State of the Science on Ozone

Updating the Regional Ground-Level Ozone Strategy

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Disclaimer

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This project was conducted under the mentorship of Metro Vancouver staff. The opinions and recommendations in this report and any errors are those of the author and do not necessarily reflect the views of Metro Vancouver or the University of British Columbia.

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Contents

List of Figures

List of Tables

Executive Summary

Ground-level ozone is an atmospheric pollutant that can induce health and environmental concerns, and the Canadian Lower Fraser Valley (Canadian LFV) is one of the regions in Canada that is especially affected by this issue in its endeavour to maintain compliance with national and regional air quality standards. The current guideline document in the Canadian LFV on this subject is the Regional Ground-level Ozone Strategy (RGLOS) 2014, which is currently being updated.

The objective of this project is to prepare a report that synthesizes the state of science with respect to the formation, transport, impacts, and management of ground-level ozone backed by evidence from relevant literature on ozone chemistry, meteorology, industrial processes, health research, ecology, and best practices adopted by other jurisdictions. The report will build upon the existing RGLOS (2014) and provide updated insight into the challenges that the Lower Fraser Valley (LFV) region is facing so as to address the evolving nature of scientific understanding of ground-level ozone and to better inform the anticipated renewal of the RGLOS.

The findings of this project are as follows:

- Recent research suggests that the description of ozone formation outlined in RGLOS remains accurate. Analysis in Washington state suggests that urban areas are generally VOC-limited and rural areas are generally NO_x-limited, which broadly aligns with the findings in RGLOS;
- Monthly mean ozone levels in Washington state have been trending up in recent decades, similar to the issues experienced in the Canadian LFV;
- Ozone concentrations are linearly correlated with temperature. While this linearity breaks down at temperatures above 37 °C, this is not expected to impact ozone formation in the Canadian LFV over the next 30 years, given that the predicted maximum temperatures in the region will be 35 °C. This does mean that climate change will lead to more ozone formation;
- Studies predict that ozone formation is increased during wildfires. Impacts from wildfires are expected to increase in the Pacific Northwest due to climate change. Wildfires could increase ozone formation in the Canadian LFV as much or potentially more than climate change in coming decades;
- Limited analysis has been completed to date on the impact of cannabis-related VOCs on ozone formation. More research is needed;
- Transboundary flows of ozone and ozone precursors contribute to the ozone concentrations experienced in the Canadian LFV. Studies suggest that the impact of transboundary flows from Asia on ozone levels in the Canadian LFV may decrease in the

future as China and other countries reduce their NO_x emissions; NO_x transport from the U.S. may become more dominant;

- The studies reviewed did not identify new novel techniques for estimating ozone background levels. RGLOS partners should utilize the data available from the Amphitrite station and consider periodic monitoring there in the future, to confirm results;
- Review of other jurisdictions' reduction strategies suggests that the RGLOS approach remains one of the current best practices for ozone management in North America.

Introduction

The Regional Ground-Level Ozone Strategy (RGLOS) developed in 2014 provides guidance on the most effective approaches for Metro Vancouver, Fraser Valley Regional District and other project partners to control the formation of ground-level ozone in the Canadian Lower Fraser Valley (LFV) region. Reducing ground-level ozone concentrations will reduce the health impacts associated with this air contaminant.

To support ongoing work to refresh (or confirm) the guidance in RGLOS, this paper gathers and synthesizes recent research findings on the current understanding of ozone issues in the Canadian LFV and surrounding regions. It focuses on several key areas:

- The Canadian Ambient Air Quality Standards (CAAQS) will become more stringent in 2020, alongside ambient air quality objectives for ozone set by Metro Vancouver and the B.C. government;
- The Canadian LFV strives to achieve (and maintain) compliance with ambient air quality objectives and standards applicable to the region;
- A series of emergent emissions sources that could contribute to increased generation of ground-level ozone in the Canadian LFV include:
    - Wildfires;
    - Cannabis production;
    - Transboundary flows;
- Climate change is also expected to increase ozone formation;
- The Ucluelet background ozone monitoring station was closed in 2017;
- The Canadian LFV seeks to:
    - Improve its methodology of identifying background ozone levels;
    - Learn from best practices from other regions;
    - Continue to implement actions to reduce ozone precursors.

The report reviewed 36 articles from 2006 to 2019.

Background

Ground-level ozone chemistry

Ground-level ozone refers to ozone present in the troposphere, the lowest layer of the atmosphere near the surface of the earth. It does not typically originate from direct emissions (*i.e.*, it is not a primary pollutant); instead, it is formed when NO_x and VOCs, namely the precursors,

react in the presence of sunlight (*i.e.*, it is a secondary pollutant). Peaks in ground-level ozone concentrations are typically observed in late afternoons of hot, sunny summer days with stagnant weather conditions. This is largely because the kinetic rate (*i.e.*, speed) of chemical reactions through which ozone is formed is generally positively correlated to temperature. The strength of correlation is often numerically characterized by the Pearson correlation coefficient (r), whose magnitude ranges from 0 (weakest correlation) to 1 (strongest correlation) and can be either negative or positive. The confidence in r is quantified by the significance level, or the p-value, which denotes the probability that one would have found that r were in fact zero. Conventionally, if $p < 0.05$, r is deemed statistically significant. Under a "NO_x-limited" regime, reducing VOCs has little impact on ozone reduction due to the abundance of VOCs to react with the relatively small amount of NO_x; similarly, under a "VOC-limited" regime, reducing NO_x would not be effective in lowering ozone concentrations (Metro Vancouver, 2014). As demonstrated in Figure 1, the VOC/NO_x ratio is a key deciding factor in quantifiably determining if a "VOC-limited" or a "NO_x-limited" regime is present. Conventionally, VOC/NO_x = 8 is defined as the borderline between the two types of regimes: a NO_x-limited regime has a VOC/NO_x ratio over 8, while a VOC-limited regime has a VOC/NO_x ratio under 8 (Environment Canada & U.S. EPA, 2014).

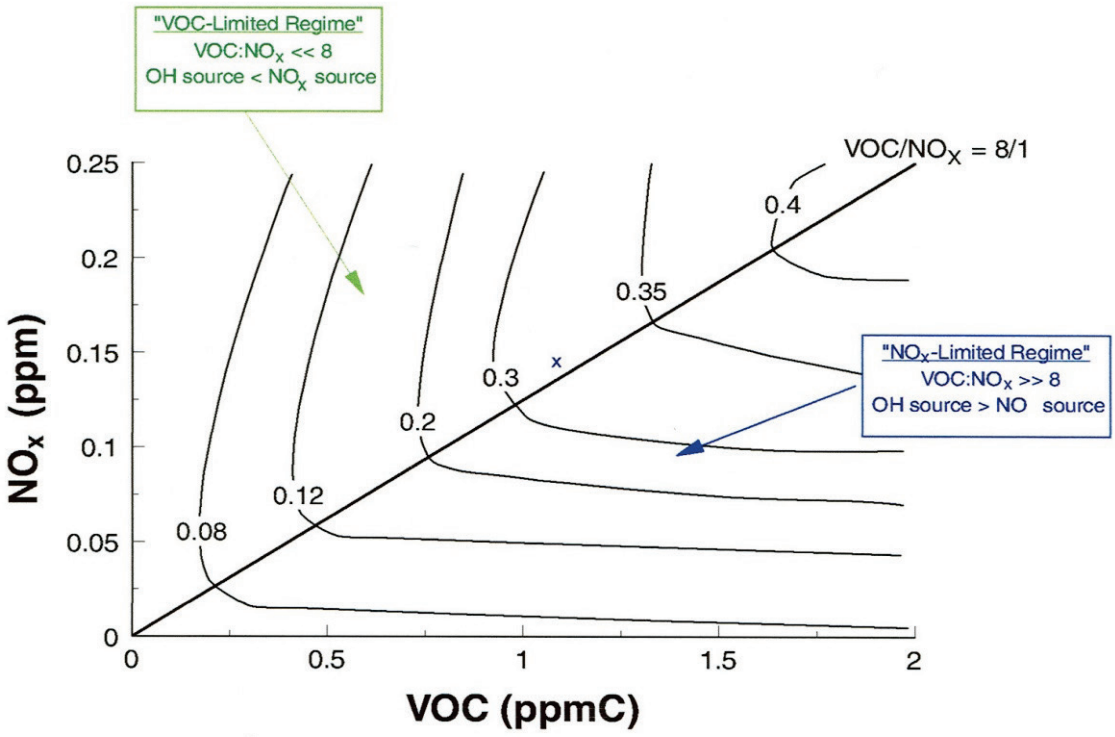


Figure 1: Relationship between NO_x, VOCs, and ozone (Environment Canada & U.S. EPA, 2014).

Peroxyacetyl nitrate (PAN, $CH_3C(O)OONO_2$) is formed when hydrocarbons (C_xH_y) are oxidized in the presence of NO_x and light. It is not soluble in water and is not removed by deposition. The main loss pathway of PAN is through thermal decomposition (University of Washington, *n.d.*):

$$PAN\ (+\ heat) \rightarrow CH_3C(O)OO + NO_2$$

Such chemical property enables PAN to act as a "NO_x reservoir", allowing NO_x to be transported across a great distance from the source region (see Figure 2).

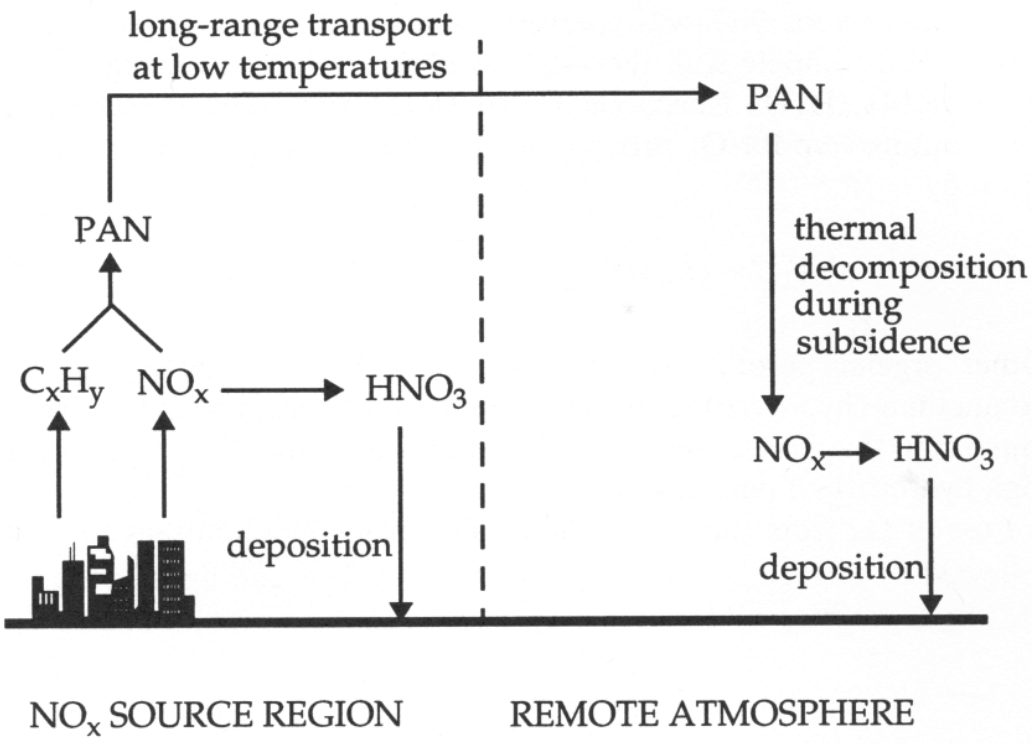


Figure 2: Long-range transport of anthropogenic NO_x facilitated by PAN (University of Washington, *n.d.*).

