However, the WHO (2006) recommended an annual average concentrations of 20 µg/m^3 for the protection of forests and natural vegetation, and a guideline level of 10 µg/m^3 specifically for the protection of lichens. Both India and China use a criterion of 20 µg/m^3 for ecologically sensitive or protected areas, while the European Union and the United Kingdom have adopted this same level as a general standard for all areas in their countries. The United Kingdom also uses a standard of 20 µg/m^3 to be achieved in winter months between October 1st and March 31st, which corresponds to the recommendations of the WHO (2000) which noted that there is abundant evidence for increased sensitivity of crops growing slowly under winter conditions, as well as evidence for periods of high sensitivity of conifers during periods of needle elongation.

A number of other countries, specifically Brazil, Belize, and Bhutan, have also set annual average criteria for the protection of ecologically sensitive areas. Mongolia uses a value of

10 µg/m^3, while Bhutan uses a level of 15 µg/m^3 and Singapore has adopted a level of 15 µg/m^3 as a target to be achieved by 2020.

South Africa has an annual average standard of 50 µg/m^3. Brazil has a secondary standard of 40 µg/m^3 for the protection of human health, flora and fauna, materials damage and the general environment, but its primary standard for the protection of human health is set at 80 µg/m^3. All other jurisdictions use annual average criteria ranging from 50 to 80 µg/m^3, while the U.S. NAAQS of 80 µg/m^3 was revoked in 2010.

2.4 SUMMARY OF REGULATORY CRITERIA

Within Canada, only the Province of Quebec and the City of Montreal currently use SO_2 criteria for averaging periods less than 15 minutes, and only in the context of air quality indices for communicating information about air quality to the general public. Montreal uses the WHO guideline of 500 µg/m^3 (10-minute average) while the province of Quebec uses a 4-minute average of about 530 µg/m^3. Metro Vancouver has incorporated the WHO guideline value into an air emission permit for an oil refinery.

Internationally, only a few jurisdictions have adopted some form of a short-term criterion for averaging periods $\leq$20 minutes:

- 500 µg/m^3 (10-minute average) -Trinidad and Tobago, South Africa and Tanzania (i.e., the WHO guideline value);
- 500 µg/m^3 (20-minute average) - Russian Federation;
- 266 µg/m^3 (15-minute average) - United Kingdom; and
- 265 µg/m^3 (15-minute average) defines 'Good' air quality - State of Hawaii.

New Zealand repealed its former use of the WHO guideline value, while Australia considered and subsequently rejected the need for establishing a national standard based on the WHO guideline for 10-minute average SO_2 concentrations.

Figure 3.1 provides a summary of the numerical values[22] for 1-hour average SO_2 criteria for international jurisdictions. It indicates that Metro Vancouver's current AAQO of 450 µg/m^3 falls within the mid-range of those jurisdictions which have adopted a 1-hour average criterion. The Maximum Acceptable NAAQO in Canada and the Level B objective in British Columbia are among the least stringent criteria, comparable to the level adopted in Indonesia. Among the more stringent criteria are those adopted in the United States and Singapore (196 µg/m^3), the Dominican Republic and Sri Lanka (200 µg/m^3), although China has a criterion of 150 µg/m^3 for

[22] Excluding the relative stringency of the criteria implementation (e.g., allowable exceedances, percentiles)

sensitive areas. However, it is worth noting that the VIHA in Victoria, B.C. considers 1-hour average SO_2 concentrations in the range of 95-200 $\mu g/m^3$ as posing a moderate risk for a very small number of people who are unusually sensitive to SO_2, with concentrations in the range of ~200-490 $\mu g/m^3$ as being unhealthy for sensitive groups (e.g., asthmatics), but not to the general public.

Apart from the U.S. EPA secondary NAAQS based on 3-hour average SO_2 concentrations, only two other countries have adopted criteria for averaging periods between 1-hour and 24-hours: 1) Argentina (3-hour average) and 2) Trinidad and Tobago (8-hour average).

The numerical values for 24-hour average criteria for international jurisdictions depicted in Figure 3.2 indicate that the Metro Vancouver AAQO of 125 $\mu g/m^3$ falls within the upper third tier of the more stringent jurisdictions, while the Canadian Maximum Acceptable and the B.C. Levels B and C criteria fall within the lower third tier of jurisdictions. Fifteen countries and the State of California have more stringent criteria than Metro Vancouver, although the criteria in a few of those countries are only slightly more stringent. Only Mongolia has adopted the WHO guideline value of 20 $\mu g/m^3$, while Singapore has adopted this level as a target to be achieved by 2020. Bhutan and Belize have both adopted slightly less stringent criteria of 30 $\mu g/m^3$ for ecologically sensitive areas.

As indicated in Figure 3.3, Metro Vancouver's current AAQO of 30 $\mu g/m^3$ (annual average) is one of the more stringent criteria amongst international jurisdictions. Only the EU, Mongolia and Sweden have adopted more stringent criteria, while the WHO criterion of 20 $\mu g/m^3$ is meant to be protective of forests and natural vegetation and should be protective of human health as well if the WHO criterion of 20 $\mu g/m^3$ (24-hour average) is achieved. Singapore has defined a target level of 15 $\mu g/m^3$ for annual average SO_2 concentrations to be achieved by 2020. Canada's Maximum Acceptable level and British Columbia's Level B objective falls in the mid-range of criteria for annual average concentrations amongst international jurisdictions.

Figure 2.1 Summary of Numerical Values for 1-hour Average SO_2 Regulatory Criteria

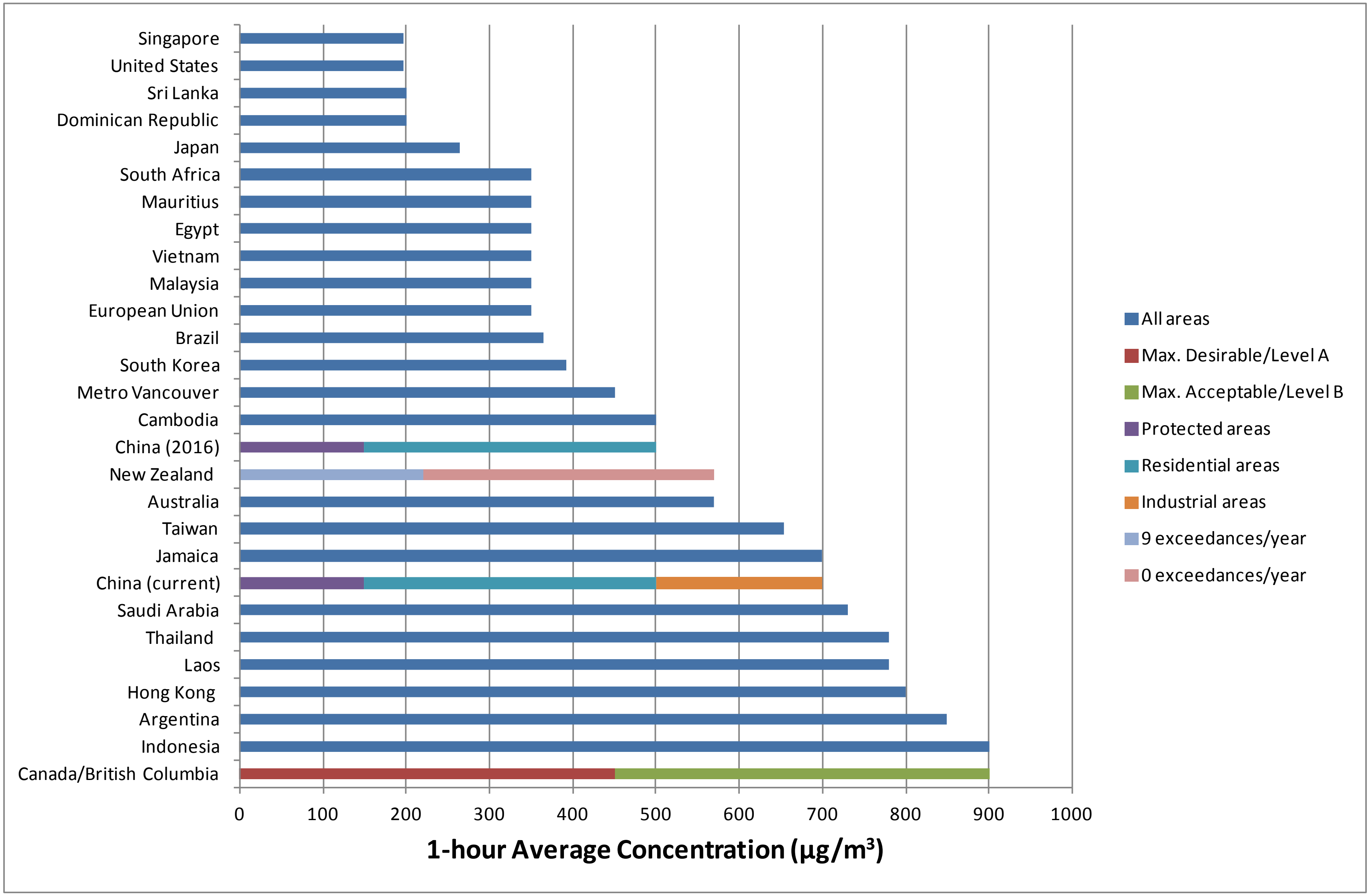


Figure 2.2 Summary of Numerical Values for 24-hour Average SO_2 Regulatory Criteria

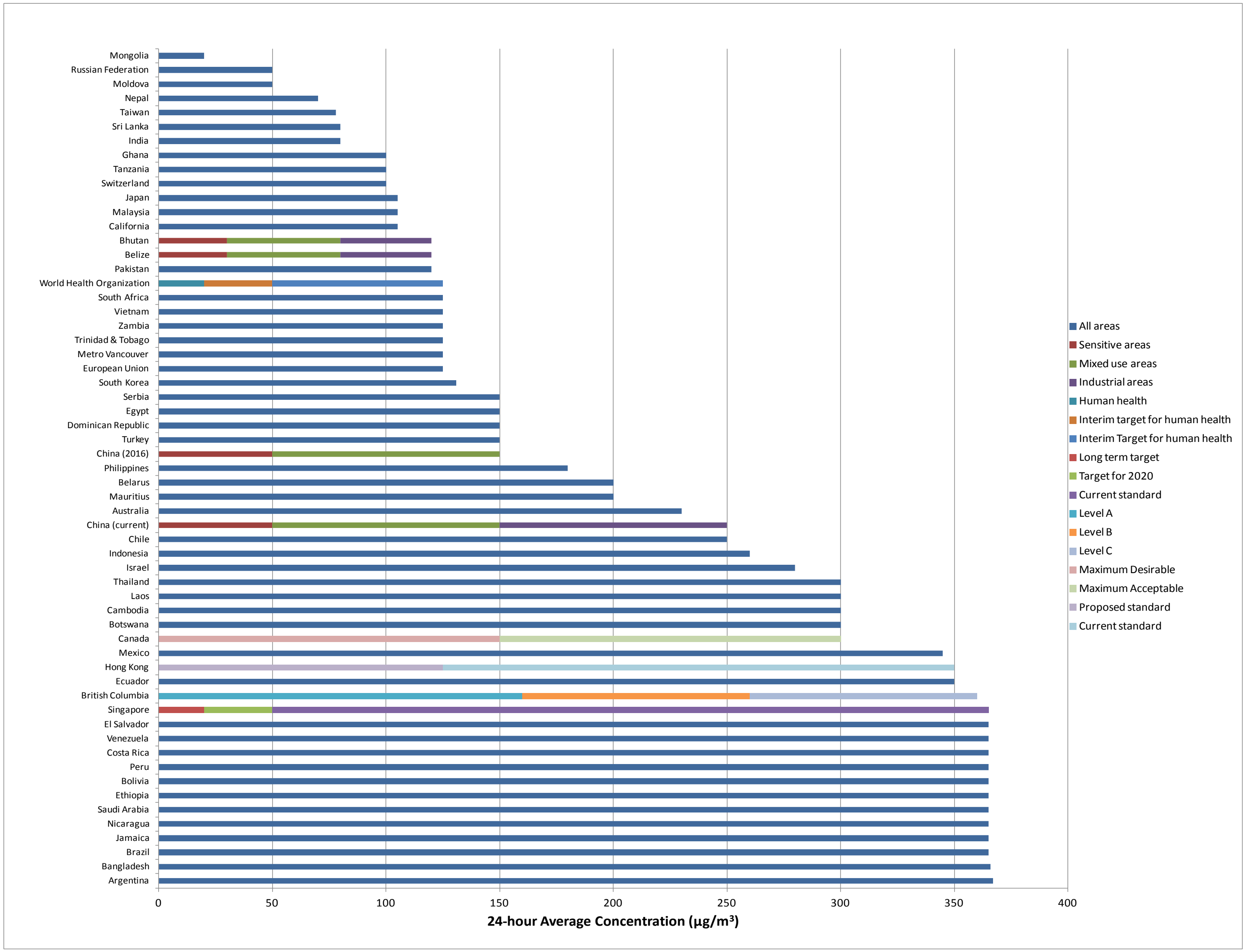
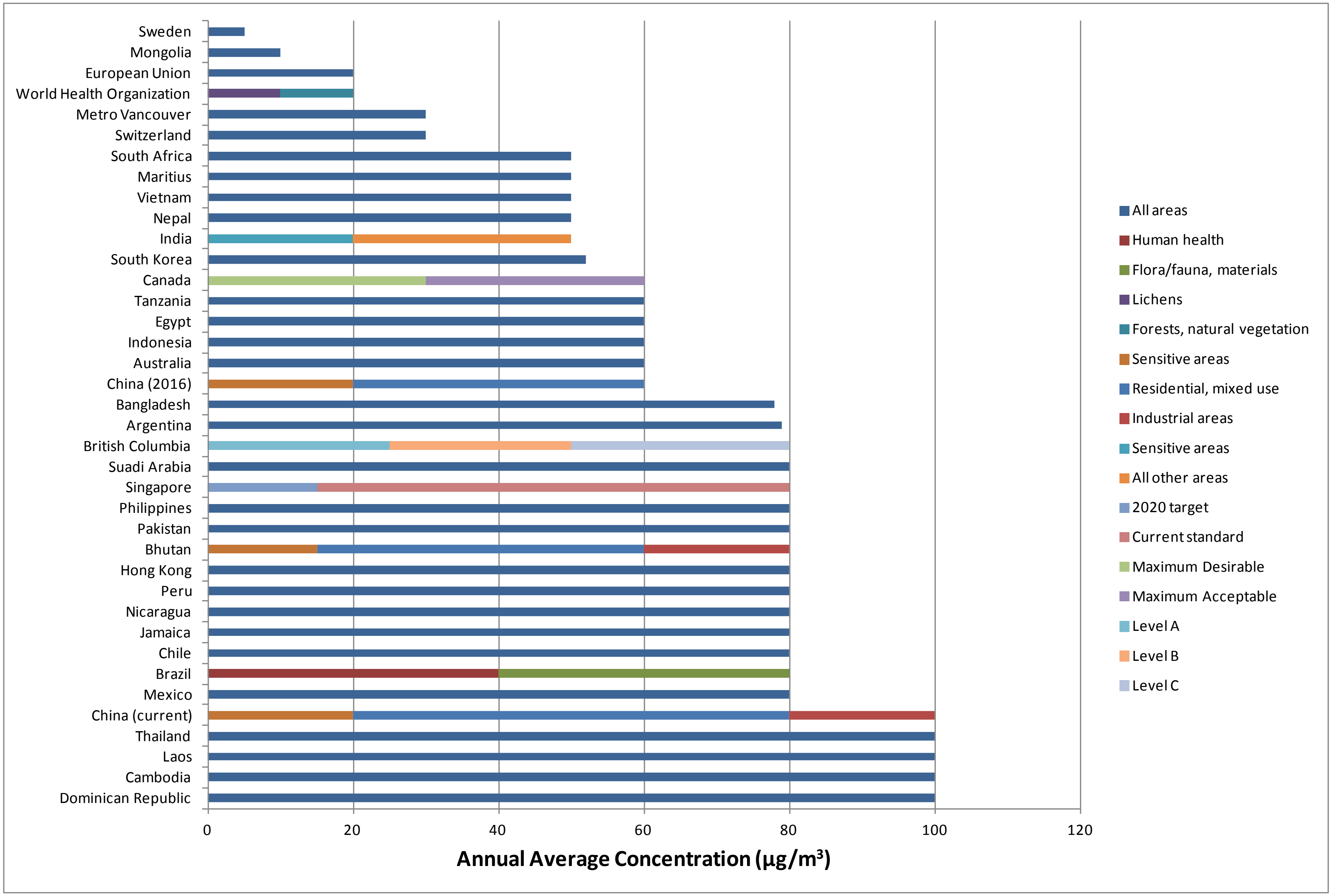


Figure 2.3 Summary of Numerical Values for Annual Average SO_2 Regulatory Criteria



3.0 HUMAN HEALTH AND ECOLOGICAL EFFECTS REVIEW

This section provides a summary of the review of available documents related to human health and ecological effects from exposure to SO_2 in ambient air. Relevant data are summarized and evaluated within the context of existing guidelines for ecological and human health.

