Disparities in Climate-Induced Health Outcomes in the Greater Toronto Area.*

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The growing impact of climate change in Canada demonstrates a clear and current threat to human health. These threats are becoming revealed in Canada as the country continues to face the consequences of warming almost at twice the global rate. The focus for this paper is on tempreture increases, lower air quality and more pollution and a decline in health for Toronto. Once the data for this research was collected, the data cleaning process begun which entailed of using packages in R like tidyverse, janitor, dplyr, …. Duplicate and irrelevant observations were removed, as well as unwanted outliers. The process was complete once the data was correct, consistent and usable.

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*Code and data are available at: https://github.com/sarahmansoorr/SUDS2022

Introduction

As climate change worsens, the danger it presents to human health worsens as well (Hansen and Karl 2013). The health impacts due to climate change are already being demonstrated in parts of Canada. Canada is warming at almost twice the global rate and if this continues, emissions will exceed 2 degrees Celsius worldwide (Proulx and Staka 2022).

The Paris Agreement within the United Nations Framework Convention on Climate Change includes 175 countries that have agreed to limit the average global temperature rise to below 2 degress Celcius (Proulx and Staka 2022). Canada had signed to the Paris Agreement as well and committed to cutting emission 30% below the 2005 levels by 2030 (Proulx and Staka 2022). However, Canada's emission increased in 2016 compared to 1990. As a response to this increase, the Government of Canada developed a national climate change plan called *The Pan-Canadian Framework on Clean Growth and Climate Change* (Proulx and Staka 2022). This framework notes that human activities are driving severe changes to the Earth's climate which poses substantial risks to human health.

Urgent action is needed and the science shows that it will make a tangible difference. The health impacts from climate change can be prevented by improving efforts both in societies and health systems in Canada. Changes in measures can prevent health impacts and build health systems and facilities that are more resilient to climate change.

I collected data from the Government of Canada's website for both temperature and pollution. Once the data was collected for the available years between 2002 and 2022, it was cleaned using multiple packages in R which I will describe in the next section. Then the analysis begun and I found the following: temperatures have continued to increase since 2002, winters are less cold and summers are hotter, pollution levels for NO, NO2, CO, and SO2 have gone down since 2002 due to laws and regulations put in place and these pollutants typically have higher pollution levels in winter months, O3 pollution levels have remained mostly the same since 2002 and these levels are higher in summer months, temperature does seem to have a normal relationship with NO, CO, and SO2 levels and a positive relationship with NO2 and O3 levels. The presence of these pollutants have affects on health including lung irritation, increase in allergens for those with asthma, shortness of breath, respiratory illnesses, heart disease, cardiovascular diseases, infections, and reduced lung function.

This paper outlines the data, how it was collected, variables of interest and how the data was processed and cleaned. Next I will look at the trends in temperature from 2002 to 2022 followed by the trends in pollution levels for each pollutant from 2002 to 2020. From here, the relationship between pollution levels and temperature will be analyzed followed by limitations and results and lastly next steps to take.

Data

Data Collection

Temperature data was collected from the Government of Canada's website on Weather, Climate and Hazard's page containing past weather and climate data for the station "Toronto City". This data was collected from January 2002 to May 2022. The original data contains daily data on maximum temperature, minimum temperature, mean temperature, heat degree days, cool degree days, total rain (mm), total snow (cm), total precipitation (mm), snow on ground (cm), direction of maximum gust, and speed of maximum gust (km/h). For this research, I will focus on only maximum temperature, minimum temperature, and mean temperature.

Pollution data was collected from the Government of Canada's National Air Pollution Surveillance (NAPS) Program website. This website contains pollution data from 2002 to 2020. Each year contains a file with continuous data and integrated data. I will be using continuous data for each year. The continuous data contains annual summaries and hourly data. I will be looking at the hourly data for CO (Carbon Monoxide), NO (Nitric Oxide), NO2 (Nitrogen Dioxide) , O3 (Ozone), and SO2 (Sulfur Dioxide). This data includes the city (which is Toronto in our case), the levels of each pollutant for each hour of every day. I reduced the data to the mean of pollution levels by pollutant of each day.

Variables of Interest

Temperature variables of interest:

- City
- Maximum Temperature
- Minimum Temperature
- Mean Temperature
- Day
- Month
- Year

Pollution variables of interest:

- City
- Pollutant
- Mean pollution for pollutant each day
- Day
- Month
- Year

Data Processing

Temperature data

The data for temperature was processed using R studio and R (R Core Team 2020). I started off by renaming the column names for each temperature data set from 2002 to 2022. Once this was done I combined the 2002 to 2022 temperature data together. The data set initially contained 31 variables. From these I selected the city, date, year, month, day, maximum temperature, minimum temperature, and mean temperature using the dplyr package (Wickham et al. 2021). I then cleaned the names of the data set using the janitor package (Firke 2021). I added a column for the names of the month by mutating the data set and changed the city rows to represent only Toronto data. From here, I dropped any NA values from the maximum, minimum, and mean temperature columns. Lastly, I saved the cleaned data into the repository as a csv file.

Pollution Data

The pollution data was also processed using R studio and R. I first loaded the different data sets for each pollutant for each year. Each year had 5 data sets for each pollutant (NO, NO2, CO, O3, SO2). I started off by also renaming the column names for the data sets from 2002 to 2020. Once this was done I combined the pollutant data sets for each year into one data frame for the year. The data initially contained 27 columns. The data sets initially contained pollution levels for each hour of every day in the respective year. I replaced these 24 columns (for each hour of the day) with one column that contained the mean pollution level for that day and pollutant. I filtered for Toronto from the list of cities in the data set using the dplyr package (Wickham et al. 2021) and removed the duplicate rows where the pollutant and date repeated. The missing values in this data set were labeled as "-999", so I replaced these values with NA and then with 0 for consistency. This process was repeated for all years from 2002 to 2020. Once this was completed, the data was combined for all the years into one data frame and the following columns were selected: city, pollutant, mean pollution, day, month, year. This cleaned data was then saved into the repository as a csv file. The units for CO were ppm while the rest were ppb. To keep the data consistent, I converted those values to ppb as well by multiplying by 1,000.

Sample

The sample includes data from Toronto of daily temperature maximum, minimum and means from 2002 to 2022 and daily pollution levels for NO, NO2, CO, O3, SO2 from 2002 to 2020.