Ground-level ozone hazards

Ground-level ozone can have detrimental impacts on both human health and the environment. Acute exposure to ground-level ozone can result in respiratory, cardiovascular, and neurological disorders, as well as cardiopulmonary-related mortality; similarly, chronic exposure can lead to deterioration of respiratory, reproductive, and developmental functions, accompanied by a higher number of premature respiratory deaths. In terms of human health effects, no lowest observable adverse effect levels (*i.e.*, "safe" levels) for ground-level ozone has been found, which indicates that ozone reductions can still yield health benefits in areas where ozone levels are already relatively low. Exposure to ground-level ozone can also harm plants and crops by inducing "visible injury, reduced growth and yield, and alternation of competitive patterns within plant communities and ecosystems" (Metro Vancouver, 2014).

Ground-level ozone objectives in the Canadian LFV

Table 1 compares some of the past (2015), current, and future (2020, 2025) national (CAAQS), provincial, and regional (Metro Vancouver) objectives for nitrogen dioxide (NO_2) and ozone. The current annual and 1-hour objectives for NO_2 and ozone in Metro Vancouver are less stringent than their counterparts in CAAQS (2020), which prompts for the need for revisions of these objectives.

AIR CONTAMINANT	AVERAGING TIME	JURISDICTION (ACHIEVEMENT YEAR)	NUMERICAL VALUE (ppb)	STATISTICAL FORM
Nitrogen dioxide	1-hour	Metro Vancouver (current)	106	Not to exceed
		CAAQS (2020), BC (2020)	60	3-year average of annual 98th percentile of daily maximum 1-hour concentration
		CAAQS (2025)	42	
	Annual	Metro Vancouver (current)	21	Annual average
		CAAQS (2020), BC (2020)	17	
		CAAQS (2025)	12	
Ozone	1-hour	Metro Vancouver (current), BC (current)	82	Not to exceed
	8-hour	Metro Vancouver (current)	65	8-hour rolling average
		CAAQS (2015), BC (current)	63	3-year average of annual 4th highest daily maximum 8-hour average concentration
		CAAQS (2020)	62	

Table 1: Comparison of the CAAQS, provincial objectives, and Metro Vancouver objectives for nitrogen dioxide and ozone (Metro Vancouver, 2019).

Findings

Ozone formation in the Canadian LFV, B.C., and Pacific Northwest

Utilizing the Weather Research and Forecasting (WRF)-Sparse Matrix Operator Kernel Emission (SMOKE)-Community Multiscale Air Quality (CMAQ) modelling system, Ainslie *et al.* (2013) conducted 2 simulations of ozone formation for 4 key ozone events representing different meteorological regimes in the Canadian LFV from 1985 to 2005, with one using 1985 emission levels and the other using 2005 levels. As shown in Figure 3, the VOC/NO_x ridgeline shifted towards the west (from the Agassiz-Chilliwack area to Abbotsford-Langley area) and the south (from the ridges of the North Shore mountains to the valley floor near Port Moody and Pitt Meadows) over the 20-year period. The western Canadian LFV (represented by the Port Moody station) remained VOC-limited; the central Canadian LFV (represented by the Chilliwack station) used to be VOC-

limited but became NO_x-limited (alternatively characterized as exhibiting mixed sensitivity, due to meteorological variability); the eastern Canadian LFV (represented by the Hope station) remains NO_x-limited during the hottest summer days.

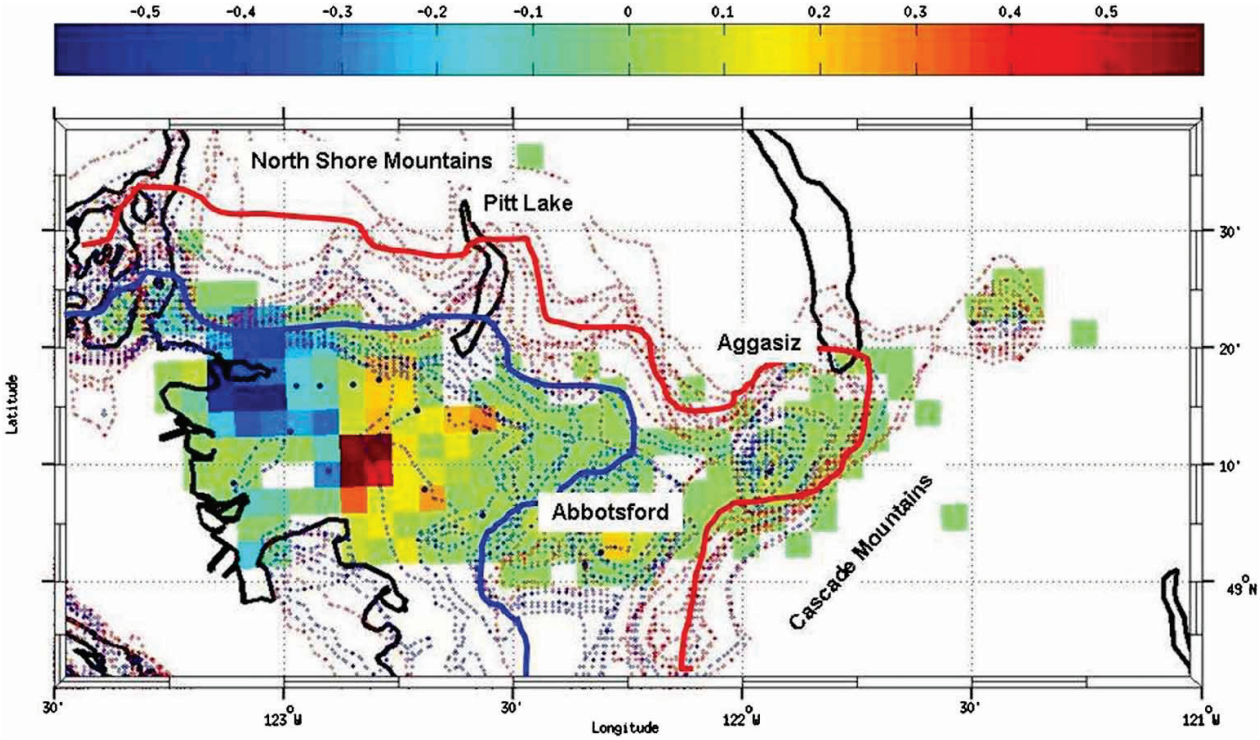


Figure 3: Simulated VOC/NO_x ridgelines (red, 1985; blue, 2005) based on the $[O_3]/[NO_y]$ = 7 ratio for all modelled ozone episodes using 1985 emissions (red dots) and 2005 emissions (blue dots) during the hottest summer days. Areas to the west of the ridgeline are VOC-limited, while those to the east of the ridgeline are NO_x-limited. Grid cells coloured in blue represent a decline in population from 1985 to 2005, while cells coloured in red suggest a population growth through the 2 decades (Ainslie *et al.*, 2013).

Meanwhile, the Washington State Department of Ecology (WA DOE) performed an investigation of the VOC/NO_x ratio in the Pacific Northwest using emissions simulated with the Air Indicator Report for Public Awareness and Community Tracking regional forecast model on a typical "high ozone day". As shown in Figure 4, urbanized areas in Western WA are generally VOC-limited, while NO_x limitation becomes increasingly evident as one moves further away from the urban core. These results align with data from the Canadian LFV and the Puget Sound geography, albeit subject to verification with observations (Environment Canada & U.S. EPA, 2014).

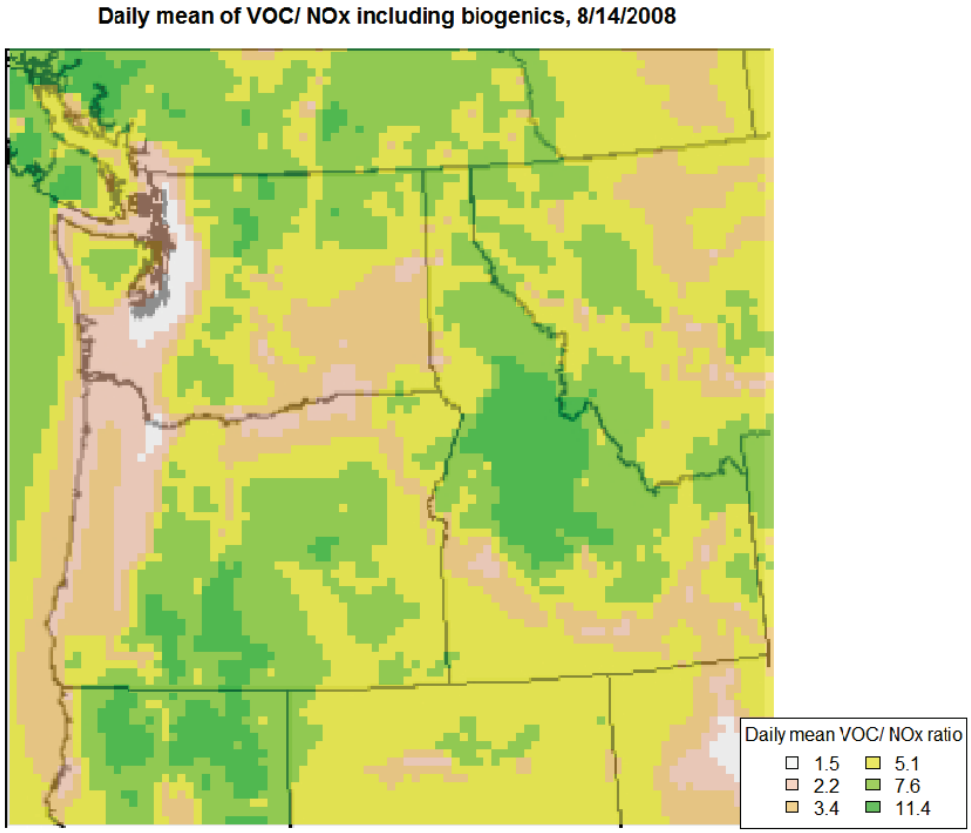


Figure 4: Spatial distribution of daily mean VOC/NO_x ratio in the Pacific Northwest region on a high ozone day (August 14, 2008) (Environment Canada & U.S. EPA, 2014).

There have not been recent studies that show a difference in where the Canadian LFV is VOC-limited or NO_x-limited since the adoption of RGLOS 2014.

