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Daily changes in ambient air pollution concentrations and temperature and suicide mortality in Canada: Findings from a national time-stratified case-crossover study

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ABSTRACT

Introduction: Worldwide, approximately 1900 people die by suicide daily. Daily elevations in air pollution and temperature have previously been linked to a higher risk of death from suicide. To date, there have been relatively few studies of air pollution and suicide, particularly at a national level. National analyses play an important role in shaping health policy to mitigate against adverse health outcomes.
Methods: We used a time-stratified case-crossover study design to investigate the influence of short-term (i.e., day to day) interquartile range (IQR) increases in air pollutants (nitrogen dioxide [NO_2], ozone [O_3], and fine particulate matter [$PM_{2.5}$]) and temperature on suicide mortality in Canada between 2002 and 2015. For air pollution models, odds ratios (ORs) derived from conditional logistic regression models were adjusted for average daily temperature, and holidays. For temperature models, ORs were adjusted for holidays. Stratified analyses were undertaken by suicide type (non-violent and violent), sex, age, and season.
Results: Analyses are based on 50,800 suicide deaths. Overall, temperature effects were stronger than those for air pollution. A same day IQR increase in temperature (9.6 °C) was associated with a 10.1% increase (95% confidence interval (CI): 9.0%–11.2%) of death from suicide. For 3-day average increase of O_3 (IQR = 14.1 ppb), $PM_{2.5}$ (IQR = 5.6 μg/m^3) and NO_2 (IQR = 9.7 ppb) the corresponding risks were 4.7% (95% CI: 3.9, 5.6), 3.4% (95% CI: 3.0, 3.8), and 2.0% (95% CI: 1.1, 2.8), respectively. All pollutants showed stronger associations with suicide during the warmer season (April–September). Stratified analyses revealed stronger associations for both temperature and air pollution in women.
Conclusions: Daily increases in air pollution and temperature were found to increase the risk of death from suicide. Females, particularly during warmer season, were most vulnerable to these exposures. Policy decisions related to air pollution and climate change should consider effects on mental health.

1. Introduction

Suicide is an important public health concern worldwide as approximately 700,000 people die due to suicide every year, and it is the fourth leading cause of death among 15–19 years old (World Health Organization, 2021). In 2019, approximately three out of every four suicide deaths (77%) occurred in low- and middle-income countries (World Health Organization, 2021). In Canada, about 10 people die daily due to suicide, and 70% of suicide deaths among those 15 years of age or older occur among men (Public Health Agency of Canada, 2021). Given the psychological burden associated with each suicide death coupled with the knowledge that many suicides are preventable with

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timely interventions, suicide prevention should be prioritized (World Health Organization, 2021; Public Health Agency of Canada, 2021).

Although age, sex, gender, poverty, and in Canada, Indigenous status, have been identified as risk factors for suicide (World Health Organization, 2021; Public Health Agency of Canada, 2021), mental disorders have also been identified as a key factors (Harris and Barraclough, 1997). There are complex connections between demographic, biological, psychological, environmental factors, and suicide. There is increasing evidence that environmental factors, such as air pollution and temperature, contribute to higher rates of mental illness and suicide (Braithwaite et al., 2019; Ng et al., 2016; Ragguett et al., 2017; Kim et al., 2016; Lin et al., 2016; Casas et al., 2017; Astudillo-García et al., 2019; Szyszkowicz et al., 2010; Bakian et al., 2015; Heo et al., 2021; Frangione et al., 2022). Most studies evaluating the association between ambient temperature and suicide have been conducted in East Asian countries, and few of these studies have addressed the possible effects of air pollutants (Heo et al., 2021). Positive associations between air pollution and suicide have been noted in some studies, and these findings have typically observed associations with nitrogen dioxide (NO_2) and particulate matter (PM_{10}) exposures in the two days that preceded death (Lin et al., 2016; Szyszkowicz et al., 2010; Kim et al., 2018). Similarly, increases in PM_{10} and ozone (O_3) were positively associated with suicide with age and seasonal differences (Casas et al., 2017). In contrast, Astudillo-García et al. (2019) found no associations between air pollution (fine particulate matter [$PM_{2.5}$], PM_{10}, O_3, NO_2, and sulfur dioxide [SO_2]) and suicide deaths in Mexico City. It has been suggested that previously reported associations between air pollution and suicide may be biased by selection bias, participation bias, and the inability to account for day of week, and holiday effects (Afshari, 2017).