The Data

Table 1: Extracting rows from the Temperature data from 2002 - 2022

Year	Month	Day	Max Temp	Min Temp	Mean Temp
2002	11	14	14.3	4.4	9.4
2003	7	6	30.1	19.9	25.0
2004	6	22	23.9	15.2	19.6
2006	1	16	-3.0	-12.4	-7.7
2007	6	1	26.6	18.6	22.6
2008	3	23	1.5	-5.6	-2.1
2011	4	8	9.3	4.5	6.9
2014	1	8	-7.7	-16.2	-12.0
2016	10	26	6.2	0.9	3.6
2019	12	12	1.9	-7.6	-2.8

Table 1 shows the rows of the Temperature data from 2002 to 2022. Variable "Year" indicates the year, variable "Month" indicates the month, and variable "Day" indicates the day. Variable "Max Temp" represents the maximum temperature on the day with the following month and year. Variable "Min Temp" represents the minimum temperature on the day with the following month and year. Variable "Mean Temp" represents the mean temperature on the day with the following month and year.

Table 2: Extracting rows from the Pollution data from 2002 - 2020

City	Pollutant	Mean Pollution	Day	Month	Year
Toronto	CO	766.67	10	4	2002
Toronto	NO2	18.79	27	9	2002
Toronto	O3	9.54	15	4	2002
Toronto	SO2	3.92	9	2	2002
Toronto	SO2	5.46	6	12	2002
Toronto	CO	0.00	24	6	2003
Toronto	NO	33.71	6	11	2003
Toronto	NO2	16.21	2	9	2003
Toronto	SO2	4.92	11	11	2003
Toronto	O3	15.17	8	9	2004
Toronto	NO	2.04	4	6	2005
Toronto	SO2	1.00	1	3	2005
Toronto	NO2	8.04	20	5	2007
Toronto	CO	304.17	14	2	2008
Toronto	NO	0.00	1	NA	2010

Table 2 shows the rows of the Pollution data from 2002 to 2020. Variable "City" indicates the city from which the data was collected. Variable "Pollutant" indicates the pollutant and includes 5 types: CO, NO, NO2, O3, and SO2. Variable "Mean Pollution" represents the mean pollution levels of the following pollutant on the following day of the month and year.

Variable “Day” indicates the day, variable “Month” indicates the month, and variable “Year” indicates the year. Variable “Max Temp” represents the maximum temperature on the day with the following month and year.

Visualizing Temperature from 2002-2022

Visualizing Temperature by Month and Year

I’m interested in finding the trends of the maximum temperatures from 2002 to 2022 by the month and year.

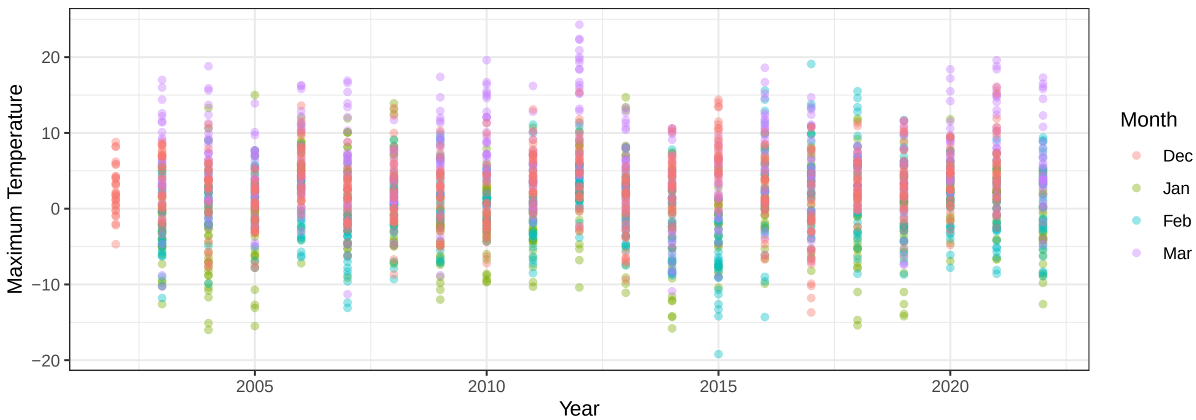

Figure 1: Temperature 2002 to 2022 for December to March

Figure 1 shows an increasing pattern for the maximum temperature from year 2002 to 2022 from December to March. Temperatures in March continue to be increasingly higher than any of the other months in this plot. It is noticeable that the temperatures for all months are the highest in 2012. According to NASA, the average temperatures in 2012 was warmer than the mid-20th century baseline and is considered to be an outlying of seasonal extremes that are warmer. Even the lowest maximum temperature in January is higher than other years in 2012. The plot shows that the average maximum temperature from December to March has been between -19.2 degrees Celsius in February of 2015 and 24.3 degrees Celsius in March of 2012.

Figure 2 shows an increasing pattern for the maximum temperature from year 2002 to 2022 from April to July. Temperatures in July are consistently higher throughout the years than any of the other months in the plot and temperatures in April are consistently lower throughout the years than any of the other months. There are some years where June has the highest temperature. The plot shows that the average maximum temperature from April to May has been between -2.4 degrees Celsius in April of 2003 and 38.2 degrees Celsius in July of 2011.

Figure 3 shows an increasing pattern for the maximum temperature from year 2002 to 2022 from August to November. Temperatures in both August and September are the highest