3.1 OVERVIEW OF AVAILABLE DOCUMENTS

A number of documents related to health effects from sulphur dioxide exposure are available and summarized in the following sections. Relevant aspects for the current data review are also noted.

3.1.1 Alberta Health Acute Exposure Health Effects of H_2S and SO_2

Alberta Health (2012) compiled a summary of health effects from acute exposure to sulphur dioxide. Concentrations of sulphur dioxide in air range from 300 µg/m^3 (0.1 ppm) to greater than 260,000 µg/m^3 (100 ppm) with a description of potential health effects. While this document does not provide specific toxicological or epidemiological data, this summary can be considered within the context of the separate summary of health effects (see Section 3.2).

Table 3-1 Alberta Health Acute Exposure Health Effects of H_2S and SO_2

Name	Alberta Health Acute Exposure Health Effects of Hydrogen Sulphide and Sulphur Dioxide
Country	Canada
Year of Publication	2012
Governing Body/ Stakeholders	Alberta Health Services
Key Words	Human health effects
Overview of Document	This document summarizes acute health effects from sulphur dioxide in air
Website	http://www.albertahealthservices.ca/eph.asp
Key Feature(s)	• Tabular summary of sulphur dioxide concentrations in air and a description of associated potential health effects
Qualitative or Quantitative?	• Quantitative
Related Documents	Alberta Health and Wellness (2006)

3.1.2 Health Effects Associated with Short-Term Exposure to Low Levels of SO_2 – A Technical Review

This document (Alberta Health and Wellness 2006) provides the supporting data for the development of the acute health effects summarized in Alberta Health (2012). A comprehensive data review was completed and the results are incorporated in the human health and ecological effects data summaries in Sections 3.2 and 3.4. Alberta Health and Wellness (2006) also provides a summary of epidemiological studies that cannot directly be translated into concentration effects, and this information is excluded from the data review in Section 3.2.

Table 3-2 Health Effects Associated with Short-Term Exposure to Low Levels of SO_2 – A Technical Review

Name	Health Effects Associated with Short-Term Exposure to Low Levels of Sulphur Dioxide – A Technical Review
Country	Canada
Year of Publication	2006
Governing Body/ Stakeholders	Alberta Health and Wellness
Key Words	Ecosystem effects, human effects, primary literature review
Overview of Document	This document provides a comprehensive review of the available primary scientific literature on sulphur dioxide in order to develop a quantitative understanding of the dose-response relationship between short-term exposure to sulphur dioxide and health effects.
Website	http://www.health.gov.ab.ca
Key Feature(s)	• Only primary studies published in peer-reviewed publications were considered for the review • Unbiased assessment of scientific literature, not a re-reporting of previously published reviews • Included 347 studies, comprised of human clinical studies, animal toxicology studies, and population studies and case reports • Studies were critically assessed and ranked based on technical quality, experimental design, conduct, and reporting • Common limitations identified: too few study subjects, too few exposure concentrations, failure to follow Good Laboratory Practice guidelines, failure to follow conventional testing protocols, critical information missing, and unmeasured or unreported exposure concentrations/times
Qualitative or Quantitative?	• Quantitative
Related Documents	Alberta Health Services (2012)

3.1.3 SO_2 Technical Assessment Report in Support of the 2013 Application to Amend the P2-00001 Multimedia Permit

This report (Rio Tinto Alcan 2013) provides an extensive review of epidemiological studies for human health effects, as well as vegetation effects from exposure to sulphur dioxide. The epidemiological studies are evaluated and selected studies are included in the data summaries in Section 3.2 and 3.4.

Table 3-3 SO_2 Technical Assessment Report in Support of the 2013 Application to Amend the P2-00001 Multimedia Permit, Kitimat Modernization Project

Name	Sulphur Dioxide Technical Assessment Report in Support of the 2013 Application to Amend the P2-00001 Multimedia Permit, Kitimat Modernization Project
Country	Canada
Year of Publication	2013
Governing Body/ Stakeholders	Rio Tinto Alcan
Key Words	Human health effects, vegetation effects
Overview of Document	This document reviews health effects from sulphur dioxide in air
Website	ftp://ftp.geobc.gov.bc.ca/publish/Regional/Smithers/RTA%20STAR%20-%20Skeena/
Key Feature(s)	• Summarizes quantitative data from epidemiological studies on short-term and long-term exposure for humans, as well as ecological effects.
Qualitative or Quantitative?	• Quantitative
Related Documents	Based on U.S. EPA (2008) and a literature review for scientific literature published after the U.S. EPA review

3.1.4 U.S. EPA Integrated Science Assessment for Sulphur Oxides – Health Criteria

This document (U.S. EPA 2008) provides a review of health effects for exposure to SO_2 for the development of NAAQS. The results are incorporated in the human health and ecological effects data summaries in Sections 3.2 and 3.4 and discussion in Section 3.3.

Table 3-4 U.S. EPA Integrated Science Assessment for Sulphur Oxides – Health Criteria

Name	Integrated Science Assessment for Sulfur Oxides
Country	USA
Year of Publication	2008
Governing Body/ Stakeholders	United States Environmental Protection Agency (U.S. EPA)
Key Words	Human health effects, ecological effects
Overview of Document	This is a concise review and evaluation of the most policy-relevant science for the development of primary (health-based) NAAQS. It includes review of toxicological studies of health effects in laboratory animals, human clinical studies of health effects for exposure to SOx and epidemiologic studies of health effects from short- and long-term exposure to SOx.
Website	http://www.epa.gov
Key Feature(s)	• Provides review of human health effects studies for SO_2 • Provides review of laboratory animal effects studies for SO_2
Qualitative or Quantitative?	• Quantitative
Related Documents	Reviews other literature sources

3.1.5 2006 Health Effects Institute Annual Conference

This document (Lippmann 2006) provides a review of epidemiological data related to human health effects from exposure to sulphur dioxide. Relevant data are considered in the data summary presented in Section 3.2.

Table 3-5 2006 Health Effects Institute Annual Conference

Name	Update on Sulfur Dioxide: Its Health Effects and Its Role as a Surrogate Exposure Index of Other Toxicants
Country	USA
Year of Publication	2006
Governing Body/ Stakeholders	New York University School of Medicine
Key Words	Human health effects
Overview of Document	Reviews recent (2005) human health effects studies and summarizes findings.
Website	N/A
Key Feature(s)	• Provides review of human health effects studies for SO_2
Qualitative or Quantitative?	• Quantitative
Related Documents	Reviews other literature sources

3.1.6 Acute Exposure Guideline Levels for Selected Airborne Chemicals

This document (NRC 2010) provides a review of toxicity data related to human health effects and animal toxicity from exposure to sulphur dioxide. Relevant data are considered in the data summary presented in Sections 3.2 and 3.4.

Table 3-6 Acute Exposure Guideline Levels for Selected Airborne Chemicals

Name	Acute Exposure Guideline Levels for Selected Airborne Chemicals
Country	USA
Year of Publication	2010
Governing Body/ Stakeholders	National Research Council (NRC)
Key Words	Human health effects, ecological effects
Overview of Document	This document provides a summary of literature studies on human health effects studies and animal toxicity tests in support of acute exposure guideline levels.
Website	N/A
Key Feature(s)	• Summarizes human health effects studies • Summarizes animal toxicity tests
Qualitative or Quantitative?	• Quantitative
Related Documents	Reviews other literature sources

3.1.7 Analysis of SO_2 Levels – James Bay Neighbourhood 2012

This report (Setton *et al.* 2013) provides an analysis of data collected in the James Bay neighbourhood of Victoria, British Columbia for the evaluation of the impact of sulphur-containing fuels used by cruise ships on the local air quality. The purpose of the study was to evaluate the ambient SO_2 concentrations with the current guidelines and objectives and to determine the frequency of exceedances, to provide further information on the pattern of SO_2 concentrations and how they relate to cruise ship visits and meteorological conditions, and the provide data for the comparison with previous SO_2 concentrations in previous years. While this document provides measured SO_2 concentrations and discusses air quality guidelines and objectives, it does not discuss quantitative human health effects data.

Table 3-7 Analysis of SO_2 Levels – James Bay Neighbourhood 2012

Name	Analysis of Sulfur Dioxide Levels, James Bay Neighbourhood
Country	Canada
Year of Publication	2013
Governing Body/ Stakeholders	British Columbia Ministry of Environment
Key Words	Monitoring data for ambient air
Overview of Document	Report provides an analysis of data collected in the James Bay neighbourhood of Victoria, British Columbia to evaluate the impact of sulphur-containing fuels used by cruise ships on the local air quality.
Website	N/A
Key Feature(s)	• Provides monitoring data related to sulphur dioxide levels under various conditions and correlation with cruise ships • Vancouver Island Health Authority health guidelines for ambient sulphur dioxide
Qualitative or Quantitative?	• Quantitative monitoring data, and reports health guidelines for ambient sulphur dioxide • Does not provide unique quantitative information related to health effects
Related Documents	Setton and Poplawski 2012; Poplawksi and Setton 2010; Vancouver Island Health Authority 2010

3.1.8 Analysis of SO_2 Levels – James Bay Neighbourhood 2011

This report (Setton and Poplawski 2012), similar to Setton *et al.* (2013), provides an analysis of data collected in the James Bay neighbourhood of Victoria, British Columbia for the evaluation of the impact of sulphur-containing fuels used by cruise ships on the local air quality. While this document provides measured SO_2 concentrations and discusses air quality guidelines and objectives, it does not discuss quantitative human health effects data.

Table 3-8 Analysis of SO_2 Levels – James Bay Neighbourhood 2011

Name	Analysis of Sulfur Dioxide Levels, James Bay Neighbourhood
Country	Canada
Year of Publication	2012
Governing Body/ Stakeholders	British Columbia Ministry of Environment
Key Words	Monitoring data for ambient air
Overview of Document	Report provides an analysis of data collected in the James Bay neighbourhood of Victoria, British Columbia to evaluate the impact of sulphur-containing fuels used by cruise ships on the local air quality.
Website	N/A
Key Feature(s)	• Provides monitoring data related to sulphur dioxide levels under various conditions and correlation with cruise ships • Vancouver Island Health Authority health guidelines for ambient sulphur dioxide
Qualitative or Quantitative?	• Quantitative monitoring data, and reports health guidelines for ambient sulphur dioxide • Does not provide unique quantitative information related to health effects
Related Documents	Setton *et al.* 2013;Poplawski and Setton 2010; Vancouver Island Health Authority 2010

3.1.9 MAML – James Bay Air Quality Study, Data Collection Report

This report (Poplawski and Setton 2010) summarizes monitoring data collected under various conditions for the purposes of correlating measured sulphur dioxide levels with cruise ships in the vicinity of the sampling site. While this document provides measured SO_2 concentrations and discusses air quality guidelines and objectives, it does not discuss quantitative human health effects data.

Table 3-9 MAML – James Bay Air Quality Study, Data Collection Report

Name	Mobile Air Monitoring Laboratory (MAML), Data Collection Report – James Bay Air Quality Study, June – August 2009
Country	Canada
Year of Publication	2010
Governing Body/ Stakeholders	Vancouver Island Health Authority, British Columbia Ministry of Environment
Key Words	Monitoring data for ambient air
Overview of Document	Report provides an analysis of data collected in the James Bay neighbourhood of Victoria, British Columbia to evaluate the impact of sulphur-containing fuels used by cruise ships on the local air quality.
Website	N/A
Key Feature(s)	• Provides monitoring data related to sulphur dioxide levels under various conditions and correlation with cruise ships • Vancouver Island Health Authority health guidelines for ambient sulphur dioxide
Qualitative or Quantitative?	• Quantitative monitoring data, and reports health guidelines for ambient sulphur dioxide • Does not provide unique quantitative information related to health effects
Related Documents	Setton *et al.* 2013;Poplawski and Setton 2010; Vancouver Island Health Authority 2010

3.1.10 Health Review and Response to James Bay Phase III Air Quality Monitoring

This document (VIHA 2010) reviews the data collected for the James Bay air quality monitoring (Poplawski and Setton 2010) and evaluates the potential for health effects in the community. Some discussion on specific health effects is provided based on exceedances of the WHO guidelines.

Table 3-10 Health Review and Response to James Bay Phase III Air Quality Monitoring

Name	Health Review and Response to James Bay Phase III Air Quality Monitoring
Country	Canada
Year of Publication	2010
Governing Body/ Stakeholders	Vancouver Island Health Authority
Key Words	Mitigation, potential health effects
Overview of Document	Review and Response of the 2009 data described in the MAML Report (Poplawski and Setton 2010) to provide a public health assessment and provide recommendations on actions to mitigate potential health impacts.
Website	N/A
Key Feature(s)	• Review and response based on WHO guidelines, rather than current Canadian or BC guidelines, which are not as stringent as the WHO guidelines • Provides mitigating actions
Qualitative or Quantitative?	• Quantitative, discusses potential health effects associated with exceedances of the WHO guidelines
Related Documents	Setton *et al.* 2013; Setton and Poplawski 2012; Poplawski and Setton 2010

3.1.11 Burrard Inlet Area Local Air Quality Study, Monitoring Program Results

This document (Metro Vancouver 2012) provides a detailed analysis of data collected through an air quality monitoring program developed for the Burrard Inlet Area of Vancouver, British Columbia. Discussion of health effects associated with air pollutants is provided, as well as comprehensive investigation of air quality results and potential related sources of the air pollutants. While this document provides measured SO_2 concentrations and discusses potential health effects, it does not discuss quantitative human health effects data.