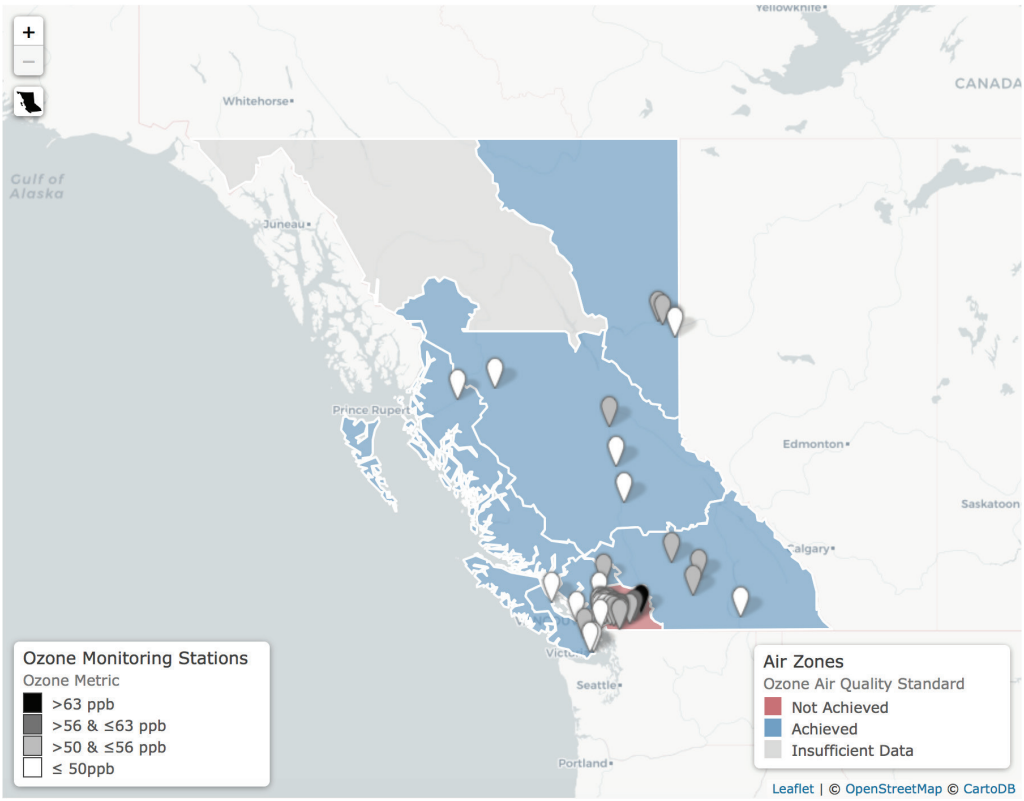
Ozone concentrations in the Canadian LFV, B.C., and Pacific Northwest

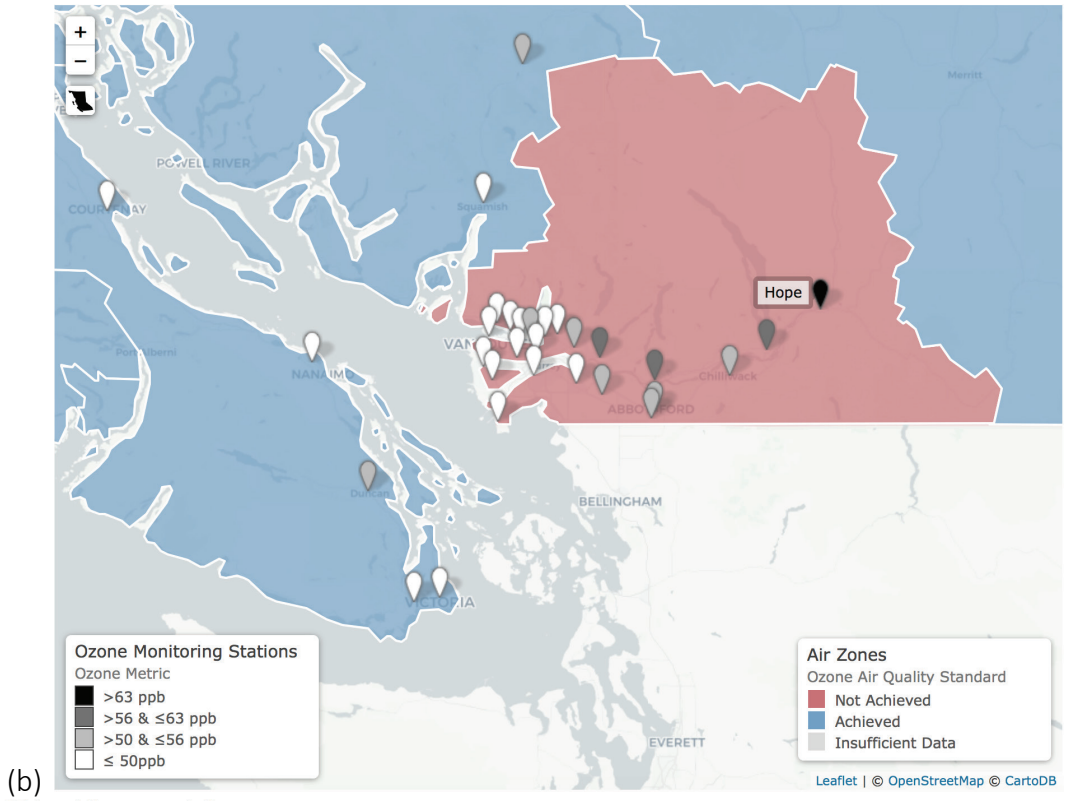
Summertime ozone concentrations in the Canadian LFV have generally declined since the mid-1980s owing to policies and programs to control ozone precursor emissions by local and provincial governments and related federal agencies. This decrease is uneven across different parts of the Canadian LFV. Peak ozone levels have dropped considerably in the western part of the Canadian LFV, while the eastern part has witnessed "little to no improvement" in their 8-hour averaged ozone maxima (Ainslie *et al.*, 2013).

Ppb (parts-per-billion) is a common dimensionless measure of quantity, denoting that the substance of interest accounts for a fraction of 10^{-9} (*i.e.*, one in a billion). Such fractions may be mass fractions, mole fractions, or volume fractions. Air units are commonly expressed as a volume-per-volume ratio, and thus the suffix "v" is often (but not always) appended to the ppb notation

to emphasize such distinction, resulting in the ppbv (parts-per-billion-volume) notation (U.S. EPA, 2016). From 2015 to 2017, out of the 6 B.C. air zones, the Lower Fraser Valley air zone was the only air zone in the province that did not achieve the CAAQS (≤ 63 ppbv, 8-hour average) and contains the only monitoring station (*i.e.*, Hope) that observed non-compliance with the standard, as shown in Figure 5 (Environmental Reporting BC, 2019).

(a)





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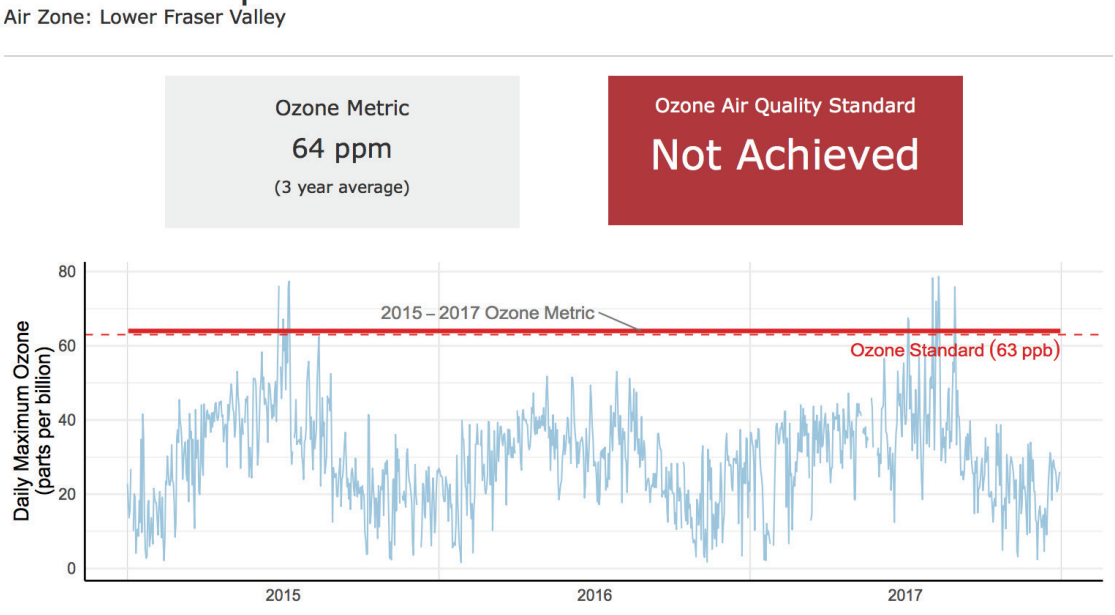

(c)

Figure 5: Status of CAAQS attainment of B.C. air zones (overview (a) and zoomed into the Canadian LFV (b)) and non-compliance of CAAQS at the Hope Station (c) based on 2015 to 2017 monitoring data (Environmental Reporting BC, 2019).

In 2014, Environment Canada and the United States Environmental Protection Agency (U.S. EPA) jointly examined the long-term ozone trends observed at select monitoring sites (see Figure 7) in the Puget Sound Basin (see Figure 6) and in the Pacific Northwest (see Figure 4). As Figure 7 suggests, monthly means of the de-seasonalized (*i.e.*, with seasonal variation patterns removed) maximum daily 8-hour average (MDA8) ozone concentrations at all the monitoring sites except Mount Rainier experienced a rate of increase in ozone concentrations of approximately 0.3 ppbv/yr over their respective observation periods (varying from 4 to 15 years), and MDA8 ozone levels at all the sites have remained below 50 ppbv. The observed ozone reductions at Mount Rainier coincide with the NO_x control measures implemented at the nearby TransAlta Centralia Power Plant, which is deemed the most likely NO_x source affecting ozone levels at Mount Rainier.

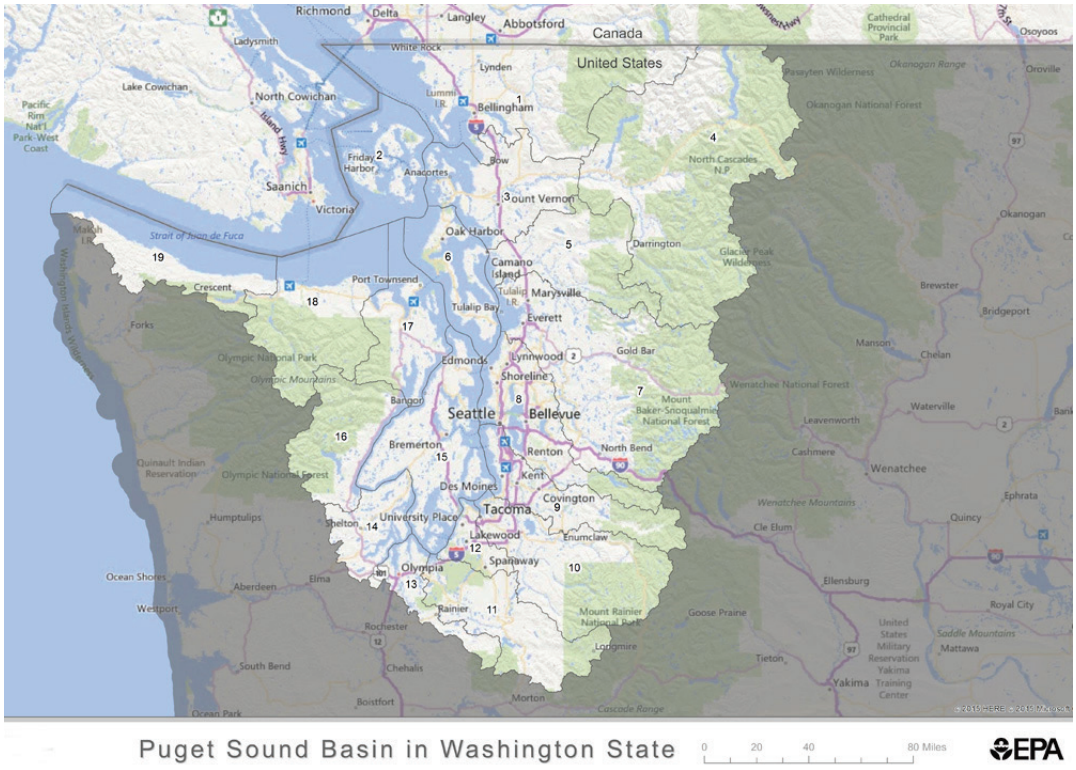

Figure 6: Location of the Puget Sound Basin in the State of Washington (U.S. EPA, 2019).