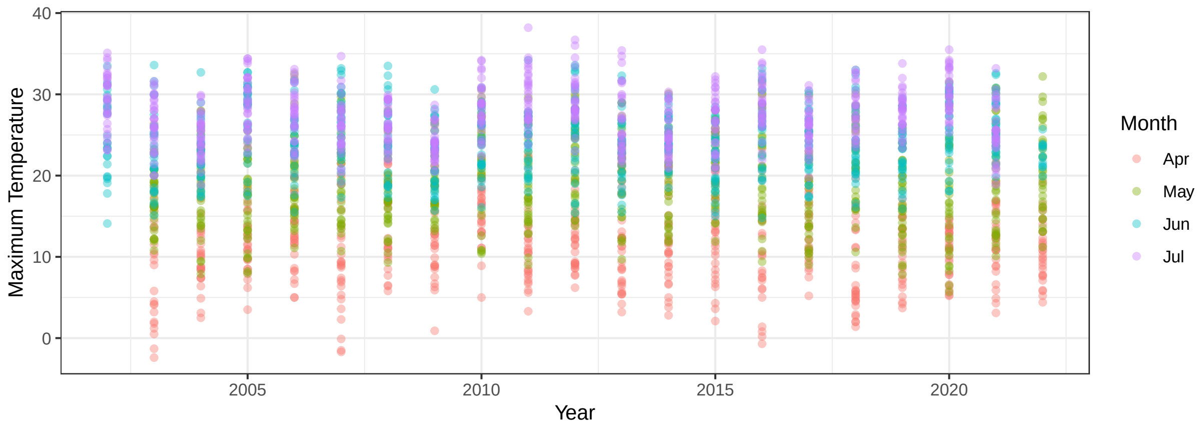

Figure 2: Temperature 2002 to 2022 for April to July

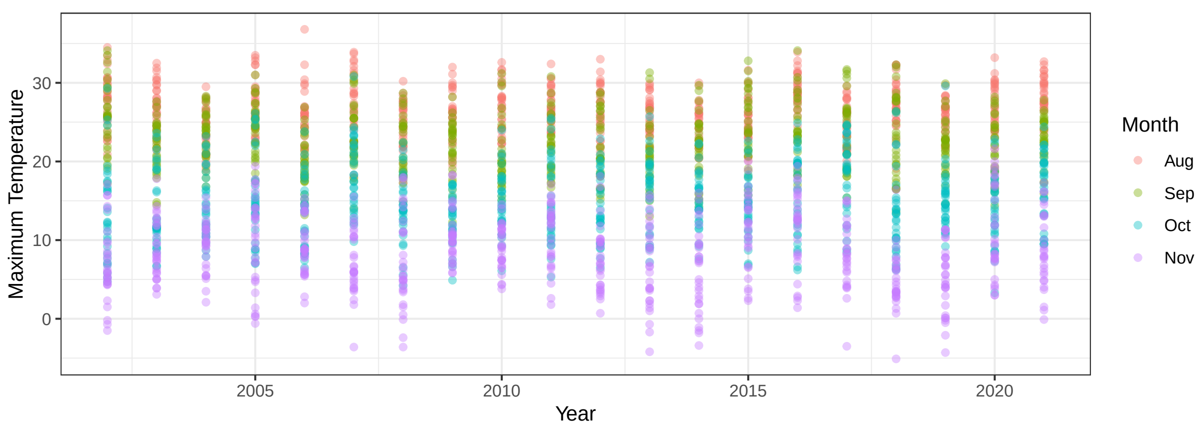

Figure 3: Temperature 2002 to 2022 for August to November

throughout the years compared to November and October. Temperatures in November are consistently the lowest throughout the years compared to the other months. There are a few high temperatures in October throughout the years as well and this is typically seen when the August and September have some of the highest temperatures compared to other years. The plot shows that the average maximum temperature from April to May has been between -5.1 degrees Celsius in November of 2018 and 36.8 degrees Celsius in August of 2006.

Visualizing Pollution from 2002-202

I'm interested in finding the trends of the mean pollution levels from 2002 to 2020 by year.

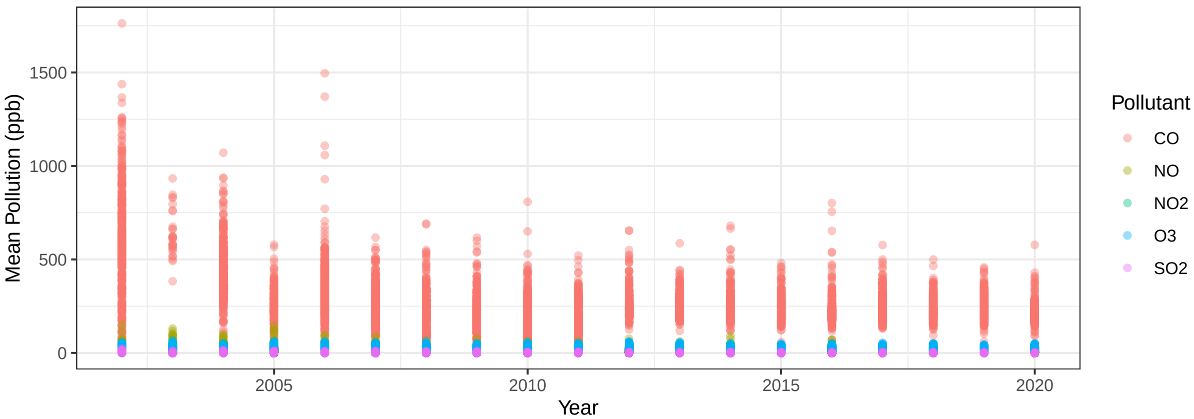

Figure 4: Mean Pollution 2002 to 2020 for NO, NO2, O3, SO2 and CO by Year

Figure 4 shows a decreasing pattern for the mean pollution from year 2002 to 2020 for NO by year. We can notice that O3 and SO2 levels remain mostly the same throughout the years. The highest levels of pollution are as follows: 150.3 ppb for NO in 2002, 65 ppb for NO2 in 2005, 65.95833 ppb for O3 in 2003, and 22.79167 ppb for SO2 in 2002. There is also a decreasing pattern for the mean pollution from year 2002 to 2020 for CO by year. The highest level of pollution for CO is 1762.5 ppb in 2002. We can notice that there is a drop in the pollution levels from 2003 to 2005 but it rises again in 2006. Looking back at figure 3, this was the same year some of the highest temperatures were recorded from August to November.

Figure 5 suggests that the highest levels of CO are during winter and the colder months. This might be due to the fact that heaters are used the most in this time and do emit carbon monoxide. This plot does not tell us much else about the other pollutants due so from here we will take a look at each pollutant and how it has behaved from 2002 to 2020 by year and month.

Visualizing NO (Nitric Oxide)