Table 3-11 Burrard Inlet Area Local Air Quality Study, Monitoring Program Results

Name	The Burrard Inlet Area Local Air Quality Study, Monitoring Program Results
Country	Canada
Year of Publication	2012
Governing Body/ Stakeholders	Metro Vancouver
Key Words	Monitoring data for ambient air
Overview of Document	This document provides a summary of the results of the monitoring program developed for the Central Burrard Inlet Area (CBIA) air quality. The monitoring program was designed to determine how air quality in the CBIA compares to other local areas, to evaluate the spatial and temporal variability in air pollutants, and to provide information for the determination of the major sources for air pollutants.
Website	http://www.metrovancouver.org/Pages/default.aspx
Key Feature(s)	• Provides an overview of health effects associated with air pollutants, including SO_2 • Provides detailed analysis of data from monitoring program
Qualitative or Quantitative?	• Quantitative monitoring data • Qualitative discussion of health effects
Related Documents	N/A

3.1.12 2012 Lower Fraser Valley Air Quality Monitoring Report Summary

This document (Metro Vancouver 2013) provides a summary of air quality data collected through the Lower Fraser Valley Air Quality Monitoring Network in British Columbia. While this document provides measured SO_2 concentrations and discusses air quality objectives, it does not discuss quantitative human health effects data.

Table 3-12 2012 Lower Fraser Valley Air Quality Monitoring Report Summary

Name	2012 Lower Fraser Valley Air Quality Monitoring Report Summary
Country	Canada
Year of Publication	2013
Governing Body/ Stakeholders	Metro Vancouver
Key Words	Monitoring data for ambient air
Overview of Document	This document provides a summary of the results of air quality monitoring data collected by the Lower Fraser Valley (LFV) Air Quality Monitoring Network. The report provides a summary of air quality monitoring activities and programs completed in 2012, as well a report on the state of ambient air quality in the area.
Website	http://www.metrovancouver.org/Pages/default.aspx
Key Feature(s)	• Provides trends in pollutant levels measured over time • Compares monitoring results to established objectives
Qualitative or Quantitative?	• Quantitative monitoring data
Related Documents	N/A

3.1.13 Morbidity & SO_2: Evidence from French Strikes at Oil Refineries

This document (Neidell and Lavaine 2012) evaluated respiratory outcomes during a temporal shut down at an oil refinery. A discussion of other literature sources is provided.

Table 3-13 Morbidity & SO_2: Evidence from French Strikes at Oil Refineries

Name	Morbidity and Sulfur Dioxide: Evidence from French Strikes at Oil Refineries
Country	USA/France
Year of Publication	2006
Governing Body/ Stakeholders	Columbia University/Paris School of Economics
Key Words	Human health effects
Overview of Document	Assessed the impact of change in air pollution concentration during a temporal shut down at oil refineries on respiratory outcomes. Results suggest that daily variation in SO_2 air pollution has health effects at levels below the current standard.
Website	N/A
Key Feature(s)	• Combines pollution concentration measures for SO2 with simultaneous measure of morbidity, weather, and socioeconomic data (i.e., daily change in SO2 on the number of respiratory hospital admissions)
Qualitative or Quantitative?	• Quantitative
Related Documents	Setton *et al.* 2013; Setton and Poplawski 2012; Poplawski and Setton 2010

3.1.14 Association of Daily SO_2 Air Pollution Levels with Hospital Admissions for Cardiovascular Diseases in Europe (The Aphea-II Study)

This document (Sunyer *et al.* 2003) evaluates short-term effects of sulphur dioxide in ambient air on hospital admissions for cardiovascular diseases. The qualitative information provided is not incorporated in the data summary in Section 3.2.

Table 3-14 Association of Daily SO_2 Air Pollution Levels with Hospital Admissions for Cardiovascular Diseases in Europe (The Aphea-II Study)

Name	The Association of Daily Sulfur Dioxide Air Pollution Levels with Hospital Admissions for Cardiovascular Diseases in Europe (The Aphea-II study)
Country	Spain and Europe
Year of Publication	2003
Governing Body/ Stakeholders	N/A
Key Words	Human health effects
Overview of Document	This study assesses the short-term effects of SO_2 air pollution levels on hospital admissions for cardiovascular diseases.
Website	N/A
Key Feature(s)	• Statistical evaluation of cardiovascular hospital admissions in cities across Europe with daily SO2 levels • Analysis of association with other factors, such as humidity, climatic, smoking, socio-economic variables
Qualitative or Quantitative?	• Qualitative
Related Documents	Provides data from other literature sources

3.2 SUMMARY OF AVAILABLE DATA – HUMAN HEALTH EFFECTS

Tables 3-15 to 3-19 provide a summary of the available quantitative concentrations related to human health effects from exposure to sulphur dioxide. The selected exposure durations are based on health criteria that are currently being used by the British Columbia, U.S. EPA (2008), and the WHO (2006):

- Table 3-15 Acute exposure (<10 minutes)
- Table 3-16 Short-term exposure (10 minutes to 1 hour)
- Table 3-17 Moderate exposure (>1 hour to 6 hour)
- Table 3-18 24-hour duration
- Table 3-19 Annual duration

Table 3-20 provides a summary of data from epidemiological studies that were not considered due to limitations in the available data. In some cases, the exposure duration is not provided or is not relevant for the current evaluation; in others, results from the multi-pollutant analysis are not significant and these studies were considered to be inconclusive.

Table 3-15 Human Health Effects – Acute Exposure (<10 min)

Concentration µg/m^3 (ppm)	Exposure Duration	Effects	Study Details	Reference
260 (0.1)	3 min	Bronchoconstriction, occurred at lower concentrations in dry air than in humidified air	Adults with asthma or other chronic pulmonary disease	Sheppard *et al.* 1984
500 (0.2)	5 min	No effect	Adult asthmatics	Linn *et al.* 1983
600 (0.25)	10 min	Increased airway resistance	Adults with asthma or other chronic pulmonary disease	Bethel *et al.* 1985
800 (0.3)	10 min	Increased bronchoconstriction, returned to normal levels 30 min after exposure	Adults with asthma or other chronic pulmonary disease	Linn *et al.* 1988
1,048 to 1,572 (0.4 to 0.6)	5-10 min	Decreased lung function with respiratory symptoms (e.g., wheezing, chest tightness)	Exercising mild to moderate asthmatics	U.S. EPA 2008
1,130 (0.4)	5 min	69% increase in specific airway resistance, 10% reduction in maximum flow calculated at 50% vital capacity and maximum flow calculated at 75% vital capacity	Adult asthmatics	Linn *et al.* 1983
1,300 (0.5)	3 min	Increased specific airway resistance	Adults with asthma or other chronic pulmonary disease	Sheppard *et al.* 1983
1,300 (0.5)	1 to 5 min	Dryness, irritation, burning of throat	Healthy adults	Kreisman *et al.* 1976
1,300 (0.5)	1 to 5 min	Chest tightness, wheezing, dyspnea	Adults with asthma or other chronic pulmonary disease	Balmes *et al.* 1987
1,300 (0.5)	5 min	Increased bronchoconstriction, increased specific airway resistance	Adults with asthma or other chronic pulmonary disease	Bethel *et al.* 1983
1,300 (0.5)	10 min	Dose-dependent change in respiratory function	Adults with asthma or other chronic pulmonary disease	Gong *et al.* 1995
1,300 (0.5)	10 min	Reduction in forced expiratory volume in 1 second, maximum flow calculated at 50% vital capacity, and maximum flow calculated at 75% vital capacity	Adults with asthma or other chronic pulmonary disease	Trenga *et al.* 1999
1,600 (0.6)	5 min	Decreased respiratory function	Adults with asthma or other chronic pulmonary disease	Linn *et al.* 1984
1,600 (0.6)	10 min	Decreased respiratory	Adults with asthma or	Linn *et al.* 1983

Concentration µg/m³ (ppm)	Exposure Duration	Effects	Study Details	Reference
		function	other chronic pulmonary disease	
1,600 (0.6)	5 min	Increased specific airway resistance	Adults with asthma or other chronic pulmonary disease	Linn *et al.* 1985
2,000 (0.75)	5 min	Increased airway resistance with hyperventilation		Islam *et al.* 1994
2,000 (0.75)	10 min	Increased specific airway resistance	Adults with asthma or other chronic pulmonary disease	Linn *et al.* 1983
<2,600 (<1)	1 to 5 min	Chest tightness, wheezing, dyspnea	Adults with asthma or other chronic pulmonary disease	Witek *et al.* 1985
2,600 (1)	1 to 5 min	Increased airway resistance	Adults with asthma or other chronic pulmonary disease	Tam *et al.* 1988, Balmes *et al.* 1987
2,600 (1)	0.5 to 1 min	No specific airway resistance effect	Male asthmatics	Horstman *et al.* 1988
2,600 (1)	2 to 5 min	Increased specific airway resistance	Male asthmatics	Horstman *et al.* 1988
2,800 to 22,600 (1 to 8)	10 min	Decreased respiratory volume and increased respiratory rate	Healthy male adults	Amdur *et al.* 1983
5,200 (2)	4 min	Changes in airway resistance	Adults with asthma or other chronic pulmonary disease	Tam *et al.* 1988
5,300 (2)	10 min	Changes in airway resistance	Adults with asthma or other chronic pulmonary disease	Horstman *et al.* 1986
13,000 (5)	10 min	Decreased airway conductance in all subject		Sheppard *et al.* 1980
14,100 (5)	10 min	Dryness in throat and upper respiratory passages	Healthy male adults	Amdur *et al.* 1983
25,000 (9)	25 seconds	Significant decrease in breathing depth (deviation of 10%)	Non-smoking healthy volunteers	Kleinbeck *et al.* (2011)
26,000 (10)	3 min	Bronchial obstruction, returned to control levels by 45-60 min after exposure	Adults with asthma or other chronic pulmonary disease	Gokemeijer *et al.* 1973
39,000 (15)	10 min	Increased pulmonary flow resistance (greater with oral exposure than nasal exposure)	Health adults	Speizer and Frank 1966b

Table 3-16 Human Health Effects – Short-Term Exposure (10 min to 1 hr)

Concentration µg/m³ (ppm)	Exposure Duration	Effects	Study Details	Reference
300 (0.1)	15 min	Slight reduction in forced expiratory volume in 1 second, maximum flow calculated at 50% vital capacity	Children or adolescents with asthma or other chronic pulmonary disease	Koenig *et al.* 1990
530 (0.2)	1 hr	Increase in heart rate variability (total power) among healthy subjects, reduction in heart rate variability observed in asthmatics; No significant effect on lung function, respiratory symptoms, markers of inflammation, or antioxidant levels.	12 healthy adults, 12 asthmatics	Tunnicliffe *et al.* 2001, 2003
700 (0.25)	10 to 40 min	No effect	Healthy and asthmatic adults, exercising and non-exercising	Schacter *et al.* 1984
1,130 (0.4)	20 min	No effects on respiratory function parameters, throat irritation, concentration dependent	Healthy non-smoking adults	Sandstrom *et al.* 1988
1,300 (0.5)	30 min	Increased airway resistance	Adults with asthma or other chronic pulmonary disease	Jorres and Magnussen. 1990
1,300 (0.5)	30 min	Dose-dependent effect on forced expiratory volume in 1 second, maximum flow calculated at 50% vital capacity, and maximum flow calculated at 75% vital capacity	Adults with asthma or other chronic pulmonary disease	McManus *et al.* 1989
1,300 (0.5)	50 min	Reduction in forced expiratory volume in 1 second, maximum flow calculated at 50% vital capacity, and maximum flow calculated at 75% vital capacity	Children or adolescents with asthma or other chronic pulmonary disease	Koenig *et al.* 1985
1,300 (0.5)	1 hour	No effect – no significant effect on pulmonary function parameters for asthmatics	Adults with asthma or other chronic pulmonary disease	Bailey *et al.* 1982
1,400 (0.5)	10 to 40 min	No effects	Non-exercising asthmatics	Schacter *et al.* 1984
1,400 (0.5)	20 min	Increase 131% in specific airway resistance	Adult asthmatics	Magnussen *et al.* 1990

Concentration μg/m^3 (ppm)	**Exposure Duration**	**Effects**	**Study Details**	**Reference**
1,550 (0.55)	10 min	No nasal or eye irritation	Healthy adults	Dautrebrande and Capps 1950
1,600 (0.6)	1 hour	No effect – no significant pulmonary effects for normal and atopic subjects with exercise	Healthy adults and adults with asthma or other chronic pulmonary disease	Linn *et al.* 1987
2,100 (0.75)	10 to 40 min	Increased specific airway resistance, decrease FEF and FEV1	Exercising asthmatics	Schacter *et al.* 1984
2,100 (0.8)	1 hour	No effect – no effect on pulmonary function for patients with COPD with exercise	Adults with asthma or other chronic pulmonary disease	Linn *et al.* 1985b
2,600 (1)	15 min	Decreased maximum expiratory flow from one half vital capacity	Healthy adults	Snell and Luchsinger 1969
2,600 (1)	30 min	Functional impairment of alveolar macrophages		Knorst *et al.* 1996
2,600 (1)	1 hr	Increased specific airway conductance	Adults with asthma or other chronic pulmonary disease	Kehrl *et al.* 1987
2,600 (1)	10 to 40 min	Increased specific airway resistance, decrease FEF and FEV1	Exercising asthmatics	Schacter *et al.* 1984
2,600 (1)	40 min	No effect – no changes in pulmonary function for healthy subjects	Healthy adults	Schachter *et al.* 1984
2,600 (1)	10 to 30 min	No effects	Healthy male adults	Frank *et al.* 1962
2,600 to 5,600 (1 to 2)	30 min	No effects	Health non-smoking male adults	Frank *et al.* 1964
5,200 (2)	30 min	No effect – no changes in pulmonary function while free breathing, forced oral, and forced nasal	Healthy adults	Bedi and Horvath 1989
5,300 (2)	30 min	Difference in ventilatory parameters between forced oral and free-breathing exposures	Healthy adults	Bedi and Horvath 1989
5,600 (2)	20 min	Throat irritation, concentration dependent	Healthy non-smoking adults	Sandstrom *et al.* 1988
6,600 (2.5)	10 min to1 hr	Decreased specific airway conductance (greater in oral exposure than nasal exposure)	Healthy adults	Melville 1970
6,600 (2.5)	30 min	Dose-dependent increase in ciliary beat frequency		Kienast *et al.* 1994, Kienast *et al.* 1996
9,400 (3.6)	30 min	No effect – no significant changes in pulmonary function parameters after	Healthy adults	Burton *et al.* 1969