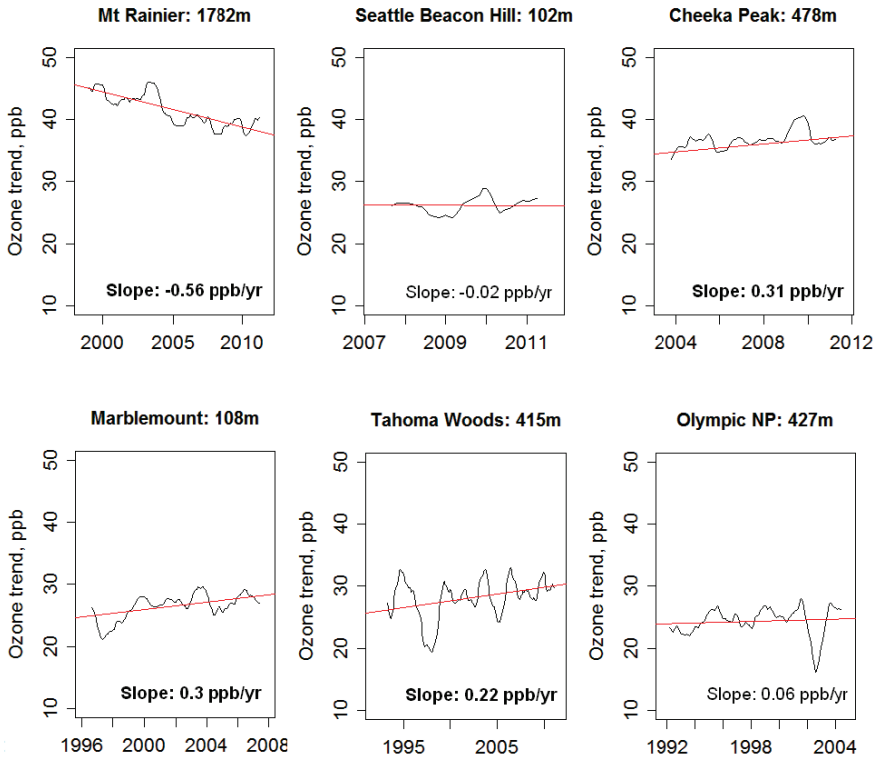

Figure 7: Long-term de-seasonalized monthly means of maximum daily 8-hour average ozone concentrations (in ppbv) at select year-round monitoring stations in the Puget Sound Basin in Washington, United States (Environment Canada & U.S. EPA, 2014).

Expected impacts of increasing temperature on ozone formation

Increasing concentrations of greenhouse gases are changing our climate, including in the Canadian LFV. The temperature is anticipated to rise by about 3°C over the next 30 years in the Canadian LFV, which may accelerate ozone formation and prompts for a better understanding of how ground-level ozone responds to rising temperatures.

Correlation between surface ozone concentration and temperature

As pointed out in RGLOS 2014, peak ozone levels are typically associated with hot, sunny summer afternoons (Metro Vancouver, 2014). Studies have generally shown that the relationship between ground-level ozone concentration and surface air temperature is linear, owing to the direct accelerating effect of temperature on kinetic rates of chemical reactions through which ground-level ozone is formed. As an example, Rubio & Eduardo (2014) studied the summertime 8-hour average ozone levels with respect to maximum daily temperature at two locations in Santiago de Chile, Chile, with the Las Condes station in the city's outskirts and the Parque O'Higgins station in the city's downtown area. As shown in Figure 8, a linear regression analysis was performed for both stations and the analyses yielded correlation coefficients (*r*) of 0.707 (Las Condes) and 0.755

(Parque O'Higgins), respectively (p < 0.0001 for both locations), which indicates a fairly strong correlation between the ozone concentration and temperature, and supports the use of temperature as a predictor of ozone levels within the range of temperature covered in this study.

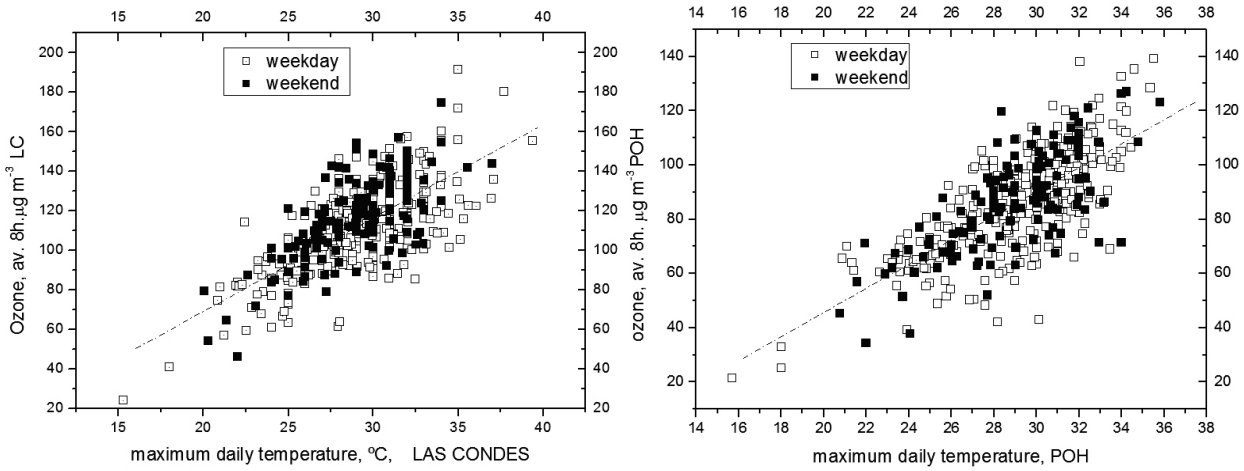

Figure 8: Linear regression analyses performed between 8-hour average ozone concentration (in µg·m^{-3}) and maximum daily temperature (in °C) in (A, left) Las Condes and (B, right) Parque O'Higgins.

Ozone suppression

RGLOS 2014 has not addressed deviations from the positive ozone-temperature correspondence, such as ozone suppression. Meanwhile, according to the Climate Projections report by Metro Vancouver (2014), the hottest day temperature is expected to rise from 31 °C to around 35 °C by the 2050s.

After reviewing the ozone-temperature relationship in 4 air basins in California across 25 years (1980-2005), Steiner *et al.* (2010) found from a series of simulations that the linearity breaks down above about 37 °C, as shown in Figure 9. This is partly attributed to lower ground-ozone production from peroxyacetyl nitrate (PAN) decomposition as the PAN sink for NO_x shrinks exponentially with increasing temperature. Another explanation is that some plant species emit a lower amount of isoprene (a highly reactive VOC) at higher temperatures, which reduces the amount of VOCs available for ozone reactions.

The ozone suppression is also highlighted in and supported by studies of Meehl *et al.* (2018), Shen *et al.* (2016), among others. The studies cited in this section in support of the ozone suppression phenomenon are all conducted in continental U.S., with a number of sites showing the phenomenon in California. Since ozone suppression mostly results from the co-influence of various meteorological factors, it is reasonable to presume that the findings also apply to Metro Vancouver, whose climate shares plenty of common traits with that of California. Given the climate projections, temperature will still be a reasonably linear indicator of ozone concentrations in the Metro Vancouver region within the coming decades.

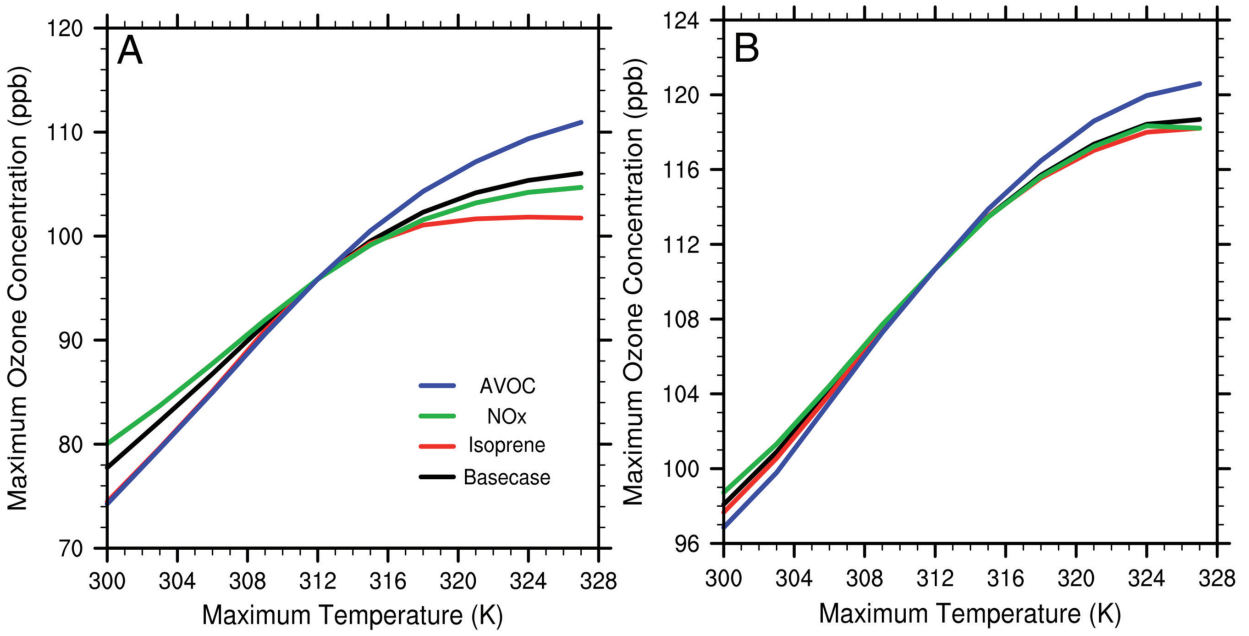

Figure 9: Simulated relationship between maximum ozone concentration (ppbv) and maximum temperature (Kelvin, K) (0 K ≈ -273 °C; linear correspondence between Kelvin and Celsius) modelled in (A) Sacramento, CA and (B) Fresno, CA for a present-day scenario (basecase, black), a scenario with temperature-dependent anthropogenic VOC emissions due to changes in evaporative emissions (blue), a scenario with temperature-dependent NO_x emissions attributed to changes in energy demand (green), and a scenario (red) with variable isoprene emissions owing to biophysical high-temperature constraints above approximately 310 K (~37 °C) (Steiner *et al.*, 2010).