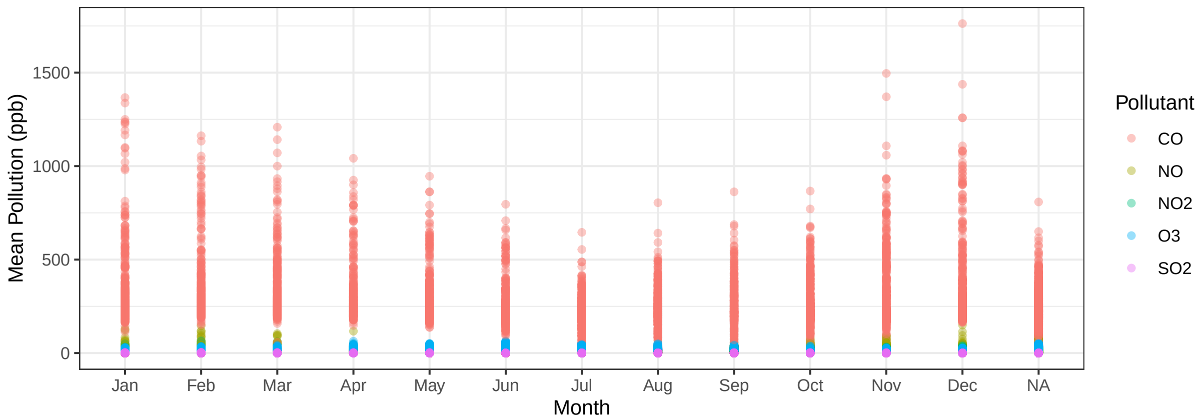

Figure 5: Mean Pollution 2002 to 2020 for NO, NO2, O3, SO2 and CO by Month

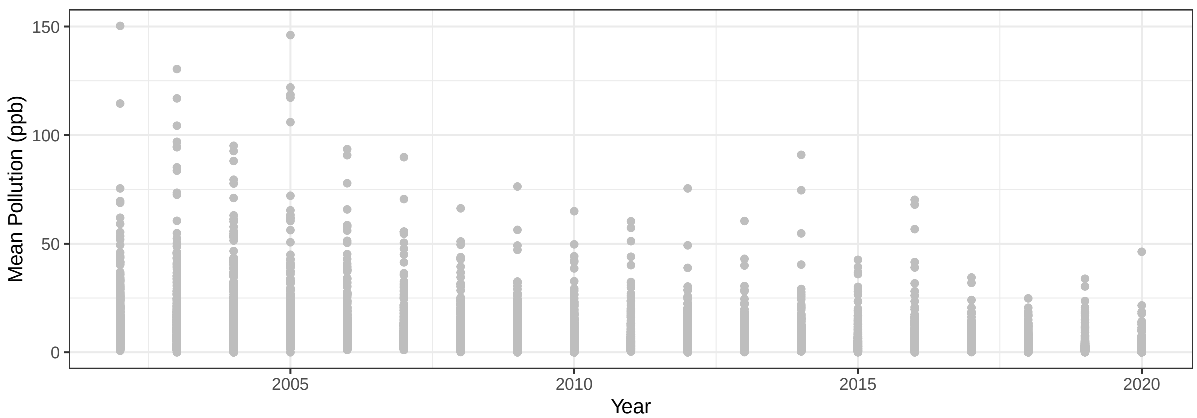

Figure 6: Mean Pollution 2002 to 2020 for NO by Year

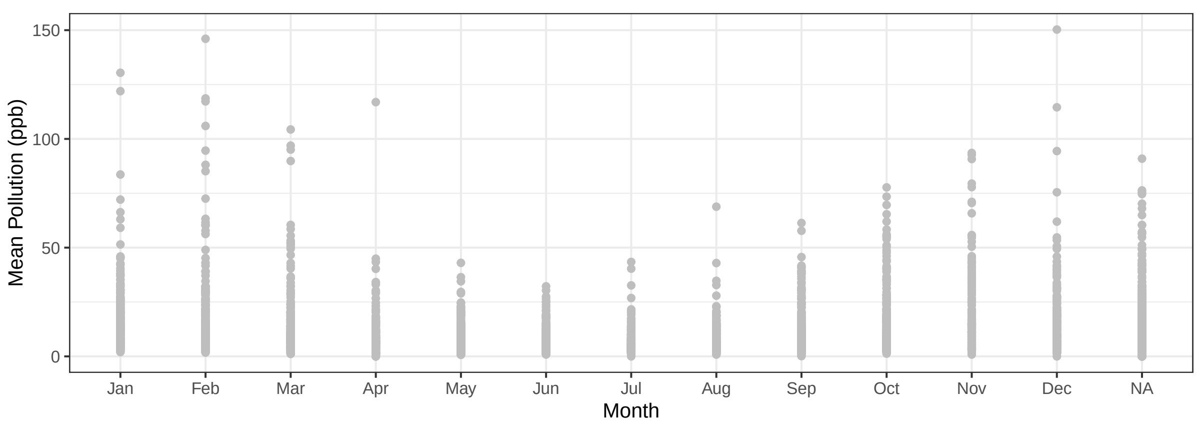

Figure 7: Mean Pollution 2002 to 2020 for NO by Month

Figure 6 shows a decreasing trend from 2002 to 2020 of the level of nitric oxide in the air. The highest level of pollution was in 2002 where the level was 150.2917 ppb. Figure 7 shows that in the colder months the levels of NO in the air are much higher than in the warmer months. The highest level in 2020 was around 49 ppb, a drastic drop from 2002. The highest level that was mentioned previously was seen in the month of December. However, it looks like on average the level of pollution for winter months is around 80 ppb. There are only some points that show high levels for the winter months.

Visualizing NO2 (Nitrogen Dioxide)