There are compelling pathways whereby exposure air pollution contribute to an increased risk of suicide events. Air pollution is recognized to cause oxidative stress, and may promote brain neuroinflammation and dysregulation, including alterations in the functioning of the hypothalamic-pituitary-adrenal axis, which has been associated with depression, aggressive behaviours, and suicide (Heo et al., 2021; Yang et al., 2019). Biological brain response to air pollutants likely differ by age, and oxidative stress impacts seems to be stronger in females and to contribute to depressive disorders in adults (Guo et al., 2014; Thomson, 2019). In addition, exposure to high temperatures has been related to an imbalance of serotonin and neuroinflammation in the brain, which have been associated with higher levels of aggression, and suicidal risk (Cianconi et al., 2020; Bushman et al., 2005; Hill et al., 2020).

There have been relatively few studies that have investigated associations between short term increases in air pollution (i.e., day to day) suicide using national data (Heo et al., 2021). A national mortality study of deaths in Korea between 2004 and 2017 found that daily increases in PM_{10} increased the risk of suicide among those with major depressive disorder (Hwang et al., 2022). While national analysis of temperature and suicide risk for Canada have been reported (for deaths between 1986 and 2015) (Yu et al., 2020), there have been no national analyses done with air pollution. Indeed, the existing evidence for air pollution and suicide has been drawn largely from studies done at a regional level. Large-scale studies that cover multiple jurisdictions within a country are helpful to increase the statistical power, and produce findings that are more generalizable which can strengthen the implementation of national policies to reduce harm. Moreover, as most countries regulate air pollution concentrations using national standards, analyses of national data are well-suited to inform these regulations.

Air pollution and ambient temperature are closely related, and both are highly affected by climate change (Anenberg et al., 2020). With respect to temperature, previous work has provided compelling evidence that higher daily temperatures increase the risk of suicide (Kim et al., 2016, 2019; Frangione et al., 2022). Moreover, short-term increases in ambient temperature have been associated with annual rhythms in violent suicide rates in Belgium (Maes et al., 1994). There is evidence supporting that high temperatures affect the capacity of the nervous system to regulate levels of anxiety, agitation, and mood (Fernandez-Arteaga et al., 2016), and potential biological mechanism might include differences in cerebral blood flow, neurological function, and oxygen consumption under hyperthermic conditions (Liu et al., 2013; Lohmus, 2018).

With respect to recent Canadian analyses of air pollution and suicide, a previous study in Vancouver reported associations between carbon monoxide, NO_2, SO_2, and PM_{10} and emergency department visits for suicide during colder periods (Szyszkowicz et al., 2010). While multiple attempts to die by suicide precede death, associations between air pollution and suicide attempts may not necessarily be generalizable to the association with suicide deaths.

Given that suicide is a leading cause of death worldwide, the contribution of environmental factors on mental health, and the adverse effect of extreme changes in temperature and air pollution on health outcomes related to climate change, it is very important to understand the degree of association between air pollution, temperature, and suicide deaths. Thus, we conducted a time-stratified case-crossover study design to evaluate how short-term increases in air pollutants and ambient temperature affect suicide deaths from 2002 to 2015 in Canada. We also sought to evaluate factors that modify these associations by conducting stratified analyses by sex, age group, type of suicide death, and season.