Emergent ozone sources

Wildfires

Wildfires are uncontrolled fires involving the combustion of vegetation in rural areas, often spreading to a wide surface area and releasing a considerable amount of atmospheric pollutants, which may include ground-level ozone as a secondary pollutant. RGLOS 2014 has not addressed the potential impact on surface ozone from wildfires in the vicinity of the Canadian LFV.

As local temperatures increase due to climate change, the incidence of wildfires will increase. Wildfires release a considerable amount of ozone precursors; in addition, researchers of a number of observational boreal fire studies suggest subsequent ozone generation either locally or downwind of wildfires. Wildfires are generally NO_x-limited, and ozone production therein can be dramatically accelerated by oxygenated compounds. Nonetheless, both photosynthesis and photolysis (*i.e.*, photochemical decomposition) rates of ozone can be significantly lowered by the reduced transmission of solar radiation owing to aerosols, and the interplay of cloud processing (*i.e.*, in-cloud chemical processes) and heterogenous reactions (involving reagents in different physical phases) further complicates the composition of compounds involved in ozone reactions during a wildfire (Jaffe & Wigder, 2012). On a global scale, wildfires annually produce about 170

million tonnes of ozone as a secondary pollutant, which is 3.5% of the total tropospheric ozone production worldwide (Jaffe & Wigder, 2012).

Yue *et al.* (2015) performed a comprehensive estimate of ozone emissions stemming from forest fires in Alaska and Canada by the mid-21st-century (2046-2065), utilizing a series of climate models to simulate meteorology and regression analyses. Figure 10 showcases the simulated extent of wildfire-induced ozone present-day and mid-21st-century in North America: wildfires in BC currently account for 0-3 ppbv of ozone, while this can increase by 2-6 ppbv to roughly 2-9 ppbv within several decades. Meanwhile, as illustrated in Figure 11, the predicted ozone level changes in the upcoming decades in the Pacific Northwest region mostly source from wildfires in Alaska and Canada. Although the grid that contains the Canadian LFV ("the LFV grid") seems to have similar ozone contributions from climate change, western U.S. fires, and boreal fires, about half of the LFV grid is made up of ocean water bodies and the immediately neighbouring grid above it suggests that most of the forecast ΔO_3 is attributed to boreal fires. Notably, wildfires in the summers of 2015, 2017, and 2018 had smoke impacts on the Canadian LFV that were progressively unprecedented in terms of geographic scope, duration and intensity of smoke impacts. This further emphasizes the need for increased attention to ozone impacts stemming from wildfires on the region.

The Canadian LFV could experience additional ozone formation due to rising temperatures in the next few decades. However, increased ozone formation due to wildfires could have an equal or larger effect on ozone concentrations in the LFV (Yue *et al.*, 2015).

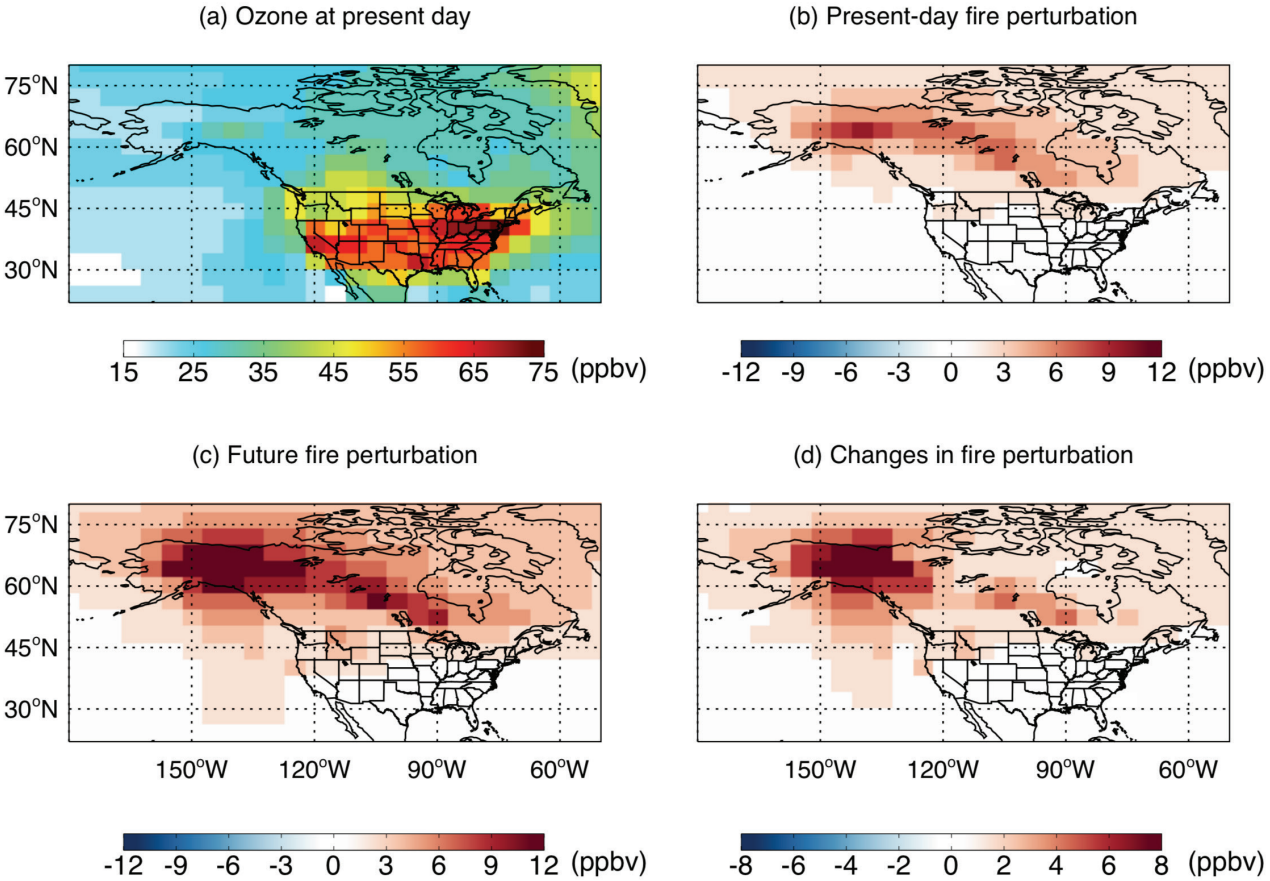

Figure 10: Simulated maximum 8-hour average summertime (June to August) surface ozone levels for four scenarios: (a) Present-day levels; (b) Contribution of wildfires to present-day levels; (c) Contribution of wildfires to mid-21st-century levels; (d) Change in contribution of wildfires from present day to mid-21st-century (Yue *et al.*, 2015).

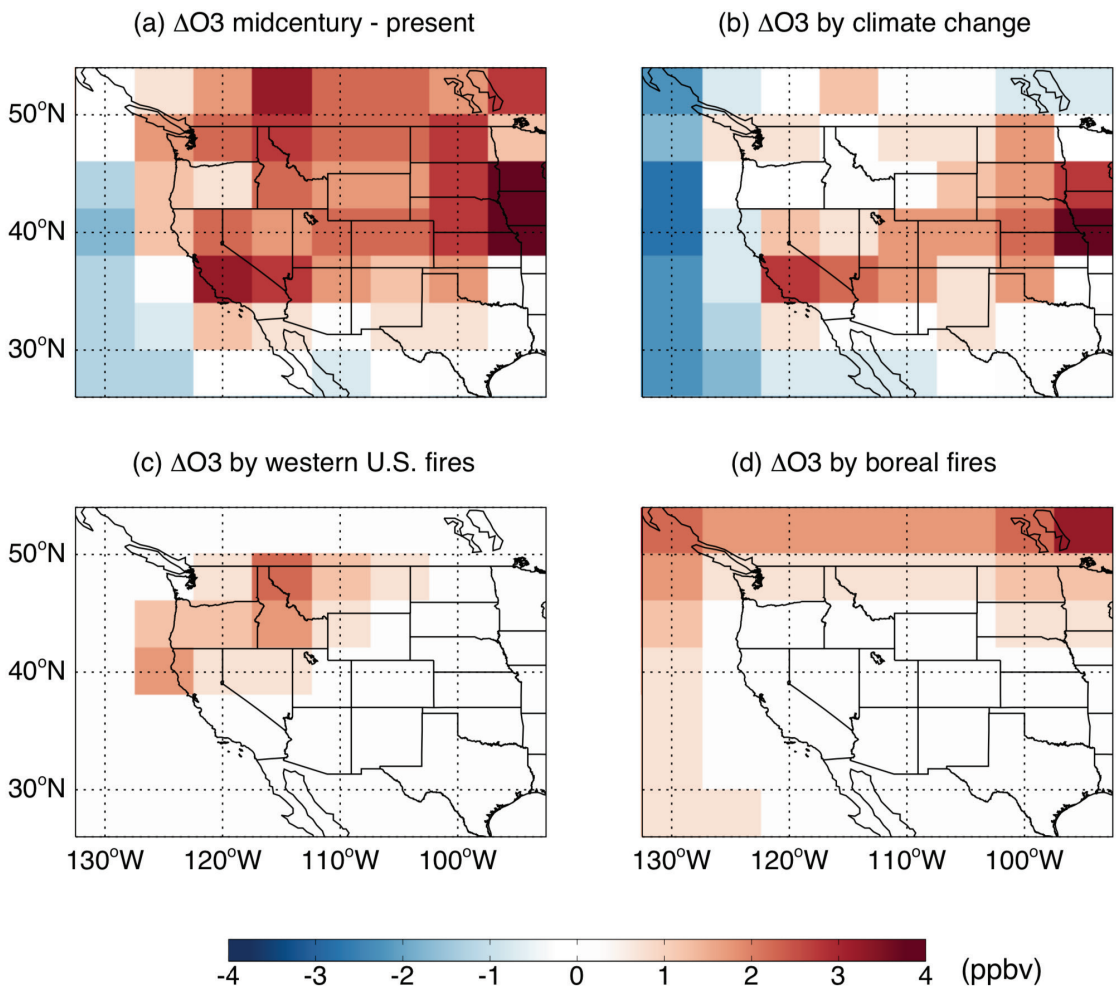

Figure 11: (a) Simulated changes in maximum daily 8-hour average summertime surface ozone levels from present day to mid-21st-century over the western and central U.S., broken down into contributions to the changes in (a) from (b) climate change, (c) changes in western U.S. fire emissions, and (d) changes in Alaskan and Canadian fire emissions (Yue *et al.*, 2015).

In July 2012, a wildfire plume was transported to the Pacific Northwest from Siberia, contributing to exceedances of ozone objectives in various areas in the region. In the Interior of B.C. and in Whistler, increases in 8-hour ozone levels of 34-44 ppbv were observed at monitoring stations; coastal B.C. and Washington state also saw 10-12 ppbv increases in 8-hour ozone. Such wildfire impacts on ozone are expanded because PAN acts as a NO_x reservoir, which redistributes primary wildfire emissions and expands the areas over which wildfires can increase ozone formation. This event highlights not only the far-reaching impact of wildfires but also the need to incorporate wildfire emissions into chemical transport models and to derive effective parameterizations to better study how downwind meteorology, plume age, entrainment pathways, and other factors can affect air quality impacts (Teakles *et al.*, 2017; Jaffe *et al.*, 2013).