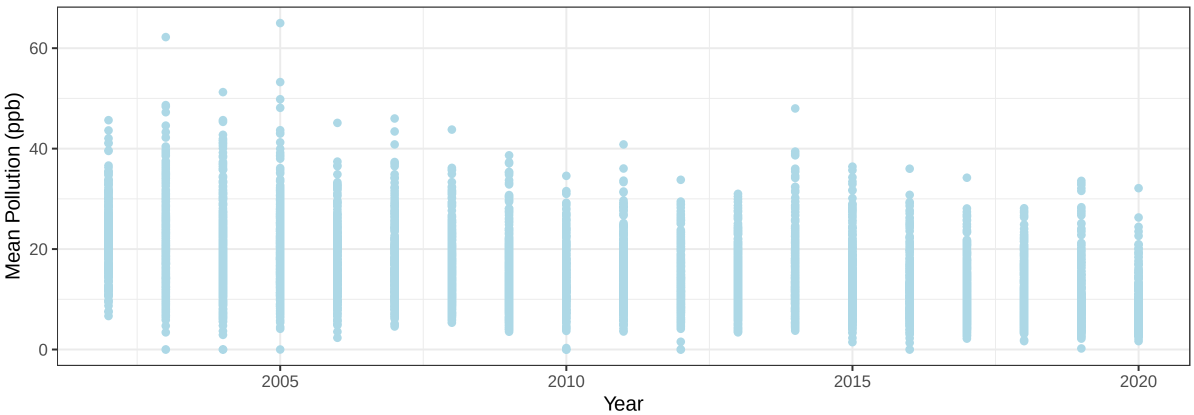

Figure 8: Mean Pollution 2002 to 2020 for NO2 by Year

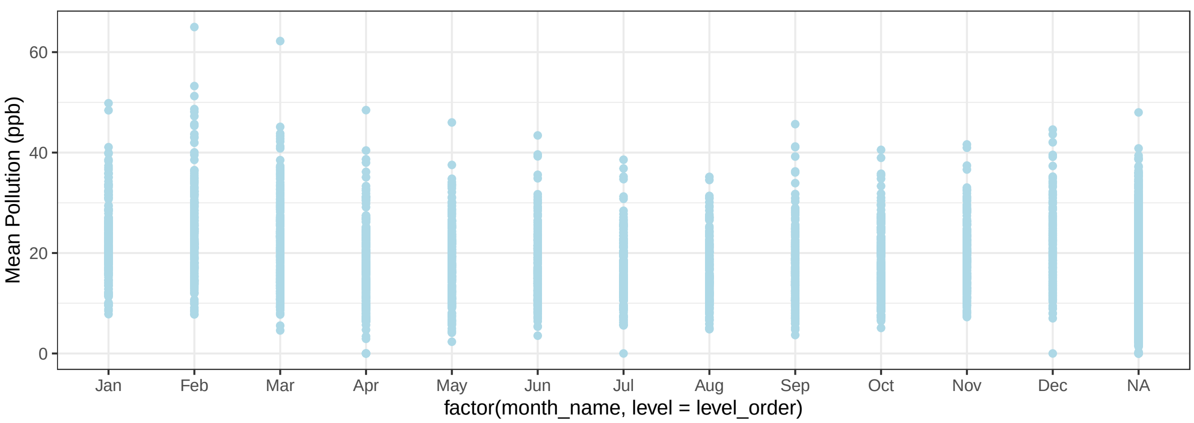

Figure 9: Mean Pollution 2002 to 2020 for NO2 by Month

Figure 8 shows the mean pollution for NO2 has been consistently decreasing from 2002 to 2020. The highest value was seen in 2005 where the level was 65 ppb.The highest level in 2020 was around 31 ppb. There are some years between 2002 and 2020 where the level increases again in 2011 and 2014. The mean levels of pollution by month in figure 9 appear to have higher levels in the winter months than in the summer months, but not by a lot. The average levels are around 40 ppb for most months.

Visualizing O3 (Ozone)

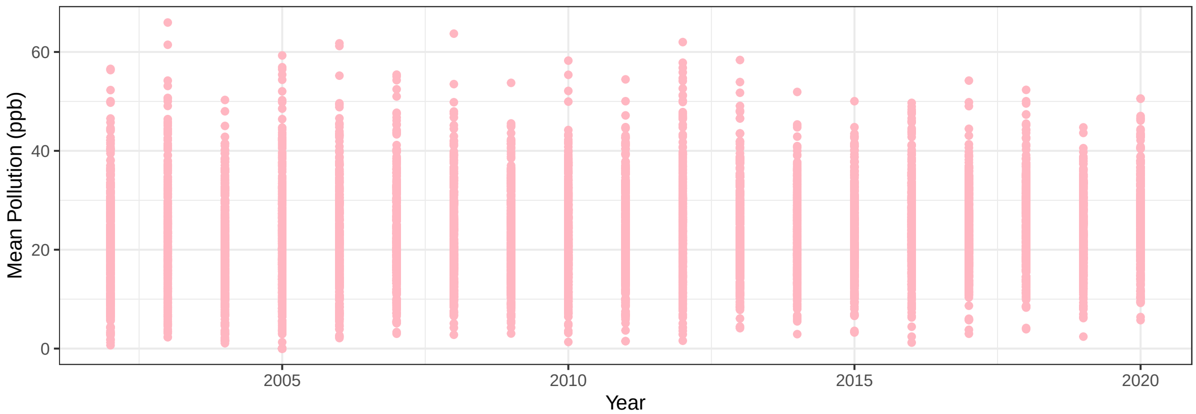

Figure 10: Mean Pollution 2002 to 2020 for O3 by Year

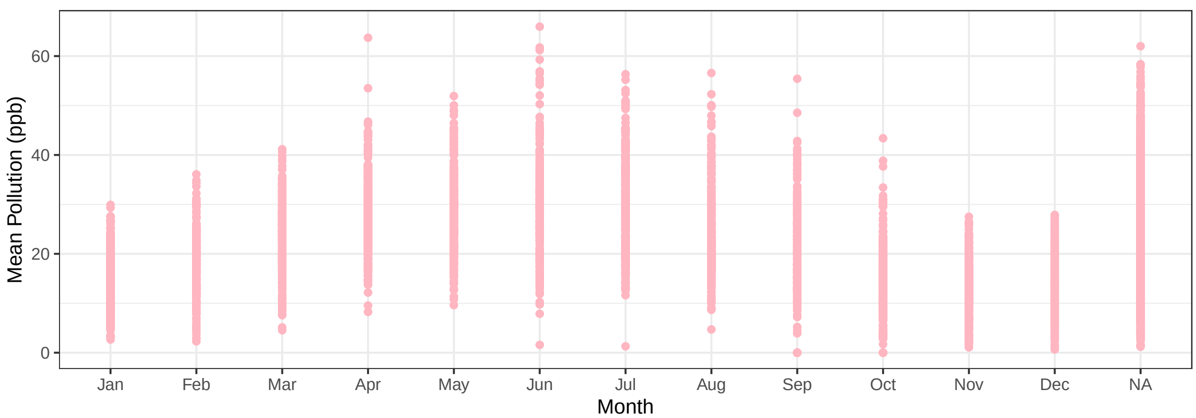

Figure 11: Mean Pollution 2002 to 2020 for O3 by Month

In figure 10, we can see that the mean pollution levels for ozone do not change much from 2002 to 2020. There is a slight decrease from the earlier years to the more recent years but not much. The highest level of CO was in 2003 with 65.95 ppb. In 2006, 2008, and 2012 the levels were also higher than 60 ppb. The average high levels are around 50 pb and that does not change from 2002 to 2020. This suggests that the level of ozone in our air has not been getting better and continues to affect our air and health. In figure 11, the hotter months for O3 have higher levels of pollution than the winter months. This suggests that ozone has a relationship with the high levels of temperature and that may be why the levels of pollution have not decreased since 2002, as our average global temperatures also keep rising. The highest value of 65.95 ppb was seen in June.

Visualizing CO (Carbon Monoxide)