Concentration µg/m³ (ppm)	**Exposure Duration**	**Effects**	**Study Details**	**Reference**
		exposure with normal breathing and hyperventilation		
10,000 (4)	20 min	Increased alveolar activity in bronchoalveolar lavage	Healthy adults	Sandstrom *et al.* 1989a
11,300 (4)	20 min	Throat irritation, concentration dependent, Nasal irritation in 5 out of 8 participants	Healthy non-smoking adults	Sandstrom *et al.* 1988
11,300 to 16,900 (4 to 6)	30 min	Increase in pulmonary flow resistance	Health non-smoking male adults	Frank *et al.* 1964
14,100 (5)	10-30 min	39% increase in pulmonary flow resistance	Healthy male adults	Frank *et al.* 1962
21,000 (8)	20 min	Increases in macrophages, lymphocytes, and mast cells in bronchoalveolar lavage	Healthy adults	Sandstrom *et al.* 1989b
37,000 (13)	10-30 min	72% increase in pulmonary flow resistance, peak response 5-10 min	Healthy male adults	Frank *et al.* 1962
42,000 (15)	10 min	Increase pulmonary flow resistance, 3% nose, 20% mouth	Health non-smoking male adults	Frank *et al.* 1964
82,000 (29)	10 min	Increase pulmonary flow resistance, 18% nose, 65% mouth	Health non-smoking male adults	Frank *et al.* 1964

Table 3-17 Human Health Effects – Moderate Exposure (>1-hr to 6 hr)

Concentration μg/m^3 (ppm)	**Exposure Duration**	**Effects**	**Study Details**	**Reference**
520 (0.2)	6 hr	No significant effect on pulmonary function in asthmatics	Adults with asthma or other chronic pulmonary disease	Devalia *et al.* 1994
520 (0.2)	6 hr	Confirmed Devalia *et al.* (1994) – no significant effect on pulmonary function	13 asthmatics	Rusznak *et al.* 1996
1,000 (0.4)	2 hr	No change in forced expiratory volume in 1 second in healthy males with moderate exercise	Healthy adults	Bedi *et al.* 1979 Bedi *et al.* 1982
1,300 (0.5)	3 hr	No effect on pulmonary function parameters	Healthy adults	Jaeger *et al.* 1979
2,000 (0.75)	4 hr (with 2 – 15 min exercise periods)	No effect on pulmonary function during or after exposure with exercise in healthy subjects	Healthy adults	Stacy *et al.* 1983
2,000 (0.75)	2 hr	Increased specific airway resistance	Healthy adults	Stacy *et al.* 1977
2,000 (0.75)	3 hr	Increased specific airway resistance, decreased to pre-exposure levels after 1 hr of exposure	Adults with asthma or other chronic pulmonary disease	Hackney *et al.* 1984
13,000 (5)	4 hr	Decreased nasal mucous flow rate	Healthy adults	Anderson *et al.* 1977

Table 3-18 Human Health Effects – 24-Hour Exposure

Concentration µg/m³ (ppm)	Exposure Duration	Effects	Study Details	Reference
5.0 to 18.1 (0.002 to 0.006)	Daily average SO_2 concentrations (mean values)	Diastolic blood pressure significantly increased, systolic blood pressure significantly decreased, and pulse blood pressure significantly decreased with increasing SO_2 concentrations	9,238 non-smoking adults (age >30 yrs)	Chen *et al.* 2012
5.5 to 21.1 (0.002 to 0.007)	Daily average SO_2 concentrations (mean values)	Increasing trend in emergency room visits for gastroenteric disorders. No multi-pollutant analysis was completed.	0 to 2 year old children in 6 Italian cities	Orazzo *et al.* 2009
5.9 to 19.7 (0.002 to 0.007)	24-hr average median	Asthma symptoms	990 asthmatic children	Scildcrout *et al.* 2006
10.9 (0.004)	24-hr average median	Cough incidence	1,844 children grades 2-5	Schwartz *et al.* 1994
12.5, 14.4 (0.005)	24-hr average median	Cough, shortness of breath, wheeze	162 9 yr olds	Ward *et al.* 2002a,b
15.1 (0.006)	24-hr average	Cough, lower respiratory symptoms, upper respiratory symptoms	Children (7-11 yrs) from 1 industrial community and 3 non-industrial community	Hoek and Brunekreef 1994
16 (0.006)	Daily average SO_2 concentrations (mean value)	Statistical association with risk of suicide	Canadian cities	Szyszkowicz *et al.* 2010
22 (0.008)	24-hr average	Asthma, wheeze	Children with physician-diagnosed asthma age 7-15	Segala *et al.* 1998
44.81, range 9.62 to 169 (0.02 , range 0.003 to 0.06)	Daily average SO_2 concentrations (mean value)	Significant association between SO_2 and hospital admissions for acute outbursts of rheumatic disease. Single-pollutant analysis only and authors suggested SO_2 could be a marker of particulate air pollution in general.	Children and adolescents in Brazil	Vidotto *et al.* 2012
75 (0.028)	24-hr average	Wheeze	Children (7-11 yrs) from 1 industrial community and 3 non-industrial community	Pikhart *et al.* 2000

Table 3-19 Human Health Effects – Annual Exposure

Concentration µg/m³ (ppm)	Concentration Type	Effects	Study Details	Reference
6.3 and 72.6 (0.002 and 0.03)	10-year average concentration	Significant increase in respiratory disease with an increase in concentration. Significant increase in lung cancer mortality with an increase in concentration. Single pollutant model.	63,500 individuals in Japan	Katanoda *et al.* 2011
10 and 15 (0.004 and 0.005)	Annual average concentrations	Significant link between SO_2 and allergic rhinitis, single pollutant analysis		Bhattacharyya 2009
50 (0.02)	Three-year average concentration	Significant link with allergic rhinitis in a single pollutant analysis, but no significance in the multi-pollutant analysis		Dong *et al.* 2011

Table 3-20 Human Health Effects – Epidemiological Study Results

Concentration µg/m^3 (ppm)	Concentration Details	Effects	Study Details	Reference
Respiratory Effects				
5 to 13.7 (0.002 to 0.005)		Increased prevalence of "usual" cough and phlegm, but no connection with asthma prevalence	Older adults in France	Bentayeb *et al.* 2010
23 and 36 (0.008 to 0.013)		Negative effect on lung function parameters (forced vital capacity, forced expiratory volume, peak expiratory flow)	Children	Linares *et al.* 2010
60 to 641 (0.02 to 0.23)	Indoor concentrations	Significant association with asthma symptoms		Zhao *et al.* 2008
524 to 786 (0.19 to 0.28)		5-30% of subjects experienced decreased lung function	Exercising mild to moderate asthmatics	U.S. EPA 2008
> 2,620 (> 0.9)		Decreased lung function	Exercising individuals without asthma	U.S. EPA 2008
Cardiovascular Effects				
1.3, 75th percentile 2.0 (0.0005, 0.0008)	Daily average SO_2 concentrations (mean values)	No clear relationship between out-of-hospital cardiac arrests and SO_2 concentrations	Melbourne, Australia	Dennekamp *et al.* 2010
2.61 to 11.0 (0.001 to 0.004)	Daily average SO_2 concentrations (mean values)	Daily non-trauma mortality significantly associated with an increase in SO_2 concentrations over 15 days. No significance found for 2-day average and 5-day average concentrations.	25,006 myocardial infarcation survivors	Berglind *et al.* 2009
2.71, 95th percentile 7.0 (0.001, 0.003)	24-hr average concentrations	positive but not statistically significant association for activations of cardioverter defibrillators among patients in London, UK.		Anderson *et al.* 2010
3.0 mean, range 2.0 to 8.9 (0.001 mean, range 0.0007 to 0.003)		Association with lipoprotein-associated phospholipase A2	200 survivors of myocardial infarcation	Bruske *et al.* 2011
3.4, 95th percentile 5.2 (0.001, 95th percentile 0.0018)	Mean estimated residential exposure	Increasing trend of pulse wave velocity (an indicator of vascular damage and arterial stiffness) with increasing concentrations. No association with carotid artery intima-media thickness (an indicator of preclinical atherosclerosis).	Young adults	Lenters *et al.* 2010

Concentration µg/m³ (ppm)	**Concentration Details**	**Effects**	**Study Details**	**Reference**
6.3 to 29.3 (0.002 to 0.01)	Mean hourly average	No significant effect on heart rate variability (HRV) or blood pressure	40 non-smoking patients with cardiovascular disease	Huang *et al.* 2012
6.6 (0.002)	Mean concentration	Significant positive association (0 lag days) with ischemic stroke in female patients. No significant association found for longer lag times in female patients or for male patients. After adjustment for O_3 and for CO (both 3 lag days) significant positive association with ischemic stroke in all patients. Link still significant in 3-pollutant analysis.	Patients in Vancouver	Szyszkowicz *et al.* 2012
7.3 +/- 1.3 (0.003 +/- 0.0005)	Mean concentrations	Statistically significant negative correlation for fibrinogen. No association for C-reactive protein and white blood cells.	2,203 healthy male participants. No statistically significant associations found for 1,456 female participants.	Steinvil *et al.* 2008
7.7 to 12 (0.003 to 0.004)	Daily average SO_2 concentrations (mean values)	Linked a marker of inflammation (interleukin-6) with increased concentrations. No link with fibrinogen (another marker of inflammation).	45 healthy non-smoking adults	Thompson *et al.* 2010
9.2, interquartile range of 5.6 (0.003, interquartile range of 0.002)	Daily average SO_2 concentration (median value)	Higher sulphate concentrations had no association with increased fatality risk for acute myocardial infarction, stroke, or different subtypes of stroke.	Acute case fatality (within 28 days), multi-pollutant model	Turin *et al.* 2012
11.4, range 0.34 to 46.6 (0.004, range 0.0001 to 0.017)	Daily average SO_2 concentrations (mean value)	No significant association for hospital admissions for myocardial infarction in Taiwan.		Hsieh *et al.* 2010
13.6 (0.005)		No significant effects on electrocardiograms with SO_2 exposure during or 10 hours before	580 men	Baja *et al.* 2010
14.1 (0.005)	Annual average concentration	Positive association between annual average SO_2 concentrations and cardio-respiratory mortality, using population data, mortality data, and socioeconomic	Brisbane, Australia	Wang *et al.* 2009

Concentration µg/m³ (ppm)	**Concentration Details**	**Effects**	**Study Details**	**Reference**
		indices, with single and multi-pollutant modelling		
24.3, range of 2.4 to 81.8 (0.009, range of 0.001 to 0.03)	Mean value of daily average concentration	Significant association between SO_2 concentrations and hospital admissions on cool days but not warm days. There was no significant association after adjustment for particulate air pollution or for carbon monoxide (warm or cool days). After adjustment for NO_2, a significant negative association was seen on cool days.	Hospital admissions for myocardial infarction in Taiwan	Cheng *et al.* 2009
73, range of 11 to 174 (0.03, range of 0.004 to 0.06)	Average concentrations	Significant increase in total, respiratory, and cardiovascular mortality associated with increased concentrations, with adjustment for other pollutants. Adjusting for demographic, medical, and lifestyle determinants found an increase of 10 µg/m³ in SO_2 concentration associated with 1.8% increase in total mortality, 3.2% increase in cardiovascular and respiratory mortality.	70,947 individuals from 31 Chinese cities	Cao *et al.* 2011
Cancer Effects				
73, range of 11 to 174 (0.03, range of 0.004 to 0.06)	Average concentration	Significant 4.2% increase in lung cancer mortality per 10 µg/m³ increase in SO_2 concentration. The significance remained after adjusting for total suspended particles and nitric oxides.	70,947 individuals from 31 cities in China	Cao *et al.* 2011
Other Effects				
5.3 (summer) to 23.1 (winter) (0.002, 0.009)	Daily average concentrations, varied seasonally	Increase in outpatient visits for non-specific conjunctivitis. Not clear if observed effects attributable to SO_2 or other pollutants.		Chang *et al.* 2012
6.5 to 26.2 (0.002 to 0.009)	Mean levels	Link between SO_2 and depression	Canadian cities	Szyszkowicz *et al.* 2009a
9.4 (0.004)	Mean	No association between SO_2 and emergency department visits for migraine or other headaches		Mukamal *et al.* 2009

Concentration µg/m³ (ppm)	**Concentration Details**	**Effects**	**Study Details**	**Reference**
12.3 (0.004)	Median monthly average concentration	Statistical association between monthly average deaths by suicide	Taiwan	Yang *et al.* 2011
15.0, maximum 41.7, interquartile range 4.8 (0.005, maximum 0.015, interquartile range 0.002)	Mean concentration	Significant increase in risk of stillbirth with increasing concentrations during first, second, and third months of pregnancy. Results were consistent in the single-pollutant and three-pollutant models.	Taiwan	Hwang *et al.* 2011
15.2 to 15.4 (0.005)	Mean concentrations for each trimester	Significant increasing trend in risk of stillbirth with increasing concentration in 1st and 3rd trimesters of pregnancy	Completed in NJ, USA	Faiz *et al.* 2012
15.6 to 29.3 (0.006 to 0.01)	Mean daily average levels	Significant effect of SO_2 on daily number of hospitalizations for epilepsy. When other pollutants were accounted for in the analysis, the statistical significance was lost.	Seven urban centers in Chile	Cakmak *et al.* 2010
51.7 (0.02)	Mean concentration	Significant effect on daily numbers of preterm births. Single- and multi-pollutant analyses completed.	Chinese city	Zhao *et al.* 2011
196 (0.07)		Association between migraine and SO_2 during increased volcanic emissions		Longo *et al.* 2010

3.3 DISCUSSION – HUMAN HEALTH EFFECTS

The following sections provide a comparison of the above summarized data with the available WHO, U.S. EPA, Canada and British Columbia guidelines and criteria as well as the Metro Vancouver objective levels which have been presented in Section 2. There are many more criteria available as discussed in Section 2. However, these five jurisdictions were considered to provide the most relevant criteria.