During an intensive wildfire in 2017 at Meridian, Idaho, USA, the nearby urban area of Boise experienced a 32% increase in MDA8 ozone levels (McClure & Jaffe, 2018). In the urban environment studied, on non-smoke[y] days, MDA8 ozone decreased as $PM_{2.5}$ increased, likely due to NO_x-titration (*i.e.*, decrease in O_3 production at very high NO_x concentrations). On smoke[y] days, MDA8 ozone is positively correlated with $PM_{2.5}$ up to a threshold around 60-70 $\mu g/m^3$ (in $PM_{2.5}$), beyond which MDA8 dropped during very high smoke events. In their study of aged wildfire plumes observed at the Mount Bachelor Observatory in Oregon, Briggs *et al.* (2016) also point out that ozone production continues as wildfire plumes are transported further downwind, owing to chemical role of PAN, whose thermal deposition (*i.e.*, the main PAN loss pathway) can be traced up to 2 weeks downwind of wildfires (Jaffe & Wigder, 2012). For an urban environment like the Canadian LFV, this demonstrates that increases of ozone concentrations due to wildfires are "capped" when the concentration(s) of NO_x and/or $PM_{2.5}$ reach(es) a threshold, similar to ozone suppression.

Cannabis production

The legalization of non-medical cannabis use in Canada in October 2018 opened doors for miscellaneous cannabis-related industries. Cannabis production could impact ozone levels in the Canadian LFV region because of the VOCs released during different production phases. It should be noted that cannabis VOC emissions were not considered as part of RGLOS 2014.

Wang *et al.* (2019) grew four strains of Cannabis spp. plants commonly found in cultivation facilities in Colorado (where use of recreational cannabis was legalized in 2014) for 90 days in an enclosure chamber, where the rate of biogenic VOCs (specifically terpenes) emissions was measured as emission capacity. Eucalyptol and β-myrcene were the most dominant amongst the terpenoids emitted.

Under the Cannabis Act, there are 44 licensed cultivators of cannabis in BC as of August 15, 2019 (Health Canada, 2019). Metro Vancouver is currently consulting on regulatory options for cannabis productions facilities; potential requirements could include:

- Keep cannabis processing enclosed in structures;
- Keep cannabis waste management enclosed in structures when occurring where cannabis production and processing take place;
- Equip structures with rapidly closing doors or a double door system;
- Draw enclosed air in structures through activated carbon filters for VOC emission control; and
- Use temporary containment and collection to direct VOC emissions from outdoor cultivation to treatment using activated carbon filters.

Metro Vancouver based these potential requirements on information about best practices for cannabis production operations obtained from authorities that are regulating these operations in Denver, Colorado and Washington state.

Transboundary flows

RGLOS 2014 noted that ozone transport from Asia carried by fast springtime jet stream had contributed to elevated springtime ozone in the Canadian LFV, and that long-range transport of pollutants due to intensifying fossil fuel use in Asia affects background ozone levels in the region.

The southern boundary of the Canadian LFV forms part of the Canada-U.S. border, and transboundary flows of ground-level ozone and its precursors can occur on a local scale (*e.g.*, within the Georgia Basin / Puget Sound airshed), a medium scale (*e.g.*, from Northern California to Southwestern B.C.), and over long ranges (*e.g.*, over the Pacific Ocean from East Asia and Siberia). Vingarzan *et al.* (2007) studied the transboundary pollutant transport on a local scale at Christopher Point on the southern tip of Vancouver Island, close to the Canada-U.S. maritime border dividing the Juan de Fuca Strait. With a full year of measurements of ambient concentrations of various atmospheric pollutants, including ground-level ozone, the researchers conducted a wind sector analysis, shown in Figure 14. This analysis indicates that almost half of the ozone measured at Christopher Point originated from the U.S. and that local emissions accounted for only 10% of the measured concentrations. The NO_x in the eastern Canadian LFV, for example, mainly comes from NO_x emissions in southwestern Metro Vancouver and northwestern Washington State, which are commonly upwind during daytime and have sizeable industrial facilities and considerable traffic volumes (Metro Vancouver, 2015). As illustrated in Figure 12, when winds are from the northwest, southwestern Metro Vancouver is the main source of NO_x transport in the eastern Canadian LFV; when winds are from the south, northwestern Washington State is responsible for most of the NO_x transport in the eastern Canadian LFV.

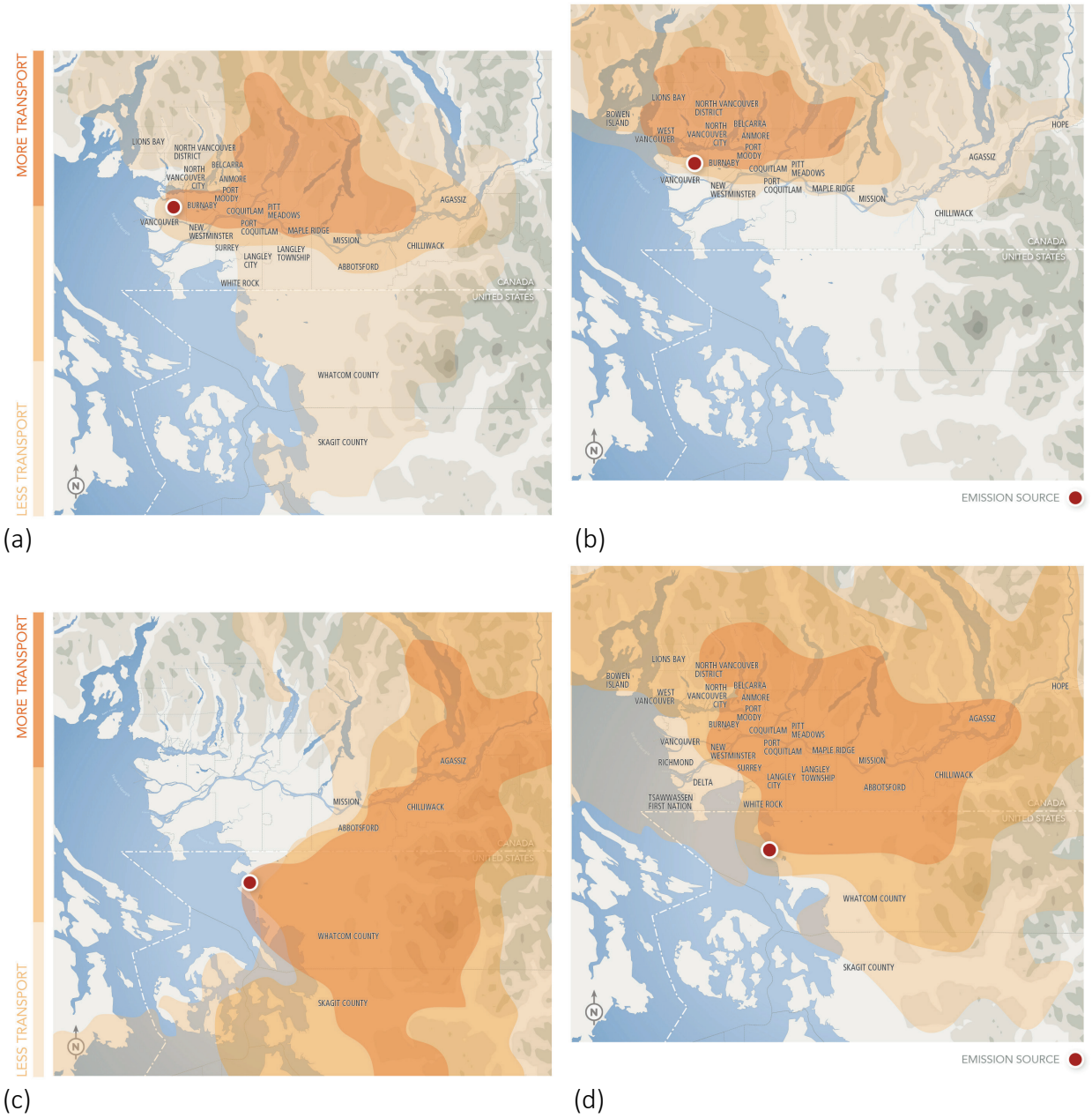

Figure 12: An average NO_x plume modelled forward in time over 11 hours (a) from a central point in the City of Vancouver, when winds are from the northwest; (b) from the point in City of Vancouver, when winds are from the south; (c) from a large industrial facility in Whatcom County, Washington State, when winds are from the northwest; (d) from the facility in Whatcom County, when winds are from the south. Darker orange areas indicate more NO_x transport (by a factor of 100) than light orange areas (Metro Vancouver, 2015).

In their extensive study of trans-Pacific transport of reactive nitrogen (NO_x) and ozone to Canada during spring, Walker *et al.* (2010) find that ozone increases in Canada are in part driven by ozone

transported from Asia across the Pacific, and ozone formed in the eastern Pacific as a result of PANs (peroxyacetyl nitrates) decomposition: PANs remove NO_x from regions of low OPE (ozone production efficiency) and inject it into regions with higher OPE, thereby facilitating ozone formation, particularly in the eastern Pacific. Subsequently, the resulting ozone-rich airmass is transported into western Canada, which is illustrated in Figure 13.

In the western U.S., anthropogenic emissions from Asia have been responsible for the majority of increases in background ozone levels for both spring and summer since 1990. As much as 65% of springtime ozone increases (0.3-0.5 ppbv yr^{-1}) are attributed to Asian NO_x emissions, which have tripled (*i.e.*, 1-2 ppbv yr^{-1} or 25-50 ppbv in total) over 25 years. During the summer, benefits of U.S. domestic emission reductions are mostly offset by the increased emissions from Asia. In coming decades, NO_x emissions are expected to decrease in China a result of air quality improvement policies and programs. Therefore, the role of NO_x emissions in tropical Asian countries (*e.g.*, India), where ozone production efficiency is higher, may become increasingly important (Lin *et al.*, 2017).

Although emissions in Asia could cause local ozone levels to increase by as high as 10 ppbv during some ozone episodes, results from the GEM-AQ/EC model suggest that a 20% reduction in ozone precursors transported from Asia would yield an ozone reduction of only 0.3-0.5 ppbv in western Canada (Environment Canada & U.S. EPA, 2014).

In short, although transport of anthropogenic NO_x emissions from Asia has been playing an important role in background ozone concentrations in North America, the importance of such role may be weakened over time for the Canadian LFV as China actively implements its initiatives to reduce its NO_x emissions, particularly for sites close to the U.S. border where U.S. NO_x transport may become increasingly dominant.