2. Methods

2.1. Study design

We used a time-stratified case-crossover study design to investigate whether daily increases in air pollutants (e.g. NO_2, O_3, $PM_{2.5}$) and average daily temperature are associated with death by suicide in Canada from 2002 to 2015. This study design has been used extensively to evaluate the health risks posed by day to day increases in air pollution, and has previously been used to evaluate associations with suicide (Kim et al., 2016, 2018; Lin et al., 2016; Casas et al., 2017). A key strength of this study design is that individuals serve as their own controls, and therefore the design controls for underlying health conditions, and behavioral risk factors that are unlikely to change on a short time scale. This feature of the case-crossover design is achieved by comparing the individual's exposure on the event date to the exposure for the same individual during control periods. Accordingly, the influences of short-term time-invariant variables (e.g. age, sex, etc.) on measures of association are controlled for by this study design. While there are many methods to select control periods, we chose the time stratified bi-directional approach. With this approach 3 to 4 control dates that correspond to the same day of the week within the same month as the suicide date are selected. This approach to the selection of control intervals has been shown to control for day of week and seasonal effects and performs better than other approaches to select control intervals (Janes et al., 2005).

2.2. Study population

We identified deaths from suicide using the Canadian Vital Statistics Death Database (CVSD). The CVSD is a census of all deaths that occur in Canada each year and contains individual-level demographic (e.g. age, sex, 6-digit residential postal code) and medical (e.g. underlying cause of death) information for all deaths occurring in Canada. The CVSD maintains an edit error rate of less than 3% (Statistics Canada, 2020). For this study, national suicide data for calendar years 2002–2015 were identified by the X60-X84 (intentional self-harm) International Classification of Disease 10 codes (ICD-10-CA) as the underlying cause of death. We further classified these suicide deaths into non-violent (ICD-10-CA: X60-X69) and violent (ICD-10-CA: X70-X84) types. Non-violent deaths include intentional self-poisoning with a variety of substances, and violent deaths include intentional self-harm using a variety of physical mechanisms.

2.3. Air pollution and meteorology data

Daily mean values of ambient concentrations of NO_2, O_3, and $PM_{2.5}$ were assigned to residential postal codes at the time of death based on air pollution concentrations obtained the nearest fixed-site air pollution monitoring station. We used hourly concentrations pollution levels to estimate a daily mean concentration for days where there were at 18 h of pollution data obtained from the National Air Pollution Surveillance Program (NAPS) managed by Environment and Climate Change Canada (ECCC) (Environment Climate Change Canada, 2019). The NAPS program includes 260 monitoring stations in 150 rural and urban communities across the country (EnvironmentClimate Change Canada, 2009). We also obtained estimates of average daily temperature, precipitation and relative humidity. Specifically, average daily temperature and precipitation were calculated as interpolated metrics available for all postal code locations using thin-plate smoothing splines implemented in the ANUSPLIN climate modeling software (McKenney et al., 2011; Customized spatial climate data files, 2017). Average daily relative humidity was assigned to each suicide death using data from the closest weather station (Environment Climate Change Canada, 2022). With the exception of relative humidity data obtained from ECCC, all air pollution and other meteorology data for the date of the suicide death, up to 2 days of single lag days prior to the suicide death were obtained from the Canadian Urban Environmental Health Research Consortium (CANUE) at postal codes level (CanMap Postal Code Suite v2015, 2015).

Ethics approval for the study was provided by Carleton University Research Ethics Board (Clearance #: 111372).