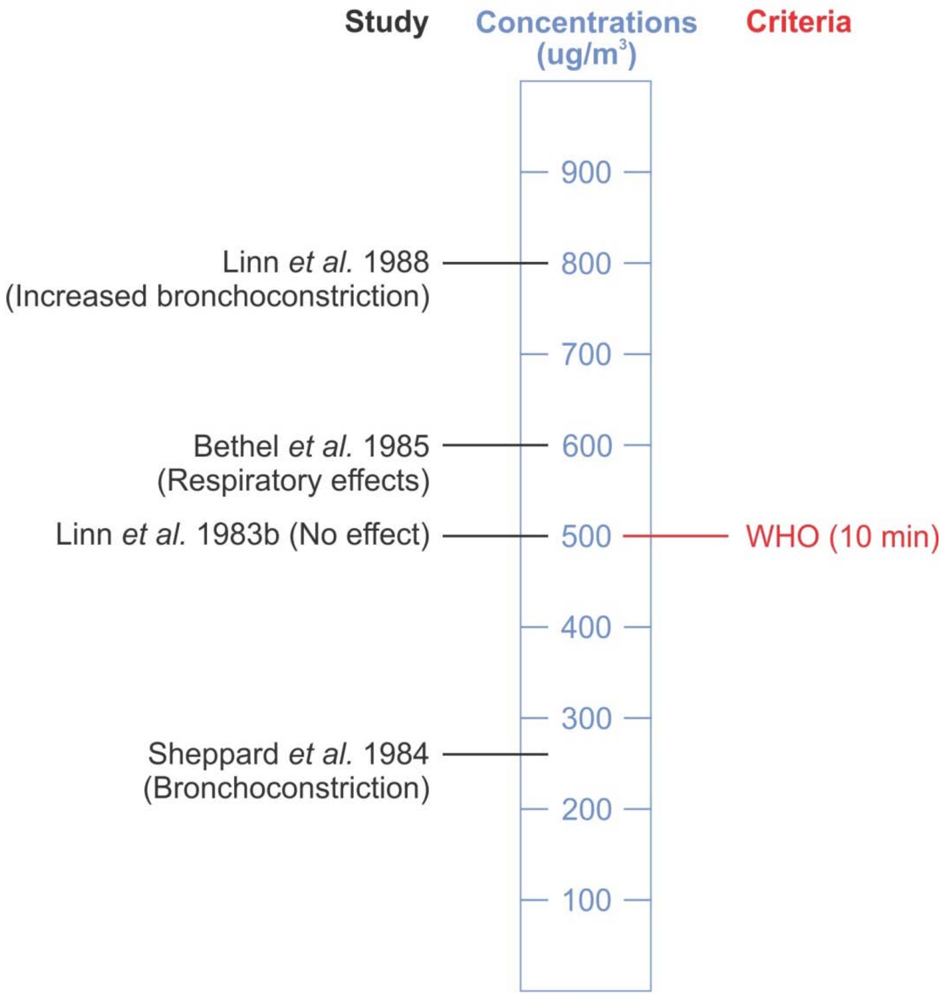
3.3.1 Acute Exposure (<10 minutes)

The U.S. EPA (2008) has concluded that there is a clear, statistically significant increase in respiratory symptoms in exercising asthmatics after 5-10 minute exposures to 1,600 µg/m^3 (0.6 ppm) to 2,660 µg/m^3 (1 ppm) concentrations of SO_2. Less severe symptoms are observed at concentrations of 1,064 µg/m^3 (0.4 ppm) to 1,330 µg/m^3 (0.5 ppm) in human clinical studies (U.S. EPA 2008). The U.S. EPA (2008) concluded that the severity and occurrence of respiratory symptoms in exercising asthmatic adults increases with increasing concentrations, between 532 µg/m^3 (0.2 ppm) and 1,600 µg/m^3 (0.6 ppm), with statistically significant increases in symptoms at concentration greater than or equal to 1,064 µg/m^3 (0.4 ppm).

Regarding lung function, U.S. EPA (2008) concluded that effects were observed in exercising asthmatics with 5-10 minute exposures to 532 µg/m^3 (0.2 ppm) to 1,330 µg/m^3 (0.5 ppm) concentrations of SO_2. An even greater percentage of the exercising asthmatics were affected at concentrations from 1,600 µg/m^3 (0.6 ppm) to 2,660 µg/m^3 (1 ppm). An increase in sputum eosinophil counts (related to airways inflammation) was found in exercising asthmatics after 10-minute exposure to 2,000 µg/m^3 (0.75 ppm) (U.S. EPA 2008). Effects were observed 2 hours after the exposure.

Figure 3-1 provides a summary of selected values presented in Table 3-13 for acute duration exposure effects from SO_2 in comparison with the available air quality criteria. The WHO SO_2 guideline of 500 µg/m^3 for a 10-minute average (Table 2-5) is considered for comparison with acute exposures. As indicated in the figure, the WHO guideline is generally supported by the literature studies as it is less than levels associated with effects from literature. However, one study (Sheppard *et al.* 1984) indicated effects at a concentration of 260 µg/m^3 related to bronchoconstriction in adults with asthma or other chronic pulmonary disease with a 3-minute exposure. Effects were more pronounced in dry air than in humidified warm air (Alberta Health and Wellness 2006).

Figure 3-1 Summary of Acute Exposure (<10 minutes) Data

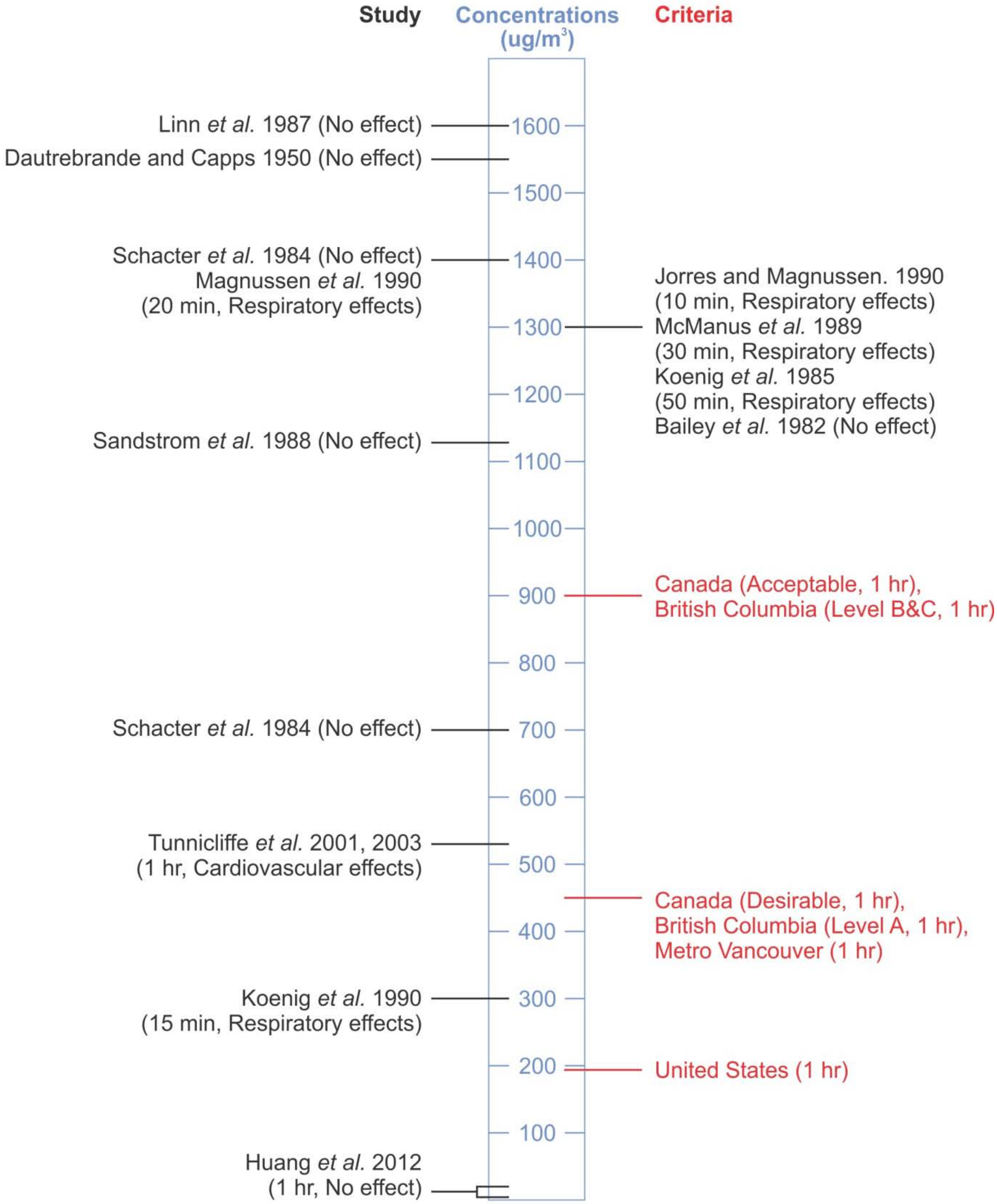


3.3.2 Short-Term Exposure (10 minutes to 1 hour)

Figure 3-2 provides a summary of selected values presented in Table 3-14 for short-term exposure effects from SO_2 in comparison with the available air quality criteria. Objectives for 1-hour average concentrations are available for Canada and British Columbia (Table 2-2). These are indicated on the figure along with the 1-hour average concentration standard for the United States (Table 2-5). As indicated in the figure, the United States standard of 196 µg/m^3 adopted in 2010 is lower than any of the available data from Table 3-14, as well as the other objectives from Canada and British Columbia. The "desirable" Canadian and British Columbia "Level A" objectives as well as the Metro Vancouver objective level of 450 µg/m^3 are below most of the available data from studies presented in Table 3-14. The exception is a study on adolescent asthmatics exposed for 15 minutes to SO_2 and a slight decrease in forced expiratory volume in 1-second and maximum flow calculated at 50% vital capacity was observed (Koenig *et al.* 1990).

The figure shows that the B.C and Canadian 1-hour objectives as well as the Metro Vancouver objective level may not be protective of all sensitive individuals.

Figure 3-2 Summary of Short-Term Exposure (10 minutes to 1 hour) Data

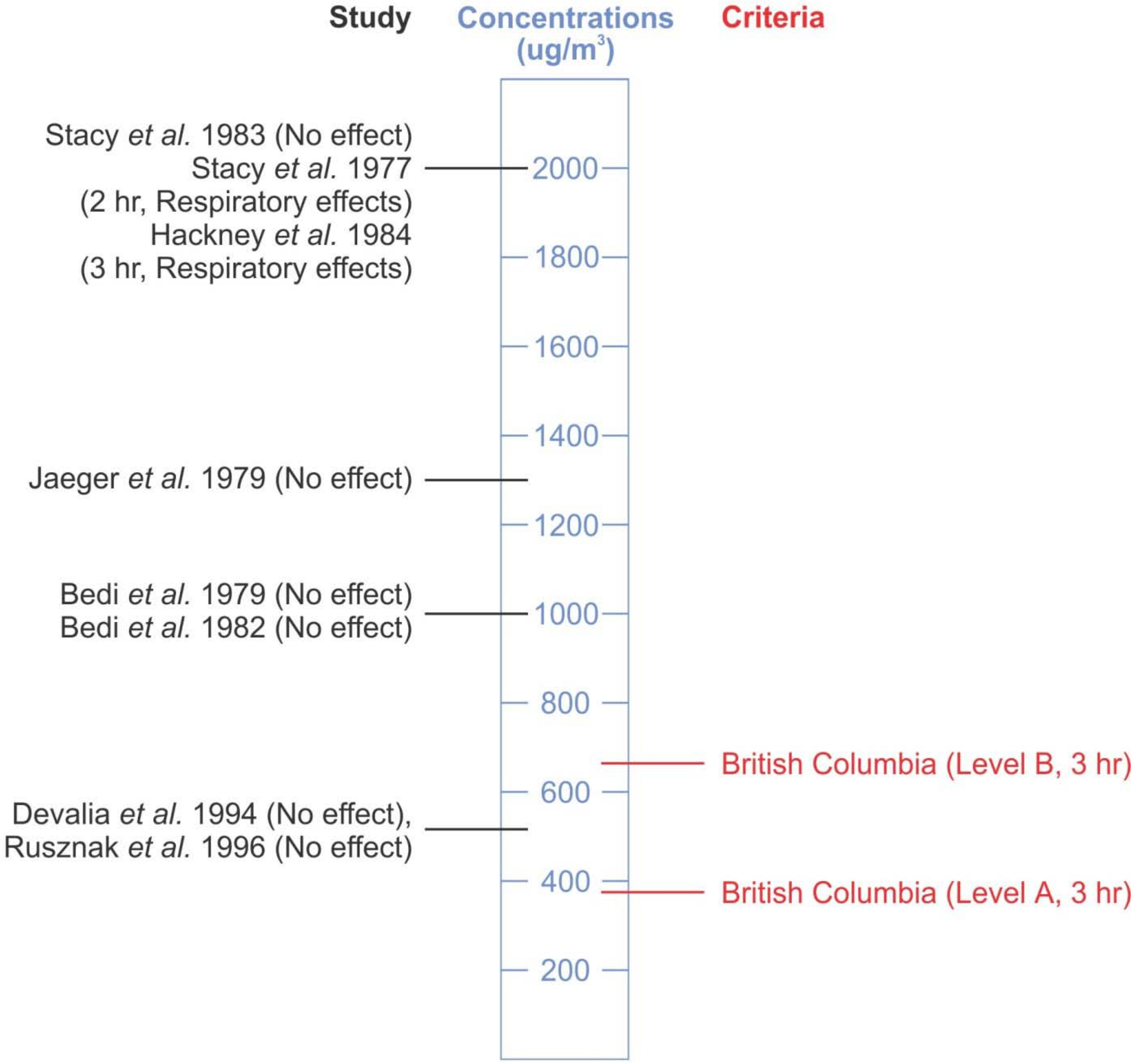


3.3.3 Moderate Exposure (>1 hour to 6 hours)

Epidemiologic studies reviewed in U.S. EPA (2008) supported an association between ambient SO_2 concentrations and increased respiratory symptoms in children, especially asthmatic children or those with other chronic respiratory symptoms. An observed association at a median range of 45 µg/m^3 (17 ppb) to 100 µg/m^3 (37 ppb) across cities for 3-hour average concentrations. Enhanced airways hyperresponsiveness to an inhaled antigen was observed with concurrent 6-hour exposure to 530 µg/m^3 (0.2 ppm) SO_2 and 0.4 ppm NO_2 among resting asthmatics (U.S. EPA 2008). The U.S. EPA (2008) found this to be consistent with other limited epidemiologic evidence that found an association with SO_2 and airways hyperresponsiveness in atopic individuals.

Figure 3-3 provides a summary of selected values presented in Table 3-15 for effects from moderate duration SO_2 exposure in comparison with the available air quality criteria. The British Columbia SO_2 criteria of 375 µg/m^3 and 665 µg/m^3 for a 3-hour average (Table 2-2) is considered for comparison with moderate duration exposures. As indicated in the figure, the British Columbia criteria are within the range of levels tested in studies that have shown no effect on pulmonary function. An increase in specific airway resistance was reported at a concentration of 2,000 µg/m^3 (Stacy *et al.* 1977, Hackney *et al.* 1984) in healthy adults after 2-hour exposure and asthmatic adults after 3-hour exposure. This figure shows that the B.C. objectives are protective of human health as most of the epidemiologic studies are related to no effects in the humans studied.