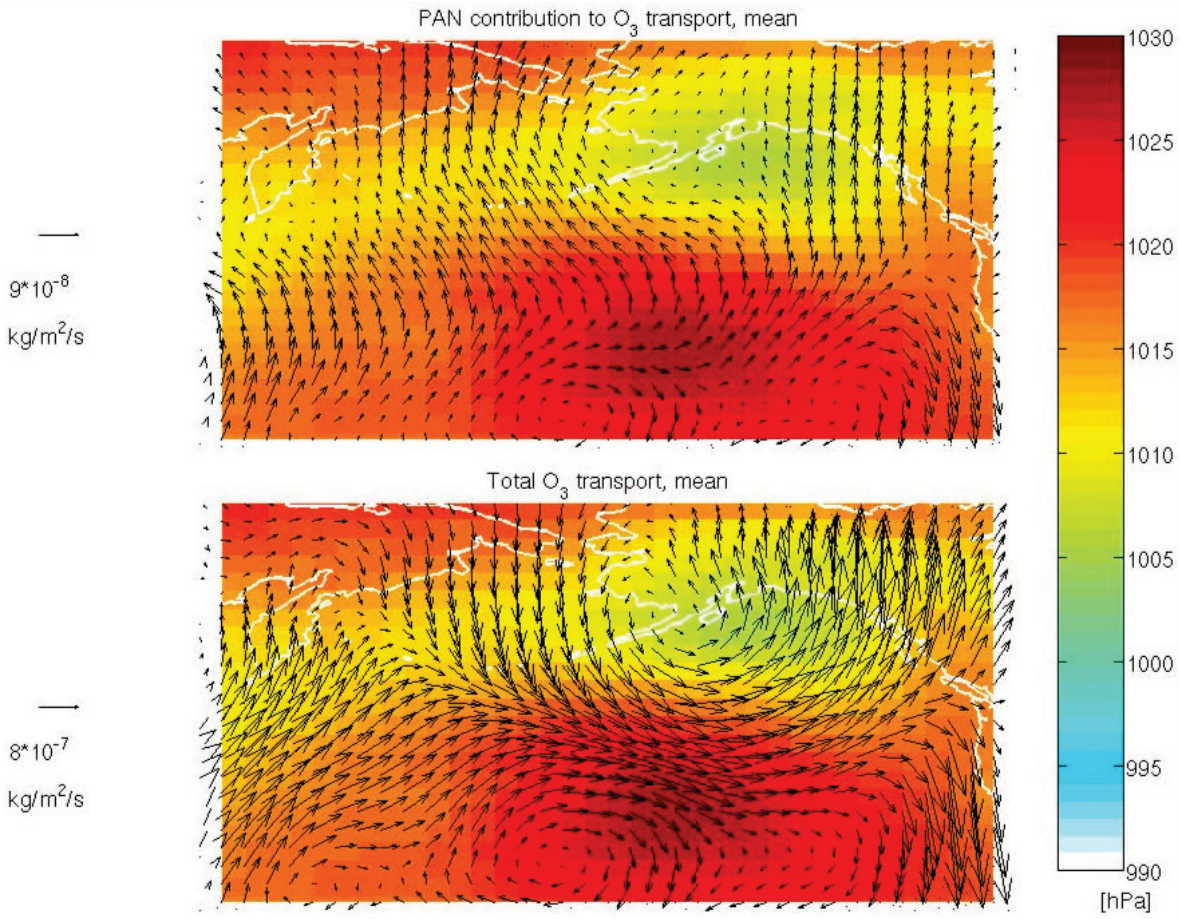

Figure 13: Simulated ozone fluxes at 2 km (elevation above sea level) averaged over the studied period (April-May 2006). Background colour indicates surface pressure; PAN contributions are obtained from difference between the baseline and "no PAN" simulations.

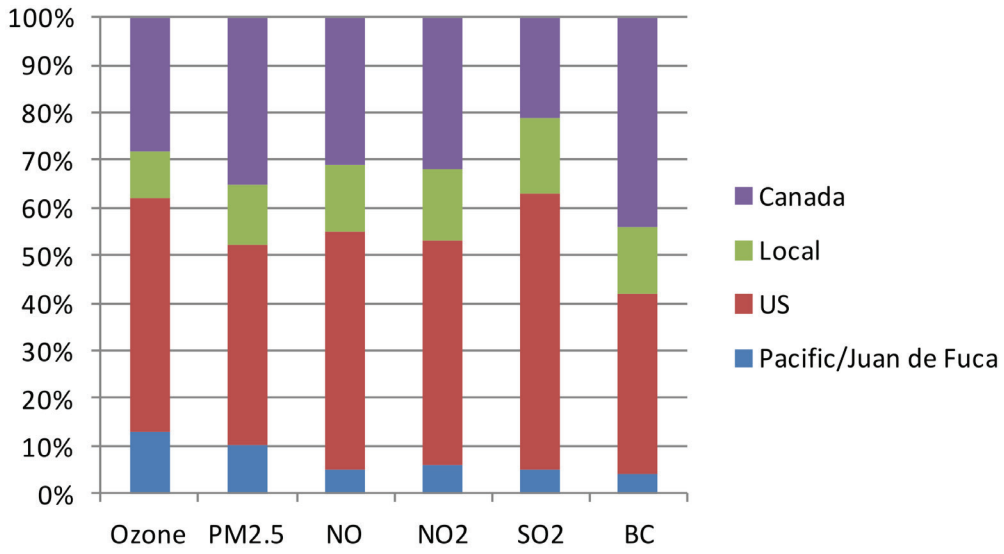

Figure 14: Wind sector analysis displaying contributions to levels measured at Christopher Point during the observation period (September 2005-2006) by each sector. Note that the "Canada" series (violet) represents pollutants transported from elsewhere in Canada, as opposed to being "local" (green). The Juan de Fuca Strait is the strait that leads to the Pacific Ocean and constitutes the international maritime boundary between B.C. and the State of Washington (Vingarzan *et al.*, 2007).

New techniques/info to identify appropriate ozone background levels

The West Coast Background Air Quality Monitoring Station had been in operation at the Amphitrite Lighthouse in Ucluelet, Vancouver Island since 2010, before monitoring was discontinued by Environment and Climate Change Canada in 2017. In response to this, regional air quality authorities are considering re-establishing future monitoring at this location for a defined duration at some prescribed frequency.

Ground-level ozone is generated from both natural processes (*e.g.*, photochemical reactions between biogenic VOCs and NO_x, forest fires, stratospheric ozone intrusion, lightning activity) and anthropogenic emissions of NO_x, one of its important precursors, can be transported long distances given appropriate meteorological conditions. Policymakers and regulatory bodies need to identify, the "background concentration" of ozone transported into their jurisdictions in order to understand the extent of local anthropogenic contributions to the total measured ozone level (McKendry, 2006). A similar metric termed "baseline ozone" is also used, which is ozone level observed at remote and/or rural sites where little to no recent and local emissions play a role. Measured background ozone levels are commonly greater than model-estimated background ozone, as baseline ozone encompasses recirculated local/domestic emissions. Nonetheless, for the purpose of providing supplementary information for the RGLOS, these two terms can be used interchangeably. In the western U.S., spring and summer seasonal mean background ozone concentration is greatest at high elevation locations; at lower elevation sites along both the West and East Coasts, contributions from background ozone to the highest ozone days are less pronounced (Jaffe *et al.*, 2018).

Common methods to quantitatively identify background ozone include using chemical transport models such as the CMAQ (Community Multiscale Air Quality Modelling System) and CAMx (Comprehensive Air Quality Model with Extensions), with the most common modelling approach being the "zero-out" method, which sets domestic anthropogenic emissions to zero. To further identify contributions by source, sensitivity methods (*i.e.*, direct perturbation modelling, where emissions from sources or regions of interests are modified within certain ranges) and tagging techniques, which assign each molecule of ozone to a particular source and do not perturb emissions (Jaffe *et al.*, 2018). As Jaffe *et al.* (2018) suggests, given the assumptions associated with each model, a multi-model approach is best advised to provide a holistic characterization of spatial and temporal variability in background ozone, alongside additional measurements of ozone-related meteorological and chemical variables for process-based evaluations of model capabilities. Instruments on the current generation of satellites cannot capture ozone mole fractions in the boundary layer and at the surface. However, it is expected that the next generation of instruments

will resolve this issue in the next 5 years (Jaffe *et al.*, 2018). In order to minimize uncertainties in quantifying background ozone, Jaffe *et al.* (2018) call for an expanded monitoring network for co-located measurements of key species (*e.g.*, carbon monoxide, NO_x, VOCs, $PM_{2.5}$ (fine particles with a diameter of 2.5 µm or less), and speciated particulate matter) with an emphasis on the under-sampled interior western U.S area, a large-scale field experiment as soon as the new satellite instruments become operational, an increased attention to uncertainty and sensitivity analysis, and a better understanding of the formation and dispersion of ozone and PM associated with wildfires.

With respect to attaining (or achieving) air quality standards for ozone, Baylon *et al.* (2016) point out that high-ozone events such as upper troposphere/lower stratosphere (UT/LS) episodes (subsidence of ozone-rich air from the UT/LS, see Figure 15) and Asian long-range transport could affect the attainment status of a site, if they were not classified as exceptional/uncontrollable events by authorities. Therefore, Baylon *et al.* (2016) suggest that long-term measurements targeting observations of exceptional events, more frequent measurements of ozone, water vapour, and other correlating factors such as CO at a network of mountaintop sites, vertical profiles of ozone and water vapour from LiDAR and ozonesondes, and satellite retrievals would be helpful in providing key data on daily and interannual variations in baseline/background ozone, thereby facilitating the forecasting of exceptional events using high-resolution chemical transport models.

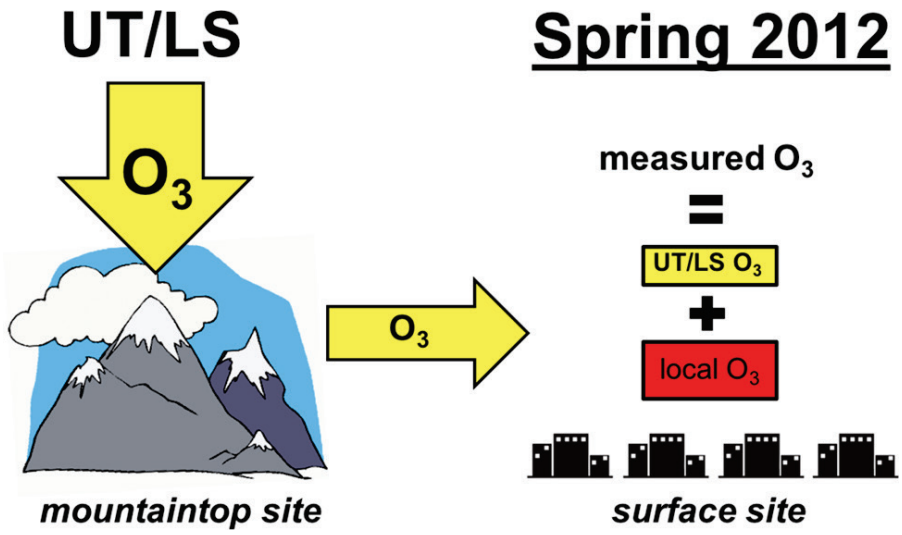

Figure 15: Illustration of an UT/LS episode, which describes the subsidence of ozone-rich airmass from the upper troposphere/lower stratosphere. Increases in the maximum daily 8-hour average ozone at a mountaintop site from an UT/LS episode are transported to nearby downwind surface sites, enhancing locally measured ozone concentrations by merging with local fluxes (Baylon *et al.*, 2016).

For the Amphitrite Point Observatory (APO) in Ucluelet on Vancouver Island, an important regional baseline ozone monitoring station for B.C., Tokarek *et al.* (2017) investigated the causes of

frequent nocturnal ozone depletion events (ODEs, depletion of ozone in the layer immediately above the ocean surface relative to atmospheric layers aloft) and find that the ODEs took place in air masses that had been in contact with vegetation near the shore such as kelp forests and trees, which served as an important source of biogenic VOCs. Despite this, the ODEs observed at the APO were primarily driven by dry deposition (*i.e.*, loss of ozone to terrestrial and aquatic systems).