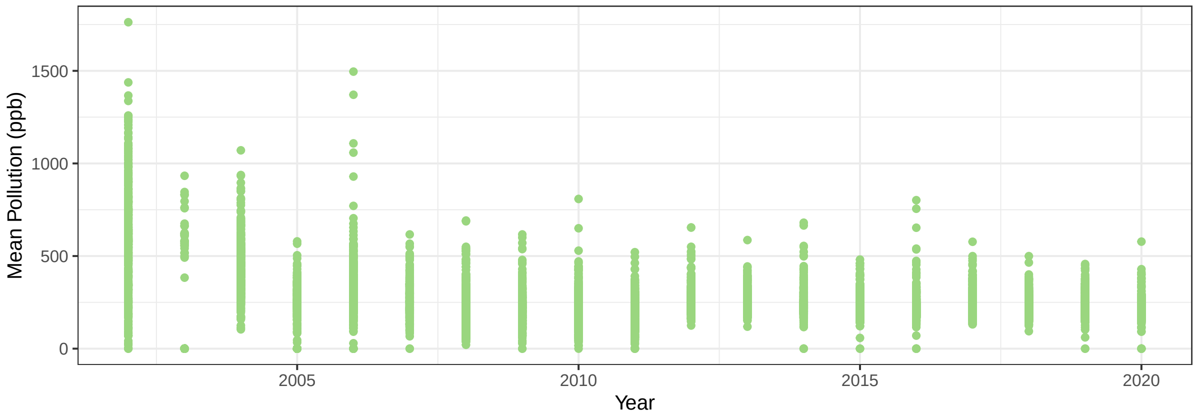

Figure 12: Mean Pollution 2002 to 2020 for CO by Year

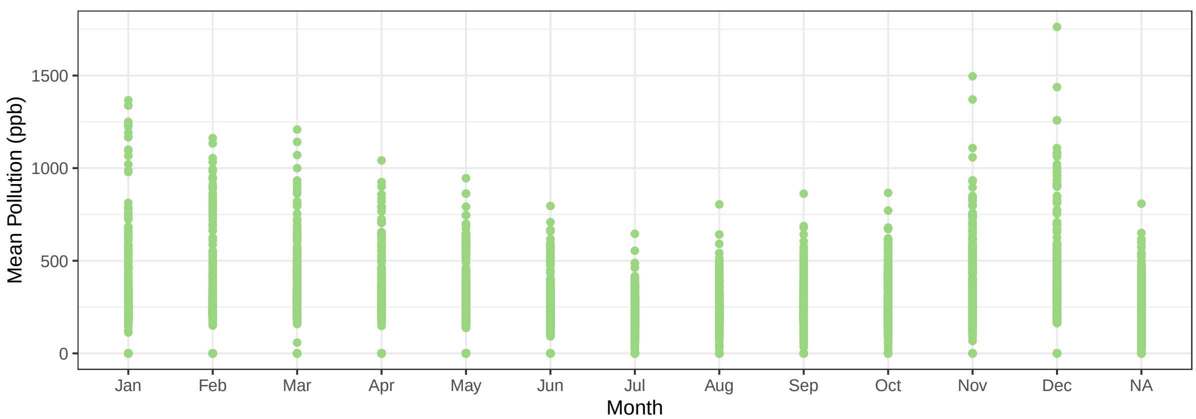

Figure 13: Mean Pollution 2002 to 2020 for CO by Month

Carbon monoxide is a product of incomplete combustion of hydrocarbon-based fuels. In figure 12 and 13 we see a similar pattern as NO and NO2 where the level of pollution is decreasing throughout the years from 2002 to 2020 and the highest levels are in the winter months. The highest level of pollution for CO was seen in 2002 with 1762.5 ppb. This level is much higher than any of the other pollutants. This suggests that carbon monoxide levels are much more widespread than any of the other pollutants we have analyzed and due to this can have a affect on our health. Even with the decreasing levels, the affects will still be dangerous. The highest level in 2020 was around 550 ppb which is almost 5 times higher than the levels of NO, NO2, and O3 in 2020.

Visualizing SO2 (Sulfur Dioxide)

In figure 14, there is a decreasing pattern for the level of SO2 in the air from 2002 to 2020.

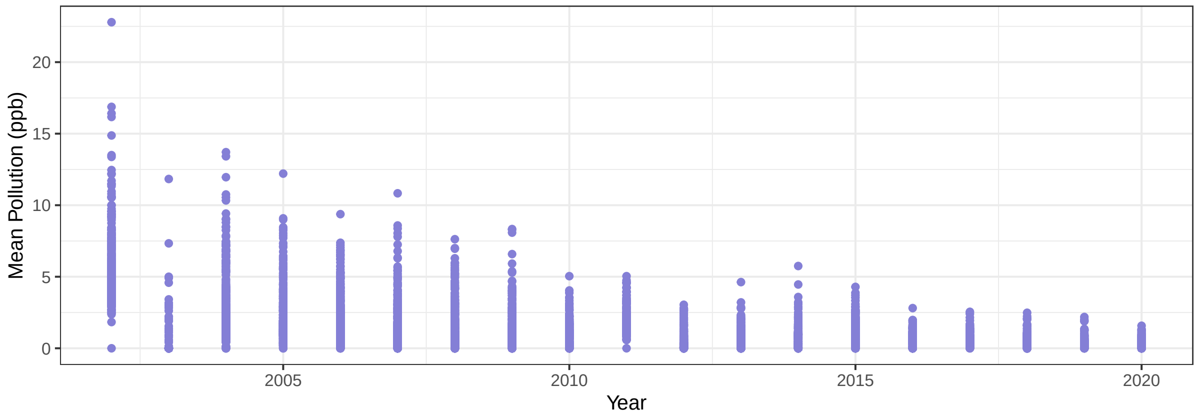

Figure 14: Mean Pollution 2002 to 2020 for SO2 by Year

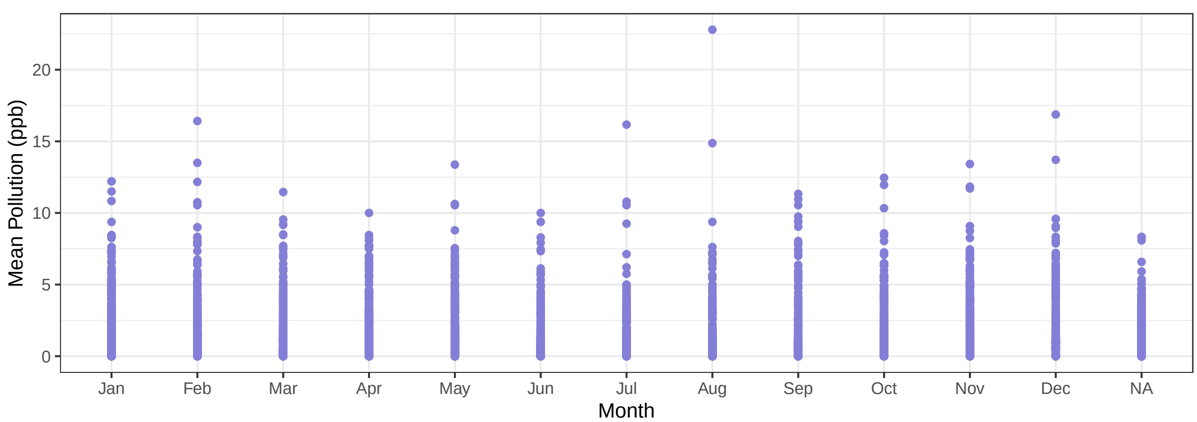

Figure 15: Mean Pollution 2002 to 2020 for NO by Month

The highest level in 2002 was 22.79 ppb and the highest level in 2020 seems to be less than 3 ppb. This is a drastic drop and suggests that the level of SO2 in the air is not affected by the increasing temperatures. In figure 15 we also see this. The levels of SO2 in the air remain consistent throughout the months and there is no difference between the winter and summer months.