Figure 3-3 Summary of Moderate Exposure (>1 hour to 6 hour) Data



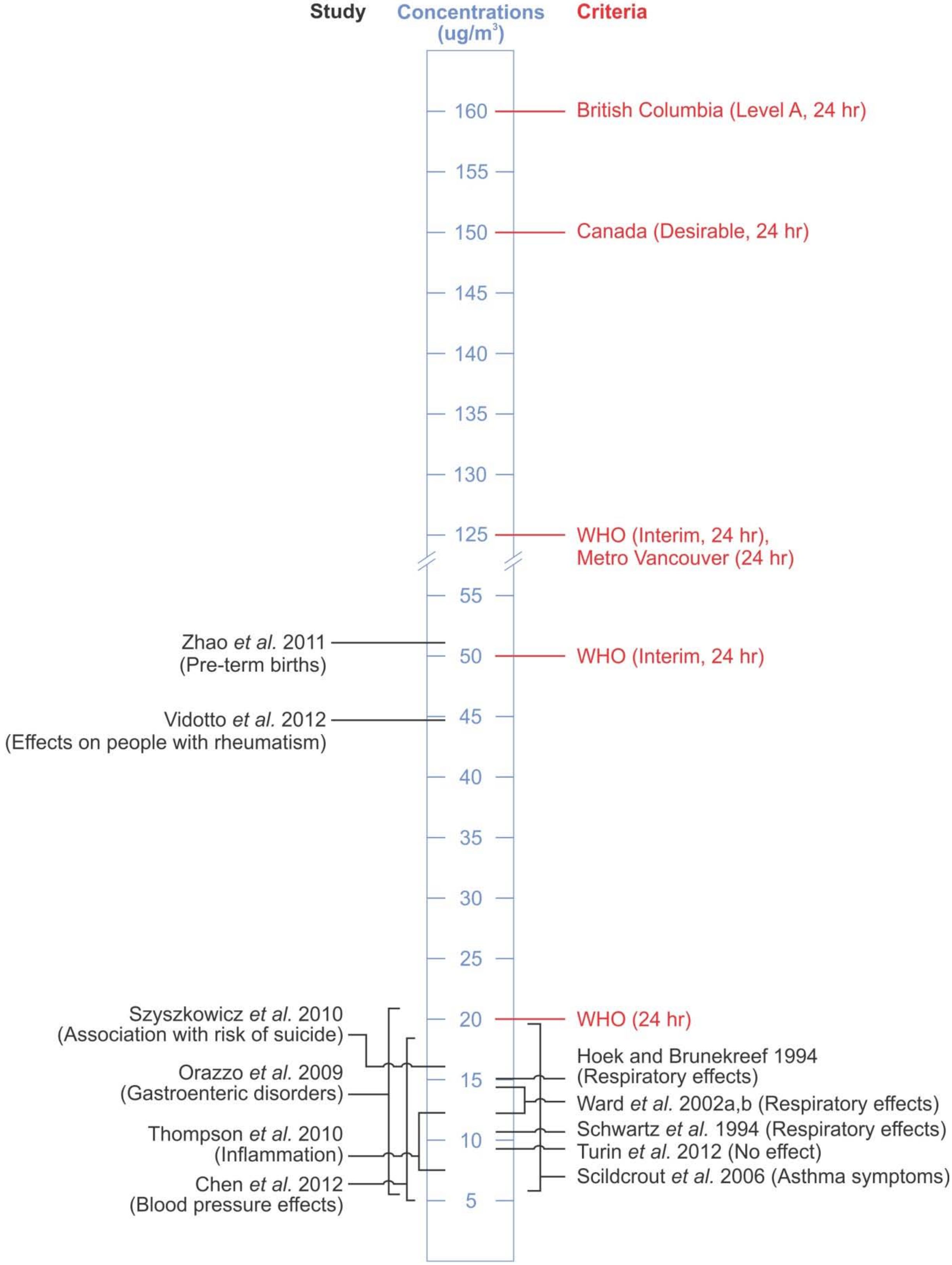
3.3.4 24-Hour Exposure

The U.S. EPA (2008) found that epidemiological studies consistently show aggravation of bronchitis at 24-hour average SO_2 concentrations of 505 µg/m^3 (0.19 ppm) to 612 µg/m^3 (0.23 ppm), and with some studies showing effects at levels below these concentrations. An association between ambient SO_2 concentrations of 5.8 µg/m^3 (2.2 ppb) to 19.7 µg/m^3 (7.4 ppb) and increased respiratory symptoms in children was also observed (U.S. EPA 2008). There is inconsistent epidemiological evidence for a similar connection for respiratory effects in adults, as well as for declines in lung function for children and adults (U.S. EPA 2008).

Based on epidemiologic studies, the U.S. EPA (2008) concluded that there was inadequate information to infer a causal relationship between short-term exposure to SO_2 and cardiovascular morbidity. There was some evidence of a positive association between 24-hour average SO_2 exposure and heart rate variability in epidemiological studies, but the evidence was weak and inconsistent from two human clinical studies. However, the U.S. EPA (2008) did conclude the possibility of causal relationship between SO_2 and mortality, with recent epidemiologic studies showing a positive association between mortality and SO_2 at mean 24-hour average concentrations less than 26.6 µg/m^3 (10 ppb). Respiratory mortality showed a stronger association with SO_2 than cardiovascular mortality (U.S. EPA 2008). There may be confounding influences of other pollutants in the studies.

Figure 3-4 provides a summary of selected values presented in Table 3-16 for daily exposure effects from SO_2 in comparison with the available air quality criteria. The Canadian guideline (“Desirable”) of 150 µg/m^3 (Table 2-2) is above the WHO guidelines for 24-hour SO_2 exposure (20, 50, and 125 µg/m^3) (Table 2-5). The Level A British Columbia guideline (160 µg/m^3) is higher than the Canadian “Desirable” guideline and the WHO guidelines. The Metro Vancouver 24-hour rolling average objective level is at the upper end of the WHO guideline. As indicated in the figure, the lowest WHO guideline of 20 µg/m^3 is generally supported by the literature studies as it is around effects levels associated with epidemiological studies, although numerous studies showed effects at lower concentrations. Thus, the approach by the WHO to steadily lower the 24 hour guideline to 20 µg/m^3 is supported by the epidemiological data. Any value above 50 µg/m^3 is not supported by the health effects data and would generally be considered a risk managed level since there are no supporting data.

Figure 3-4 Summary of 24-Hour Average Exposure Data

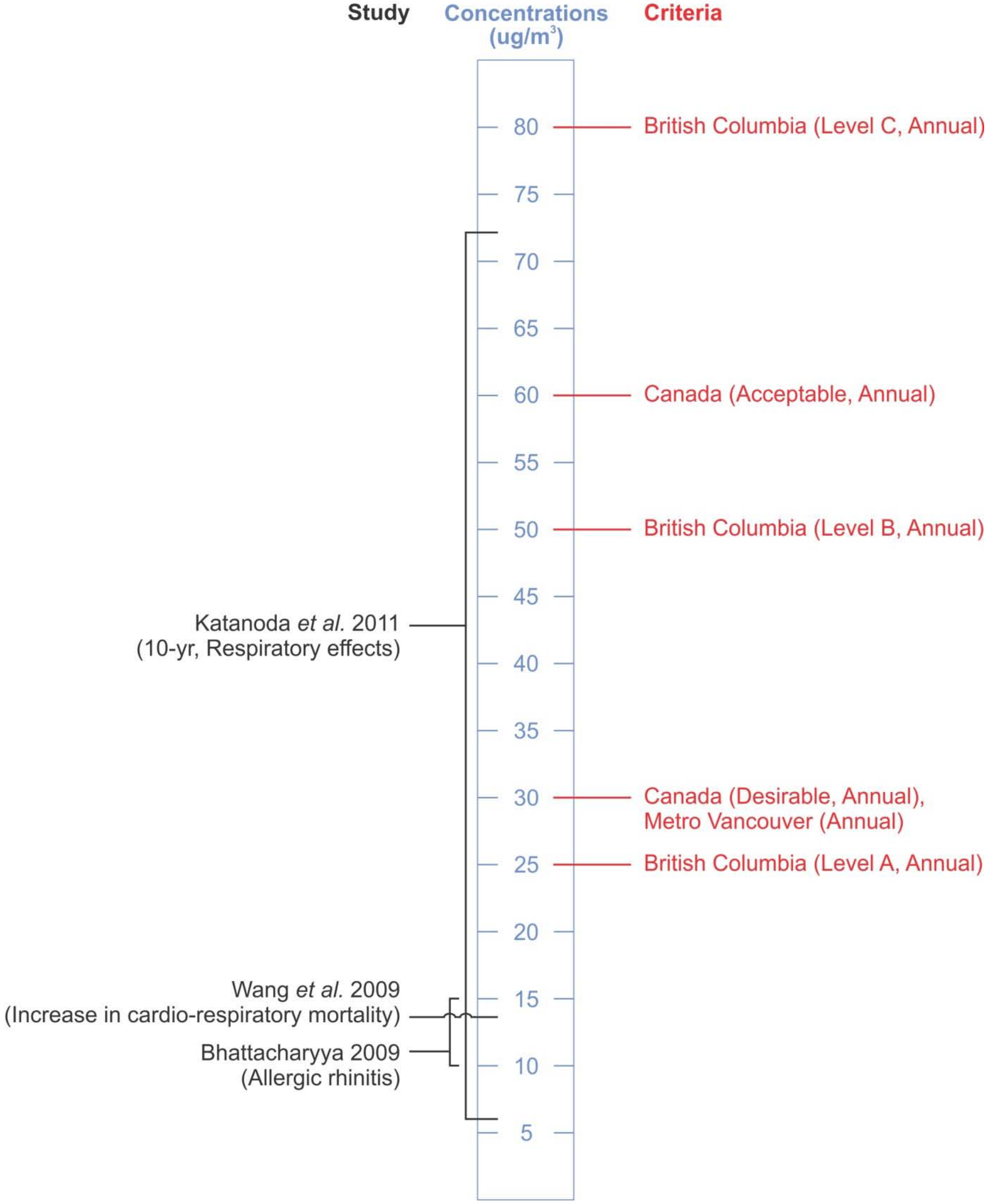


3.3.5 Annual Exposure

The U.S. EPA (2008) determined that there was inadequate evidence to suggest a causal relationship associated with long-term exposure to SO_2 and respiratory morbidity and other morbidity. There was also inadequate support to establish a causal relationship with mortality (U.S. EPA 2008).

Figure 3-5 provides a summary of selected values presented in Table 3-17 for annual exposure effects from SO_2 in comparison with the available air quality criteria. The available guidelines for British Columbia and Canada (Table 2-2) as well as the Metro Vancouver annual average objective level are indicated. The annual guideline from WHO (Table 2-5) is not a human health based value but is based on vegetation protection and is discussed in Section 3.5. The WHO indicate that, as long as exposure concentrations fall below the 24-hour guideline, then they are considered to be protective of annual exposures. As indicated in the figure, the guidelines from British Columbia and Canada generally fall within the range of observed potential effects from long-term exposure to SO_2. The Metro Vancouver annual objective of 30 $\mu g/m^3$ is the same as the Canadian guideline. Several studies fall below the "Desirable" and Level A guidelines. These were long-term epidemiological studies and in some cases, co-pollutant effects potentially confound the results.

Figure 3-5 Summary of Annual Exposure Data



3.4 SUMMARY OF AVAILABLE DATA – ECOLOGICAL EFFECTS

Tables 3-19 and 3-20 provide a summary of the available data related to effects on laboratory animals and vegetation, respectively, from exposure to sulphur dioxide.

Table 3-19 Ecological Effects – Laboratory Animals

Concentration µg/m^3 (ppm)	Exposure Duration	Effects	Study Details	Reference
80 (0.03)	4 wk	More rapid and more severe inflammatory response to influenza infection	Mice	Ukai 1977
260 (0.1)	5 hr/d for 5 d	Increased respiratory pause	Guinea pigs	Park *et al.* 2001
260 (0.1)	70 hr	Slight reduction in lung clearance	Rats	Ferin and Leach 1973
260 (0.1)	8 hr/d for 5 d	Increased antigen-specific antibodies in serum and bronchoalveolar fluid	Guinea pigs	Riedel *et al.* 1988
1,300 (0.5)	45 min	Dose-dependent increase in lung resistance	Rabbits	Barthelemy *et al.* 1988
2,600 (1)	1 hr	Increased respiratory resistance, decreased compliance	Guinea pigs	Amdur *et al.* 1983
2,600 (1)	10 min	Dose-dependent increase in bronchocontriction; decreased proportion of macrophages in white cells	Guinea pigs	Halinen *et al.* 2000
7,000 to 28,000 (2.5 to 10)	NR	Increases in molecular indices of inflammation and injury to the heart and brain	Rats	Sang *et al.* 2010, Yun *et al.* 2011
8,900 (3.4)	7 d	Increased incidence of pneumonia after exposure to SO_2	Mice	Fairchild *et al.* 1972
10,000 (4)	4 hr	Increased airway reactivity in asthmatic sheep 24 hr after exposure	Sheep	Abraham *et al.* 1981
16,000 (6)	7 d	Inhibition of virus growth	Mice	Fairchild 1977
26,000 (10)	1 hr	Inhibition of ciliary movement	Rabbits	Blanquart *et al.* 1995
26,000 (10)	4 hr	Increased airway reactivity in asthmatic sheep 24 hr after exposure	Sheep	Abraham *et al.* 1980
26,000 (10)	4 to 72 hr	Lesions of olfactory and respiratory epithelium; decrease in thickness of olfactory mucosa, severe rhinitis	Mice	Giddens and Fairchild 1982
26,000 (10)	1 hr/d for 30 d	Increased concentrations of cholesterol, total lipids,	Guinea pigs	Haider 1985

Concentration µg/m^3 (ppm)	Exposure Duration	Effects	Study Details	Reference
		gangliosides, and decreased phospholipids		
39,000 (15)	2 to 6 min	Dose-dependent increase in ciliary activity	Guinea pigs	Oomichi and Kita 1974
44,000 (17)	10 min	Dose-dependent respiratory depression	Mice	Alairie *et al.* 1973
52,000 (20)	4 hr	Delayed early clearance of upper respiratory tract	Rats	Mannix *et al.* 1983
85,000 (32)	24 hrs/day	No effect on birth weight following prenatal exposure	Mice	Singh (1989)
105,000 (40)	2 hr	Dose-dependent decrease in %SO_2 retention, respiratory rate, minute volume, increase in tidal volume	Rats	Leong and MacFarland 1965
131,000 (50)	NR	Reduction in pulmonary macrophage endocytosis	Hamsters	Skornik and Brain 1990
131,000 (50)	15 min	Reduced dynamic compliance	Dogs	Atzori *et al.* 1992
172,000 (65)	24 hrs/day	Statistically significant reduced birth weight following prenatal exposure	Mice	Singh (1989)
262,000 (100)	60 min	Increase in minute volume	Chickens	Fedde and Kuhlmann 1979
262,000 (100)	5 hr/d for 7 to 28 d	Decreased glutathione concentration and inflammation	Rats	Langley-Evans *et al.* 1996
393,000 (150)	12 x 3 hr	Increased lung resistance, decreased breathing frequency	Rabbits	Davies *et al.* 1978
524,000 (200)	15-20 min	Decreased breathing frequency, increased tidal volume	Rabbits	Davenport *et al.* 1984
1,310,000 (500)	60 min	Decreased specific airway resistance	Chickens	Fedde and Kuhlmann 1979
1,310,000 (500)	75 min	Changes to bioelectric properties and increased nonelectrolyte permeability	Dogs	Man *et al.* 1986
1,572,000 (600)	30 to 100 hr	Increased mucosal permeability	Rats	Vai *et al.* 1980
1,573,000 (600)	3 hr/d for 9, 18 or 30 d	Increase in solid material recovered by bronchial lavage	Rats	Knauss *et al.* 1976
2,096,000 (800)	8 hr	Gradient of decreasing damage in the tracheobronchial tree	Rats	Stratmann *et al.* 1991
2,096,000 (800)	1 hr	Reduction in minimal and maximal pulmonary surface tension	Rats	Kahana and Aronovitch 1968
2,620,000 (1,000)	60 min	Initial decrease then increase in specific airway resistance, increased respiratory frequency, decreased minute	Chickens	Fedde and Kuhlmann 1979