Given the closure of the APO, the Canadian LFV is in need of reliable alternative sites for background ozone monitoring. In his report prepared for the B.C. Ministry of Environment, McKendry (2006) suggests that the establishment of a long-term "pristine" background ozone monitoring site on the West Coast should be one of the top priorities for air monitoring in the province, and that a site analogous to Cheeka Peak (a mountain peak situated near the northwestern "tip" of the State of Washington, overlooking Vancouver Island across the Juan the Fuca Strait) on the west coast of Vancouver Island would be ideal, allowing for simultaneous monitoring of long-term trends in background ozone levels as well as short-term variations in trans-Pacific airmasses. Due to the high sensitivity of ozone concentration to elevation and the importance of mid-tropospheric trans-Pacific ozone transport, McKendry advocates more collaboration with Environment and Climate Change Canada, which operates and maintains a chemical monitoring station on Whistler Peak, in order to enable data collection at a high altitude. Additionally, McKendry recommends "strategically" establishing 2 or more "clean" sites for ozone outside of the Canadian LFV and Vancouver Island, with the Interior Plateau and Northeast B.C. being 2 potentially ideal candidates, enabling investigations into the spatial impact of biomass burning plumes, trans-Pacific anthropogenic sources, and stratospheric intrusions.

In brief, studies reviewed have not identified new (*i.e.*, post-2014) methods or locations that can be used to provide high quality background ozone levels for the Canadian LFV. Analysis of Amphitrite station data should continue, along with consideration of future opportunities to monitor at Amphitrite, even on short-term basis.

Ozone reduction strategies in other regions

RGLOS 2014 seeks to continue implementing existing ozone monitoring efforts and actions specifically targeting high-ozone days, as well as to enhance reductions of ozone precursors to which local ozone levels are sensitive (*i.e.*, whether "NOx-limited" or "VOC-limited") during peak ozone periods. During non-peak ozone periods, RGLOS 2014 seeks to reduce VOC emissions region-wide, particularly those that are most reactive and are associated with co-benefits. This section reviews some reduction strategies from other jurisdictions to understand if RGLOS strategies need to be updated.

Calgary region, Alberta

The objectives of the CRAZ (Calgary Region Airshed Zone) Particulate Matter and Ozone Management Plan 2014 and some of the ozone-related revised action steps are listed below (SNC-Lavalin, 2014):

Objective 1 – consistency and transparency in regional air quality management:

- Include both urban and rural considerations in air quality network;
- Revise and adjust of the ozone management plan every 3-5 years through stakeholder consultation;
- Regularly audit the ozone management plan with progress revision through dialogue with other airsheds;
- Complete an "achievement report" of the ozone plan every 3-5 years;
- Pursue opportunities to improve local air quality that do not require funding, such as local policies and programs;
- Continue liaising with the provincial government on funding.

Objective 2 – strategic promotion of sustainable economy:

- Create incentives and deterrents;
- Partner with businesses in the promotion of green energy;
- Support vehicle scrappage/retirement programs.

Objective 3 – proper regional land use planning:

- Incentivize positive air quality initiatives for urban planning and transportation;
- Evaluate the ozone impacts of transportation initiatives.

Objective 4 – building awareness of air quality issues:

- Support an air quality module in school curricula;
- Promote reduced vehicle use;
- Promote air quality related issues by partnering with local media outlets.

Objective 5 – collaboration between stakeholders to share environmental responsibility:

- Evaluate the feasibility of alternative fuels for municipal vehicles;
- Allow stakeholders to adopt a voluntary commitment model that includes individually suitable reduction targets;
- Financially incentivize homeowners to properly dispose of their old appliances.

Objective 6 – support for air quality research:

- Locate poor air quality "hot spots";
- Forecast poor air quality events;
- Continuously model photochemical pollutants in the region;
- Cumulatively assess the quantitative impact of ozone emissions;
- Potentially conducting studies on local groups particularly vulnerable to ozone pollution;
- Study the potential of ozone damage to vegetation;

- Develop an activity-based CRAZ emissions inventory.

Los Angeles County, California, USA

According to its 2016 Air Quality Management Plan (AQMP), the South Coast Air Quality Management District (SCAQMD), which administers air pollution control in Orange County and urban portions of Los Angeles County (among others), has identified reducing NO_x emissions sufficiently to meet upcoming ozone standard deadlines as the greatest challenge in the South Coast Air Basin. As shown in Figure 16, despite the existing regulatory actions, an additional 45% and 55% reduction is needed by 2023 and 2031, respectively, to attain the 8-hour ozone standards (SCAQMD, 2017).

Since 88% of the region's total NO_x emissions in 2012 were attributed to mobile sources, over which the SCAQMD has limited authority, the District worked collaboratively with CARB (California Air Resources Board) and U.S. EPA, which are the primary regulatory agencies for vehicles, to ensure that mobile sources deliver a "fair share" of contributions to NO_x emission reductions (SCAQMD, 2017) .

Aside from the conventional regulatory control measures, the 2016 AQMP also outlines incentive-based programs, co-benefits from existing greenhouse gas reduction programs, further deployment of cleaner technologies among mobile sources, and reductions from state- and federally regulated sources (*i.e.*, aircraft, locomotives, and ocean-going vessels). Public funding incentives are intended to complement regulations to encourage the turnover of high-emitting on- and off-road vehicles and equipment, as well as to advance the deployment of new cleaner technologies, which need to be secured early and sustained through 2031 (South Coast AQMD, 2017).

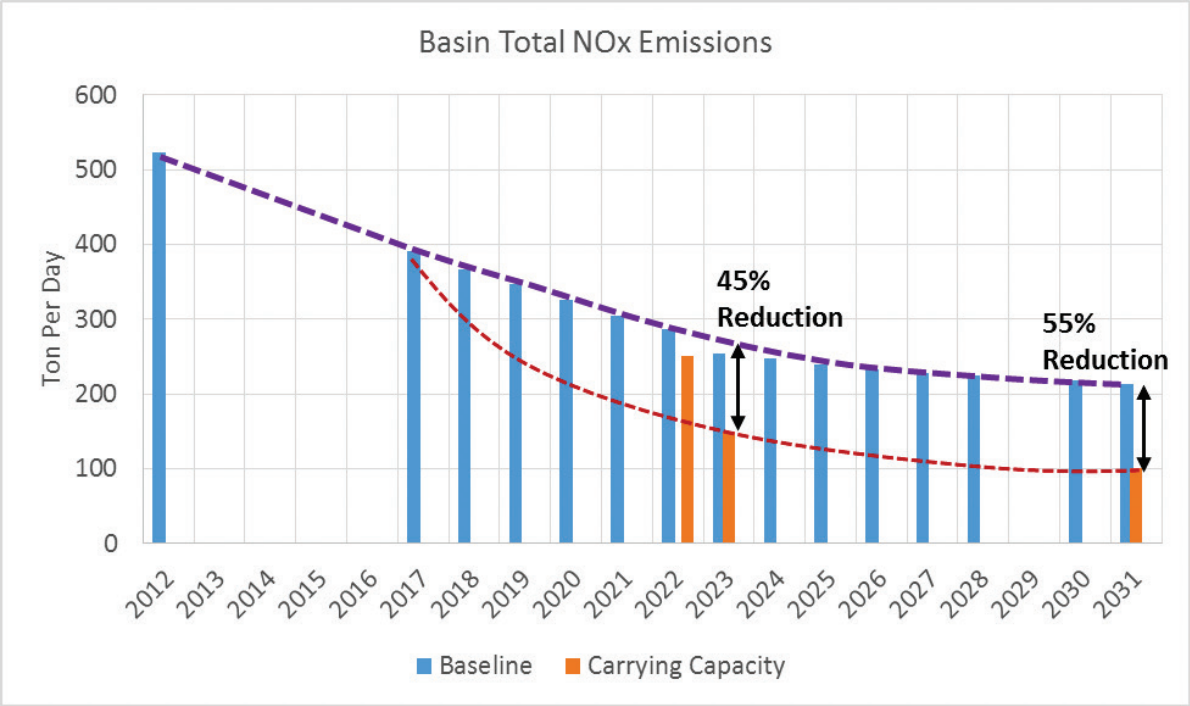

Figure 16: Projected total NO_x emission trend (purple) versus future NO_x emission standards (red) in the South Air Basin. Baseline emissions are projected NO_x emissions assuming continued implementation of already adopted regulatory measures.

San Francisco Bay Area, California, USA

As mandated by the California Clean Air Act (CCAA), the Bay Area and other air districts in California are adopting "all feasible measures" in the near future since all non-attainment areas in California have so far failed to achieve the CCAA requirement of a 5% annual reduction in ozone precursor pollutants. Air districts are also required by the CCAA to conduct periodic assessments of the transport of ozone and its precursors from upwind to downwind regions and to aid downwind air districts in fulfilling the State ozone standard by reinforcing mitigation requirements for their upwind counterparts. In addition, strategies to attain the State ozone standard in the Bay Area include (Bay Area AQMD, 2017):

- An emissions inventory system;
- A permitting system which requires Best Available Retrofit Control Technology (BARCT) on all existing permitted stationary sources;
- Measures to achieve use of a significant number of low-emission vehicles in motor vehicle fleets, Transport Control Measures (TCMs);
- Indirect source and area source programs;
- Regional public education programs;
- An assessment of cost-effectiveness of proposed control measures;

- An annual regulatory schedule;
- An annual progress report;
- A review and update of the Clean Air Plan every 3 years.

The review of other jurisdictions' reduction strategies suggests that the RGLOS approach remains one of the current best practices for ozone management in North America. Nevertheless, Metro Vancouver and other government agencies should continue to monitor best practices elsewhere for local consideration.

Conclusions

- Recent research suggests that the description of ozone formation outlined in RGLOS remains accurate. Analysis in Washington state suggests that urban areas are generally VOC-limited and rural areas are generally NO_x-limited, which broadly aligns with the findings in RGLOS;
- Monthly mean ozone levels in Washington state have been trending up in recent decades, similar to the issues experienced in the Canadian LFV;
- Ozone concentrations are linearly correlated with temperature. While this linearity breaks down at temperatures above 37 °C, this is not expected to impact ozone formation in the Canadian LFV over the next 30 years, given that the predicted maximum temperatures in the region will be 35 °C. This does mean that climate change will lead to more ozone formation;
- Studies predict that ozone formation is increased during wildfires. Impacts from wildfires are expected to increase in the Pacific Northwest due to climate change. Wildfires could increase ozone formation in the Canadian LFV as much or potentially more than climate change in coming decades;
- Limited analysis has been completed to date on the impact of cannabis-related VOCs on ozone formation. More research is needed;
- Transboundary flows of ozone and ozone precursors contribute to the ozone concentrations experienced in the Canadian LFV. Studies suggest that the impact of transboundary flows from Asia on ozone levels in the Canadian LFV may decrease in the future as China and other countries reduce their NO_x emissions; NO_x transport from the U.S. may become more dominant;
- The studies reviewed did not identify new novel techniques for estimating ozone background levels. RGLOS partners should utilize the data available from the Amphitrite station and consider periodic monitoring there in the future, to confirm results;

- Review of other jurisdictions' reduction strategies suggests that the RGLOS approach remains one of the current best practices for ozone management in North America.

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