Visualizing Pollution and Temperature from 2002-2020

Visualizing Mean Pollution by Temperature and Pollutant

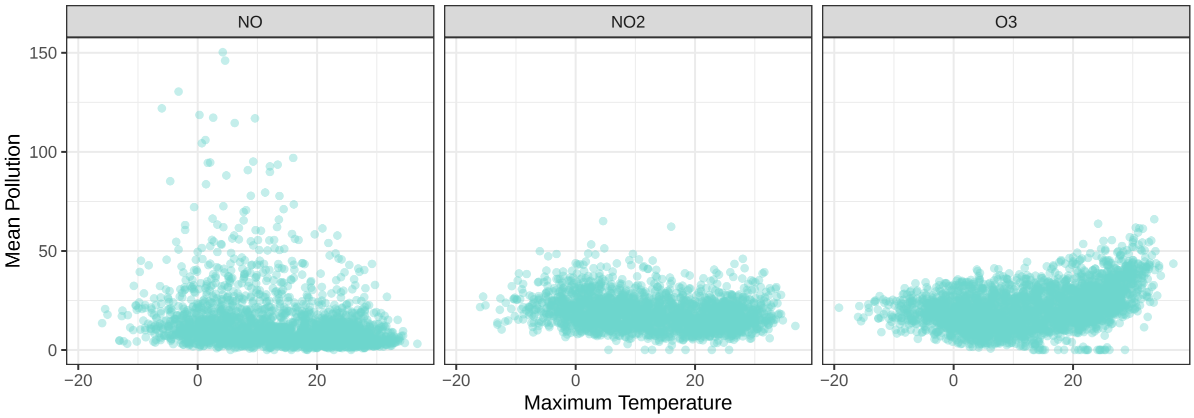

Figure 16: Mean Pollution 2002 to 2020 for NO, NO2, O3 and SO2 by Maximum Temperature and Pollutant for December to March

In figure 16,

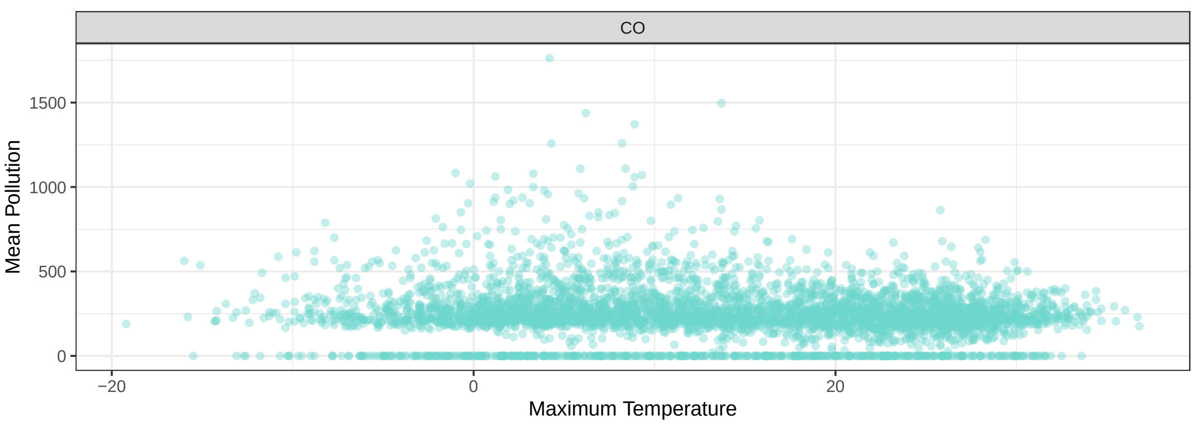

Figure 17: Mean Pollution 2002 to 2020 for CO by Maximum Temperature and Pollutant for December to March

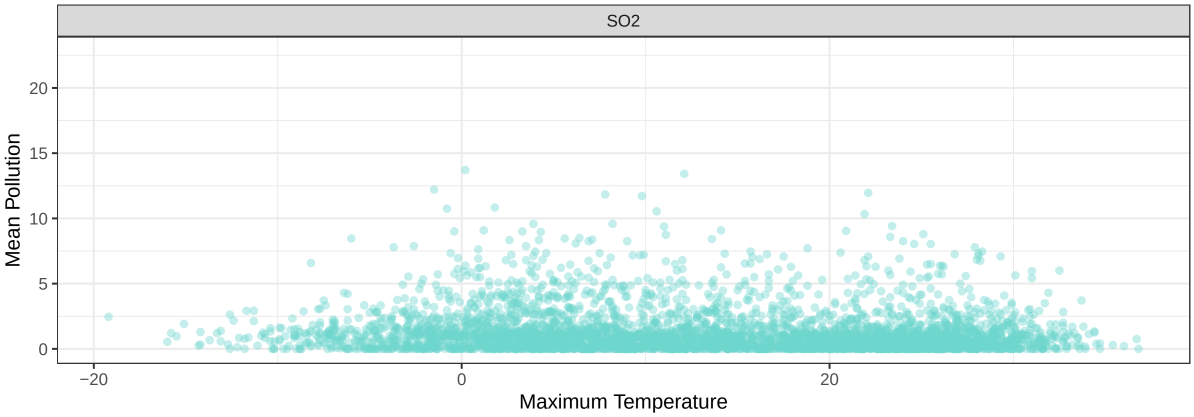

Figure 18: Mean Pollution 2002 to 2020 for NO, NO2, O3 and SO2 by Maximum Temperature and Pollutant for April to July

```
Call:
lm(formula = mean_pollution ~ max_temp, data = pollu_temp)

Residuals:
    Min      1Q  Median      3Q     Max 
 -86.65  -74.25  -63.06  -28.29 1681.70 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)    
(Intercept)  82.0493     1.6927  48.473  < 2e-16 ***
max_temp     -0.2965     0.0984  -3.014  0.00259 ** 
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 135.6 on 15933 degrees of freedom
  (1598 observations deleted due to missingness)
Multiple R-squared:  0.0005697, Adjusted R-squared:  0.0005069 
F-statistic: 9.082 on 1 and 15933 DF,  p-value: 0.002586


Call:
lm(formula = mean_pollution ~ max_temp + min_temp + mean_temp, 
    data = pollu_temp)

Residuals:
    Min      1Q  Median      3Q     Max 
 -91.85  -74.06  -63.01  -27.29 1677.69 
```

```
Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)   78.654      2.903  27.090   <2e-16 ***
max_temp     -45.867     18.927  -2.423   0.0154 *
min_temp     -46.606     19.010  -2.452   0.0142 *
mean_temp     91.978     37.870   2.429   0.0152 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 135.6 on 15931 degrees of freedom
  (1598 observations deleted due to missingness)
Multiple R-squared:  0.001021,  Adjusted R-squared:  0.0008328
F-statistic: 5.427 on 3 and 15931 DF,  p-value: 0.0009968
```

Limitations

In this limitations section, I will focus on the data used and look into why it is not easy to take the implications mentioned above directly.