Concentration µg/m³ (ppm)	Exposure Duration	Effects	Study Details	Reference
		volume		
3,210,000 (1,225)	2 hr	Pulmonary edema, greater reduction in surface tension	Rats	Kahana and Aronovitch 1968

Table 3-20 Ecological Effects – Vegetation

Concentration µg/m³ (ppm)	Exposure Duration	Effects	Study Details	Reference
10 (0.004)	NR	Community changes	Cryptogam	Will-Wolf 1981
19 (0.007)	42-d	Visible injury	Moss (*Dicranum polysetum*)	Dueck *et al.* 1992
21 (0.008)	42-d	Growth reduction	Moss (*Hypnum cupressiforme*)	Dueck *et al.* 1992
30 (0.01)	NR	Eradication of most sensitive taxa	Cryptogam	WHO 2000
50 (0.02)	42-d	Foliar injury	Mouse-ear Hawkweed (*Hieracium pilosella*)	Dueck *et al.* 1992
50 to 60 (0.02)	Long-term, 4th growing season	Reductions in fine roots	Beech (*Fagus sylvatica*)	Wollmer and Kottke 1990
50 to 60 (0.02)	Long-term, 4th growing season	Reductions in fine roots and net photosynthesis	Silver Fir (*Abies alba*)	Wollmer and Kottke 1990, Schweizer and Arndt 1990
75 (0.03)	42-d	Growth reduction	Mountain Everlasting (*Antennaria dioica*)	Dueck *et al.* 1992
120 (0.05)	Long-term	Decreased photosynthesis and transpiration	Silver Fir (*Abies alba*)	Krupa and Arndt 1990
345 (0.13)	8-hr	Foliar injury	Quaking Aspen (*Populus tremuloides*)	NRC 1978
557 (0.21)	8-hr	Foliar injury	White Birch (*Betula papyrifera*)	NRC 1978
689 (0.26)	4-hr	Foliar injury	Quaking Aspen (*Populus tremuloides*)	NRC 1978
689 (0.26)	8-hr	Foliar injury	Larch (*Larix* sp.)	NRC 1978
689 (0.26)	8-hr	Foliar injury	Balsam Poplar (*Populus balsamifera*)	NRC 1978
743 (0.28)	4-hr	Foliar injury	White Birch (*Betula papyrifera*)	NRC 1978
796 (0.30)	8-hr	Foliar injury	Willow (*Salix* sp.)	NRC 1978
875 (0.33)	4-hr	Foliar injury	Willow (*Salix* sp.)	NRC 1978
902 (0.34)	4-hr	Foliar injury	Larch (*Larix* sp.)	NRC 1978
1,008 (0.38)	2-hr	Foliar injury	Willow (*Salix* sp.)	NRC 1978
1,008 (0.38)	2-hr	Foliar injury	Larch (*Larix* sp.)	NRC 1978
1,008 (0.38)	2-hr	Foliar injury	White Birch (*Betula papyrifera*)	NRC 1978
1,035 (0.39)	2-hr	Foliar injury	Quaking Aspen (*Populus tremuloides*)	NRC 1978
1,035 (0.39)	8-hr	Foliar injury	Raspberry (*Rubus idaeus*)	NRC 1978

Concentration µg/m^3 (ppm)	Exposure Duration	Effects	Study Details	Reference
1,090 (0.41)	1-hr	Foliar injury	Willow (*Salix* sp.)	NRC 1978
1,090 (0.41)	1-hr	Foliar injury	Larch (*Larix* sp.)	NRC 1978
1,114 (0.42)	1-hr	Foliar injury	Quaking Aspen (*Populus tremuloides*)	NRC 1978
1,194 (0.45)	4-hr	Foliar injury	Balsam Poplar (*Populus balsamifera*)	NRC 1978
1,220 (0.46)	1-hr	Foliar injury	White Birch (*Betula papyrifera*)	NRC 1978
1,326 (0.50)	8-hr	Foliar injury	White Spruce (*Picea glauca*)	NRC 1978
1,406 (0.53)	4-hr	Foliar injury	Raspberry (*Rubus idaeus*)	NRC 1978
1,671 (0.63)	2-hr	Foliar injury	Raspberry (*Rubus idaeus*)	NRC 1978
1,724 (0.65)	2-hr	Foliar injury	Balsam Poplar (*Populus balsamifera*)	NRC 1978
1,857 (0.70)	4-hr	Foliar injury	White Spruce (*Picea glauca*)	NRC 1978
2,016 (0.76)	1-hr	Foliar injury	Raspberry (*Rubus idaeus*)	NRC 1978
2,096 (0.79)	2-hr	Foliar injury	White Spruce (*Picea glauca*)	NRC 1978
2,176 (0.82)	1-hr	Foliar injury	Balsam Poplar (*Populus balsamifera*)	NRC 1978
2,308 (0.87)	1-hr	Foliar injury	White Spruce (*Picea glauca*)	NRC 1978

Note: Values from NRC (1978) were reported in Rio Tinto (2013) as µg/m^3, converted from values in ppm presented in NRC (1978) using a conversion factor of 2,620 µg/m^3/ppm. The values in Rio Tinto (2013) were converted into ppm using the stated conversion factor of 2,620 µg/m^3/ppm and then concentrations in µg/m^3 were calculated for the current report using a conversion factor of 2,660 µg/m^3/ppm

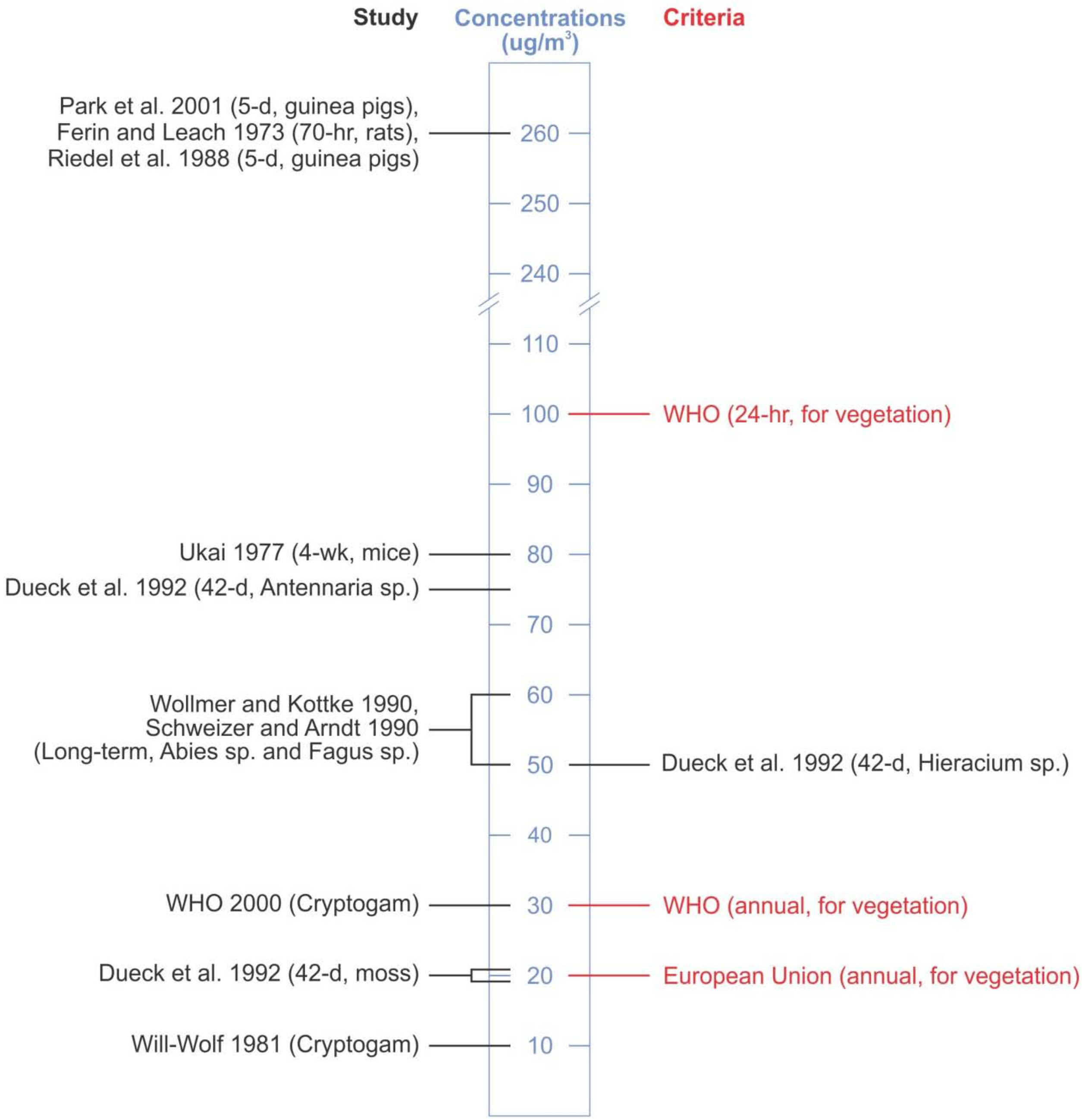
3.5 DISCUSSION – ECOLOGICAL EFFECTS

This section provides a comparison of the summarized data for ecological effects with the available WHO and European Union guidelines and criteria which have been presented in Section 2. There are more criteria for ecological effects available as discussed in Section 2. However, these two jurisdictions were considered to provide the most relevant criteria.

Figure 3-6 shows the comparison of the ecological effects data with the available ecologically-based protection levels from WHO and the European Union (Table 2-5). The figure shows that effects on cryptogams and mosses have been indicated at concentrations less than or equal to the European Union standard of 30 µg/m^3, which is lower than the WHO guidelines for 24-hour exposure and annual exposure. The WHO and European Union annual guidelines are protective of other plant species tested, as well as below effects levels indicated in laboratory animals. There are no literature studies to support an ecological protection level lower than 10 µg/m^3. The lowest concentration reported in the literature was 10 µg/m^3 for a no-effect level in vegetation. Thus, any level lower than this value, for example, the Swedish ecological target level of 5 µg/m^3, is unduly conservative.

Greaver *et al*. (2012) concluded that gaseous SO_2 may not cause direct effects in vegetation, but the acidification of the environment from SO_2 may be what is responsible for any vegetation effects.

Figure 3-6 Summary of Ecological Effects Data



4.0 DIMETHYLSULPHIDE (DMS) FROM BIOGENIC SOURCES

Dimethylsulphide ($(CH_3)_2S$) is a biologically-produced organosulphur compound that is emitted by marine phytoplankton which synthesize dimethylsulphoniopropionate (DMSP), a precursor to DMS. DMS is the most abundant biological sulphur compound emitted to the atmosphere from marine environments (Bates et al. 1992), representing approximately 95% of the natural marine flux of sulphur gases to the atmosphere, and 50% of the global biogenic contribution of sulphur to the atmosphere (Bucher Norris 2003). DMS is oxidized in the atmosphere to form sulphur dioxide (SO_2) and subsequently to sulphate (SO_4) over a time span of hours-to-days. The presence of elevated concentrations of methanosulphonic acid (MSA), an intermediate compound in the formation of sulphuric acid (H_2SO_4), in marine environments is considered to be a marker for DMS oxidation and biogenic sulphate formation (Langley et al. 2010).

4.1 DMS EMISSIONS FROM COASTAL WATERS

DMS production is not particularly high in coastal waters as compared with the open ocean, and DMS from coastal marine environments is generally thought to be a small contributor to atmospheric SO_2 downwind of large industrial or population centres and ship combustion sources (Church and Jickells 2004). However, DMS emission from marine environments exhibits both diurnal (related to solar radiation, phytoplankton productivity and tidal effects on phytoplankton species populations) and seasonal cycles, and may increase substantially in the vicinity of algal blooms, such that DMS emissions and oxidation to SO_2 may increase to levels that can be locally more important for short periods of time.

For example, Turner et al. (1988) showed that the DMS flux in the near shore waters of the North Sea was an order of magnitude higher in summer (935 µg S/m^2 per day) than in winter (16 µg S/m^2 per day), and increased by a factor of 2-5 times during an algal bloom over the average DMS flux rate in the absence of a bloom. Kwint and Kramer (1996) reported that from 30% to 50% of the total annual DMS emission in a tidal inlet in the Waddell Sea occurred over a time span of just six weeks, closely related to a phytoplankton bloom. Leck and Rodhe (1991) noted that whereas annual biogenic sulphur emissions from coastal areas of the North Sea were negligible (i.e., <1%) compared with anthropogenic emissions, the biogenic emissions from the seas surrounding the Scandinavian peninsula could reach levels as high as 20-70% of the anthropogenic emissions in Scandinavia in summer months. Consequently, from the perspective of understanding the contribution of biogenic DMS to the concentrations of SO_2 in a coastal environment, the determination of average DMS emission rates may be much less important than understanding the maximum emission rates which can occur from time-to-time on a seasonal or even episodic basis.

Nemcek, Ianson and Tortell (2008) reported that DMS concentrations in coastal waters of British Columbia varied dramatically over short distances and showed no significant correlations with any single physical or biological processes studied. DMS concentrations ranged from undetectable (<1 x 10^{-6} mol/m^3) to almost 3.0 x 10^{-5}mol/m^3 and appeared to vary independently of other parameters over large spatial scales, while exhibiting synchronous change with various physical and biological parameters across smaller scale features such as sharp mixing fronts. Ribalet *et al.* (2010) provided evidence for the episodic formation of phytoplankton 'hot spots' in the coastal waters of British Columbia off the coast of Vancouver Island which exerted a strong influence on the biogeochemistry of marine ecosystems in this region, and by extension, on DMS emission rates.

Sharma *et al.* (2003) reported on DMS measurements in the Strait of Georgia conducted in November 1999, April 2000 and August 2000. Concentrations of DMS and DMSP were highest in the spring (April) near Denman Island, an area of high phytoplankton productivity. Relatively high DMS concentrations were also found in the southern portion of Georgia Strait from the northern Gulf Islands to Boundary Bay in Delta. The DMS concentrations in water samples were averaged to provide seasonal ranges as listed in Table 4-1.

Table 4-1 Biogenic DMS Concentrations in Georgia Strait

Season	**DMS Concentration** (nmol/litre)
Fall/Winter	0.02 - 0.3
Spring	0.4 - 29.5
Summer	0.5 - 14.2

With respect to diurnal variations in DMS concentrations in Georgia Strait, Brewer *et al.* (2001) suggested that late afternoon peak levels were related to algal reproduction during the day in response to increased sunlight, while peak concentrations in the early morning were likely due to the release of DMS from zooplankton grazing. The authors reported that DMS concentrations in air were higher during the night time hours and were on the order of 2-10% of concentrations in water.