Missing Pollution Data from 2021-2022

Results and Discussion

Temperature

Toronto will continue to experience warmer climate in the long-term due to climate change (*Future Climate*, n.d.). Toronto will have more extreme hot days where the temperature will be above 30 degrees celcius and less extreme cold days where the temperature will be below -20 degrees celcius (*Future Climate*, n.d.). By 2100, Toronto is expected to have warmed by 5 degrees celcius (*Future Climate*, n.d.). These warmer temperatures have significant impacts on the health and well-being of Toronto residents. If carbon emissions continue and no changes are put in place now, the maximum average annual temperatures are expected to be: 12-14 degrees celcius by 2040, 14-16 degrees celcius by 2070, and 16-18 degrees celcius by 2100 (*Future Climate*, n.d.). With more extreme heat days, Toronto will experience a greater demand for cooling which will increase the use of air conditioning causing a strain on electrical supply. These increases can be seen in figures 1, 2 and 3. In these we saw an increase in average temperatures for the Fall, Winter and Summer months.

Pollution

Air pollution continues to affect Canadians. Smog in the air, which is a mixture of smoke and fog, contains O3, SO2, and NO. Air pollutants like these are influenced by many factors including air temperature. Canada's population and economy continues to grow thus increasing the demand for production and delivery. This means more energy will be used to meet these demands and most of this energy will come from fossil fuels which will impact the quality of the air.

From the analysis of NO, NO2, CO and SO2 we saw that there was a decline in the mean pollution levels of those pollutants. This is due to implementation of regulations and technological improvements for transportation vehicles and industrial processes. Canadians using more environmentally sustainable practices like public transport and carpooling have contributed to the decrease of lower pollution levels.

NO2 is usually formed through the burning of fossil fuels, transportation services, energy production and industrial processes (*CCME: Air Quality Report* 2019). Nitrogen dioxide at higher concentration levels has a strong and harsh odor and can be seen over large cities as a brownish haze (*CCME: Air Quality Report* 2019). NO2 can combine with H2O and form nitric acid and nitrous acid. This falls to earth through precipitation like rain, snow, and fog, and contributed to acidification and eutrophication of ecosystems (*CCME: Air Quality Report* 2019).

SO2 emissions come from natural sources like volcanoes and forest fires but these emissions are small compared to those from industrial sources (*CCME: Air Quality Report* 2019). Environment Canada accounted for 1 million tonnes of man-made SO2 emissions compared to 100 tonnes of natural SO2 emissions in 2022. SO2 is seen in acid rain and due to this early recognition policies were put in place that have reduced SO2 pollution in recent decades as seen in figure 14.

Table 3: Mean Pollution Levels of Each Pollutant

Pollutant	Mean Pollution Level
NO	13.60
NO2	14.97
O3	22.99
SO2	1.23
CO	254.43

Table 4: Mean Pollution Levels of Each Pollutant by 5-Year Intervals

Pollutant	Mean Pollution Level	5-Year Interval
NO	15.05	2002 to 2006
NO	8.57	2007 to 2011
NO	5.85	2012 to 2016
NO	3.25	2017 to 2020
NO2	19.88	2002 to 2006
NO2	15.57	2007 to 2011
NO2	13.40	2012 to 2016
NO2	10.10	2017 to 2020
O3	20.95	2002 to 2006
O3	22.55	2007 to 2011
O3	23.97	2012 to 2016
O3	24.86	2017 to 2020
SO2	2.48	2002 to 2006
SO2	1.28	2007 to 2011
SO2	0.68	2012 to 2016
SO2	0.32	2017 to 2020
CO	314.10	2002 to 2006
CO	223.65	2007 to 2011
CO	244.83	2012 to 2016
CO	230.33	2017 to 2020

Temperature and Pollution

Temperature and Health

Pollution and Health

Exposure to air pollution is known as a major cause to illnesses and death.

Exposure to NO (Nitric Oxide) can irritate the lungs, reduce lung function and increase vulnerability to allergens for those with asthma (*CCME: Air Quality Report* 2019). Nitric Oxide is seen in smog and can react with other substances to harm human health.

O3 (Ozone) is the main component of smog and has been associated with eye, nose, and throat irritations (*CCME: Air Quality Report* 2019). Ozone also causes shortness of breath, aggravation of respiratory conditions and allergies, chronic obstructive pulmonary disease and asthma (*CCME: Air Quality Report* 2019). Increased risk of cardiovascular disease is a result of exposure to O3 as well and all of these symptoms affect the young and the elderly that live near cities and/or with acute illnesses (*CCME: Air Quality Report* 2019).

Carbon monoxide can significantly impact human health by entering the blood stream through the lungs and therefore inhibiting the blood's capacity to carry oxygen to organs and tissues (*Air Pollution: Drivers and Impacts* 2022). CO is harmful to those with heart disease and those with respiratory conditions. It also affects healthy individuals by reducing their exercise capacity, visual perception, manual dexterity, learning functions, and ability to perform complex tasks (*Air Pollution: Drivers and Impacts* 2022).

SO2 (Sulfur Dioxide) can harm human respiratory systems by triggering respiratory illness and worsening existing respiratory and cardiovascular diseases (Read 2016). Sulfur dioxide is seen in smog and can react with other substances like nitric oxide to harm human health (*Sulphur Oxides Emissions* 2019). When SO2 transforms into sulfate particles and combines with other particles in the atmosphere it can contribute to the formation of particulate matter (PM2.5) which harms human health as well as the environment (*Sulphur Oxides Emissions* 2019). Sensitive populations such as children, the elderly, those with asthma are more susceptible to the affects of SO2 (Read 2016).

NO2 (Nitrogen Dioxide) has consequences on human health including emergency hospitalizations for respiratory conditions for adults that live in lower income communities in Toronto [@citestatscan]. Children are more vulnerable to these effects of respiratory damage [@citestatscan]. Children that have been exposed to NO2 have an increased risk of asthma, wheezing, infections in the ear, nose and throat, influenza, serious colds, and reduced lung function [@citestatscan].

Temperature, Pollution and Health

Next Steps

Following on from the previous section, we can make good suggestions on ways to improve the data so that the findings will be less ambiguous and more ethical to use with confidence. First off, we can start by collecting pollution data from 2021 to 2022. It is possible that this data is available but not published yet on the website. In doing this, the data scientist who gets a hold of the data will have the liberty to conduct their analysis with the full data sets for temperature and pollution for 20 years. This will not only ease the job of the data scientist but will also improve the reproducibility of their workflow and finding.

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