Using calculated flux estimates, Sharma et al. estimated that the total annual biogenic DMS emissions in Georgia Strait at about 100 Gigagrams (Gg) per year. This emission rate was estimated to account for approximately 48% of the total biogenic and anthropogenic sulphur emissions in the region. However, because of wet and dry deposition during long range transport from ocean sources to the west coast, the actual fraction of total sulphur in coastal regions that could be attributed to biogenic sources was estimated to be closer to 10% in the spring (March-

May), 5% in the summer (June-October) and 0.14% in the fall/winter (November-February) period. For onshore winds, the contribution to total sulphur levels that was deemed to be from local biogenic sources in Georgia Strait was reported to be 26% in the spring, 16% in the summer and 0.06% in the winter.

However, whereas the biogenic emissions of DMS were considered to be contributors to regional sulphate concentrations, the shorter residence time of SO_2 over the ocean resulted in rendering the oxidation of DMS from biogenic sources as a negligible contributor to atmospheric concentrations of SO_2 in the region. For example, the mean 24-hour averaged SO_2 concentration measured at Saturna Island in Georgia Strait in 2012 was 1.5 $\mu g/m^3$ while the 98^{th} percentile concentration was about 5 $\mu g/m^3$ (SENES 2013). However, the SO_2 concentrations at Saturna Island are influenced by a number of anthropogenic sources including ship emissions and emissions from a pulp and paper mill in Crofton on Vancouver Island and oil refineries at Cherry Point, WA. According to R. Vingarzan[23], the measured annual average SO_2 concentration of 0.4 $\mu g/m^3$ provides a closer approximation of the contribution from local marine biogenic sources to ambient SO_2 concentrations than do the levels of SO_2 measured at Saturna Island.

The summer DMS concentrations in Georgia Strait reported by Sharma et al. (2003) were similar to those reported by Cantin *et al.* (1996) for summertime DMS concentrations in the Gulf of St. Lawrence (<0.9-9 nM). A second study in the Labrador Sea between Newfoundland and Labrador and Greenland conducted in the spring (May-June) of 1997 estimated DMS production rates in seawater of 0.4-23.0 nM/hour (Cantin et al. 1999).

Amouroux *et al.* (2002) reported that biogenic DMS emissions exhibited a strong gradient between the open waters of the Black Sea and the estuarine waters of the Danube River, with DMS emissions increasing from open water to the river plume and being largely related to phytoplankton species rather than to total biomass. Extrapolating from measurements made during the summer of 1995, Amouroux *et al.* estimated the upper bound DMS emission rates as:

Open waters	0.0060-0.0017 mol/m^2 per year
Shelf waters	0.0008-0.0019 mol/m^2 per year
River plumes	0.0020-0.0044 mol/m^2 per year

Similar gradients in DMS emissions may also exist in the Strait of Georgia in relation to the Fraser River, but were not identified in the study by Sharma *et al.* (2003).

[23] R. Vingarzan, Head, Air Quality Science Unit, Meteorological Services of Canada, Environment Canada, personal communication, 19 November 2013.

4.2 DMS EMISSIONS FROM COASTAL WETLANDS

Whereas there is some information about biogenic DMS from open waters off Vancouver Island and in Georgia Strait, the literature search for this study identified no research on DMS emissions from tidal mud flats, salt marshes or estuaries in the Lower Fraser Valley. The information summarized below is derived for other regions of eastern North America, Europe and Asia.

Aneja (1990) provided a summary of DMS emissions from coastal wetlands, as summarized in Table 4-2. The available data indicated a wide range of emission rate values which, according to Aneja, suggested there were many sources of variability and large uncertainties in the magnitude of the measured flux rates. For warm season months (May-October), values range from a low of 0.06 g S/m^2 per year to a high of at least 0.91 g S/m^2 per year, and possibly 1.87 g S/m^2 per year.

Table 4-2 Biogenic DMS Emission Rates from Salt Marshes
(Source: Aneja 1990)

Month of Year	DMS Emission Rate (g S/m^2 per year)	Location
Oct/Nov	0.15	New York
Jul-Sep	0.66	North Carolina
May/Jul/Oct	0.54	
Aug	0.83	
n/a	0.10	
Nov	0.02	
Aug	0.48	Delaware
Aug	0.91	
Aug	0.06	Massachusetts
1 year	0.16	
n/a	1.87	Virginia

n/a - not available

Giblin and Kelman Wieder (1990c) noted that research into sulphur gas fluxes from coastal wetlands had been complicated by analytical, methodological and logistical difficulties. As a result, estimates of both individual gases and total gaseous sulphur fluxes spanned more than two orders of magnitude. Although methodological problems with measurement of fluxes were acknowledged to be part of the reason for such a high degree of variability in the results, the authors noted that a high degree of both spatial and temporal variability in flux measurements should be expected in these ecosystems which are characterized by dynamic sulphur cycles.

Table 4-3 summarizes the reported DMS flux rates for mid-latitude coastal wetlands as summarized by Giblin and Kelman Wieder.

Table 4-3 Biogenic DMS Flux Rates
(Source: Giblin and Kelman Wieder c1990)

Location	**DMS Flux** (µg S/m^2 per hour)
Saline Wetlands	
Florida	
black mangrove	0.3 - 10
Salt Marshes	
Florida	
Distichlis spicata	0.7 - 1
B. maritina	1 - 7
Juncus	0.1 - 6.4
sand flat	6.3
Spartina alterniflora	51
Juncus/Spartina (Cedar Island)	0.8 - 179
North Carolina (Cox Hole)	
vegetated marsh	46
marsh flat	<1
Delaware (Canary Marsh)	
frequently flooded	8
infrequently flooded	104
Massachusetts (Great Sippwisset)	
marsh (*Spartina sp.*)	328
creek	18
Delaware-Texas	
12 marshes	0.9 - 213
Freshwater Wetlands	
Florida	
marshes	0.7 - 1
North Carolina	
marshes	<1
New York	
temperate swamp (stagnant)	0.05
New York, North Carolina, Georgia, Ontario	
9 temperate swamps	4 - 21
Ontario	
bogs (3 areas)	3 - 9

A more recent study of a salt marsh estuary in South Carolina (Kulkarni *et al.* 2005) indicated that DMSP concentrations (and by extension DMS concentrations) were not constant and varied by tidal action. DMSP to chlorophyll-a ratios[24] were highest in the estuary at high slack tide and lowest at low slack tide. The authors concluded that the increase in the ratio at high tide was due to the an increased contribution of DMSP-rich phytoplankton taxa that enter the creeks from coastal waters during flood tide, while low ratios were the result of low DMSP-containing re-suspended benthic microalgae which were advected from the adjacent salt marsh into the tidal creeks during ebb tide. This type of variability in DMS concentrations may also be present in the tidal estuaries of the Fraser River, adding complexity to the estimation of DMS contributions to total atmospheric SO_2 concentrations in the Lower Fraser Valley.

4.3 SUMMARY OF BIOGENIC DMS EMISSIONS

Although not extensive, there have been a number of studies completed within the past decade on DMS emissions from coastal waters off Vancouver Island and Georgia Strait. These studies suggest that the contribution of biogenic sulphur from DMS emissions to regional sulphur budgets can be significant at times, especially in the late spring-early summer months. These emissions may play a role in measured concentrations of sulphate and secondary fine particulate matter in the air shed of the Lower Fraser Valley. However, the relative magnitude of these emissions to overall SO_2 concentrations is limited to <0.5 $\mu g/m^3$ on an annual average basis as determined by Sharma et al., and probably <1.0 $\mu g/m^3$ on a 24-hour average basis as determined from average SO_2 concentrations measured at Saturna Island of 1.5 $\mu g/m^3$ (which include some contribution from anthropogenic sources).

On the other hand, there is no information on DMS emissions from coastal wetlands in Georgia Strait. All of the available information on DMS emissions is based on measurements made on the east coast of North America or in Europe and Asia, and it is not clear to what extent those studies provide representative DMS emission rates for the Georgia Basin. The large degree of variability in the reported emission rates, spanning two orders of magnitude, makes it difficult to determine the relative importance of DMA emissions from wetlands in the Fraser River delta to the SO_2 and sulphate concentrations observed in the Lower Fraser Valley.

[24] Modelling studies have suggested that there is a close linkage between DMS and chlorophyll-a concentrations in open ocean waters, however attempts to correlate the two have not proven to be robust because they vary on different time scales and because the cycle of DMS in seawater is controlled by complex physical, chemical and biological processes (Masotti *et al.* 2010).

5.0 CONCLUSIONS

The literature review of regulatory criteria for SO_2 that have been adopted in various jurisdictions in Canada and around the world indicates that there exists a wide degree of variation between jurisdictions. Very few jurisdictions currently apply criteria for averaging periods less than 20 minutes, but even within this small set of criteria, numerical levels range from 265 $\mu g/m^3$ (15-minute average) as defining good air quality in Hawaii and the UK to 530 $\mu g/m^3$ (4-minute average) in Quebec. The most common short-term criterion currently in use is the WHO guideline value of 500 $\mu g/m^3$ (10-minute average) used by three countries, as well as by VIHA in Victoria and by Metro Vancouver in respect to the emissions from an oil refinery. There is evidence from health effects studies for increased airway resistance and decreased lung function for SO_2 concentrations above the WHO guideline level for adults with asthma or other chronic pulmonary disease, and no effects, or limited effects, at lower concentrations than the WHO guideline level or averaging periods less than 10 minutes.

A total of 52 countries (including Canada, and the 28 member EU block) have defined regulatory criteria for 1-hour average SO_2 concentrations. The numerical levels for the criteria range from 150 $\mu g/m^3$ up to 900 $\mu g/m^3$. Metro Vancouver's current AAQO of 450 $\mu g/m^3$ falls within the mid-range of these jurisdictions, and is within the range of levels tested in research studies that have shown no effect on pulmonary function. This suggests that the current criteria in B.C. and Metro Vancouver are protective of human health as most of the epidemiologic studies at these concentrations are related to no effects in the humans studied. However, some studies have also shown an association between median ambient SO_2 concentrations of 45-100 $\mu g/m^3$ (3-hour average) and increased respiratory symptoms in children, especially asthmatic children or those with chronic respiratory symptoms. Edmonton has recently adopted a trigger level of 113 $\mu g/m^3$ to be used for initiating mitigative measures to reduce SO_2 emissions in that city.

Numerically, the new NAAQS adopted by the U.S. EPA in 2010 represents one of the more stringent hourly averaged SO_2 criterion amongst all jurisdictions, except for Singapore (196 $\mu g/m^3$) and China (150 $\mu g/m^3$ for specially protected areas). The stated intent of the U.S. EPA's decision to adopt the new SO_2 NAAQS of 196 $\mu g/m^3$ (75 ppb; 99th percentile averaged over 3 consecutive years) was to protect against short-term exposures ranging from 15 minutes to 24 hours.[25] The U.S. EPA revoked the previous 24-hour average and annual average NAAQS because the scientific evidence appeared to indicate that short-term exposures were of greater concern, and because the previous standards for 24-hour average and annual average SO_2 concentrations would not provide any additional health benefits. The Clean Air Scientific Advisory Committee (CASAC) supported the U.S. EPA's initial proposed range of 50-150 ppb

[25] http://yosemite.epa.gov/opa/admpress.nsf/0/F137260029B9B4F385257737004E521B

(131-392 μg/m^3) for hourly averaged concentrations, and stated that the risk and exposure assessment compiled by the U.S. EPA provided sufficient rationale for the range of proposed levels beginning at a lower limit of 50 ppb (131 μg/m^3) (CASAC 2009). CASAC also concurred with the U.S. EPA that the risk and exposure assessment did not support levels greater than 150 ppb (392 μg/m^3), and noted that there was some ambiguity as to whether the 1-hour daily maximum SO_2 NAAQS should replace the 24-hour and annual standards.

During the NAAQS review process, the American Lung Association (2009) advocated for the adoption of a 5-minute NAAQS, but acknowledged that a new 1-hour average NAAQS would be a major step forward toward protecting the health of the public, specifically asthmatics. However, rather than the final standard chosen by the U.S. EPA, the American Lung Association advocated for a more stringent 1-hour average standard of 131 μg/m^3 (50 ppb; 99th percentile). In addition, it is worth noting that Greaver et al. (2012) have concluded that, although the current NAAQS is intended to provide protection from gas-phase effects on vegetation and to minimize impacts on human health, the 1-hour average NAAQS adopted in 2010 does not protect ecosystems from the effects of sulphur deposition in many parts of the United States.

A total of 79 countries (including Canada, and the 28 member EU block) have adopted 24-hour averaging criteria for ambient SO_2 exposure management. The numerical levels range from as low as 20 μg/m^3 in Mongolia to 367 μg/m^3 in Argentina. Singapore has proposed adopting the level of 20 μg/m^3 by 2020. Metro Vancouver's current AAQO of 125 μg/m^3 is consistent with the less stringent WHO Interim Target level for human health protection. Fifteen countries and the State of California have more stringent criteria than Metro Vancouver, although the criteria in a few of those countries are only slightly more stringent. The lowest WHO guideline of 20 μg/m^3 is generally supported by the literature studies as it is in the range of effects levels associated with epidemiological studies, although numerous studies showed effects at lower concentrations. Thus, the approach by the WHO to steadily lower the 24 hour guideline to 20 μg/m^3 is supported by the epidemiological data. Any value greater than 50 μg/m^3 is not supported by the health effects data and would generally be considered a risk managed level.

A total of 59 countries (including Canada and the 28 member EU block) have adopted annual average SO_2 criteria. There is a 20-fold difference between the most stringent criterion of 5 μg/m^3 in Sweden and the 100 μg/m^3 value adopted by five countries. Some long-term epidemiologic studies have demonstrated an association between annual average SO_2 concentrations as low as 10-15 μg/m^3 and allergenic rhinitis and cardio-respiratory mortality. From an ecological standpoint, the lowest SO_2 concentration level showing no effects in vegetation is an annual average concentration of 10 μg/m^3. Any phytotoxic criterion level lower than 10 μg/m^3 would appear to be unduly conservative.

With regard to biogenic sulphur emissions and their contribution to background SO_2 concentrations, the literature review indicates that DMS emissions from coastal waters contribute to ambient SO_2 concentrations of about <0.5 µg/m^3 on an annual average basis and <1.0 µg/m^3 on a 24-hour average basis. There is considerable variability in the seasonal emission rates from coastal waters, with the highest emissions occurring in the late spring and early summer period, and especially in association with periods of high phytoplankton productivity. Although biogenic DMS emissions from coastal waters result in relatively low ambient SO_2 concentrations, DMS emissions can contribute up to 10% of the total sulphur budget in coastal regions in the spring and about 5% during the summer months.

No research studies were identified in the literature review for DMS emissions from coastal wetlands in the Pacific Northwest Region. All of the available research is for areas of eastern North America or other regions of the world and it is unclear to what extent these studies would be representative of conditions in coastal wetlands of Georgia Strait. Furthermore, the variability in estimated DMS emissions from coastal wetlands in other regions spans two orders of magnitude, making it difficult to determine the relative importance of DMS emissions from wetlands in the Fraser River delta to ambient SO_2 and sulphate concentrations in the Lower Fraser Valley.

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