2.4. Statistical analysis

We calculated summary statistics by air pollutant, temperature, type of suicide and demographic characteristics for suicide deaths for the calendar years of 2002–2015, inclusively. The average weekly number of violent and non-violent suicide deaths was calculated to describe trends over the 14 year study period. We used conditional logistic regression to estimate the odds ratios (OR) and the corresponding 95% confidence intervals (95% CI) of suicide deaths in relation to interquartile range (IQR) increases of NO_2, O_3, $PM_{2.5}$ and temperature. We used the IQR for comparing effect measures of different exposures and between temperature and air pollution measurements. We used weights for the conditional model derived from the number of suicides deaths (cases) per day. As public holidays may influence the occurrence of mental health conditions (Houser et al., 2020) and traffic pollution levels, an indicator variable for holidays was added as an adjustment factor in our models. Furthermore, as temperature has been identified as a risk factor for suicide (Kim et al., 2016), we adjusted our air pollution risk estimates for daily temperature. We modeled temperature as linear and natural cubic splines (with 3 knots at the 25th, 50th, and 75th percentiles). However, as the risk estimates and the Akaike Information Criteria (AIC) were similar (differences $<$10% for all deaths models), temperature was included as a linear term in our models. We also explored how timing of exposure impacts these associations by performing lag day analyses up to 2 days prior to a suicide. For these lag day models, single day lags (0, 1 and 2), 2-day (01 lag) and, and 3-day (02 lag) moving average values were used for all exposure and adjustment factors. However, holidays were excluded as an adjustment factor for 01 and 02 lag day analyses, as the average of a categorical variable cannot be meaningfully calculated. In addition, we conducted a two-steps analysis for assessing heterogeneity of estimates across the 12 Census Metropolitan Areas (CMA) with 500 or more suicide deaths during the study period. In the first step we ran models as described before for each CMA and in the second step we conducted a random effects meta-analysis to obtained pooled estimates and heterogeneity measures. We also ran two-pollutants models for the association of pollutants and suicide deaths.

We estimated temperature effects on suicide deaths using models adjusted only by holidays with no adjustment for air pollutants because based on directed acyclic graphs (DAGs) air pollutants are not confounders of this association (Buckley et al., 2014). All models for air pollutants and temperature were stratified by type of suicide death (violent and non-violent), sex, and age group. Furthermore, the air pollutants and suicide association models were stratified by season (warm season defined between April and September and cold season between October and March).The potential modification effect of pollutant concentrations on temperature and suicide associations was assessed in the CMA of Toronto and Vancouver, which had the largest number of suicide deaths. We used stratified models by air pollutant concentration: below percentile 25, between percentiles 25 and 75, and above percentile 75 of daily concentrations during the study period for each CMA. The statistical significance of the difference in OR across strata was assessed by calculating the 95% CI of the difference of effect estimates between two strata of a potential effect modifier using previously a published formula (Yoo et al., 2021; Zeka et al., 2006), specifically,

$$95\%\ \mathrm{CI} = (Q_1 - Q_2)\ \pm 1.96\ \sqrt{(\sigma_1{}^2 + \sigma_2{}^2)} \quad (1)$$

Where Q_1 and Q_2 are the coefficients of the association for strata 1 and 2, and σ_1 and σ_2 are the respective standard errors of these to groups.

2.5. Sensitivity analyses

We performed several sensitivity analyses to assess the robustness of the findings. First, single-pollutant models adding other meteorological factors (e.g. average daily precipitation and relative humidity) were used to compare with our main models adjusting for temperature and holidays. Second, we converted to time-series data by date and province and the analysis of effects of air pollutants on suicide was run using a Poisson regression model conditioned by time (grouped by the day of the week, month, and year) (Armstrong et al., 2014); by using these conditional time-series models we also controlled by seasonality and long-term trends and assessed the consistency of results using a different statistical approach. Finally, for the analyses of the effect of temperature, we ran the same models used in the main analysis adjusted by relative humidity and precipitation and air pollutants. We used Stata 16 (Stata Corporation, College Station, TX, USA) for all analyses. The alpha level used to define statistical significance was 0.05.

3. Results

A total 50,800 suicide deaths were identified from January 1, 2002 to December 31, 2015. A total of 21,891 (43%) of suicide deaths occurred in CMAs. The mean annual rate of suicide deaths was 10.82 per 100,000 population. Among suicide deaths, about 75.8% (n = 38,504) were violent in nature, 73.2% (n = 37,182) occurred among those 25–64 years of age, and 83% (n = 42,142) of them occurred among males (Table 1).

With respect to the distribution of ambient concentrations or air pollution assigned to cases and control intervals, the median concentration of NO_2, O_3, and $PM_{2.5}$ during the study period were 8.3 ppb (interquartile range (IQR = 9.7 ppb), 23.7 ppb (IQR = 14.1 ppb), and 5.5. μg/m^3 (IQR = 5.6 μg/m^3), respectively. (Table 2). The correlation among air pollutants was higher between NO_2 and O_3 (Pearson's correlation coefficient = −0.38) compared to the correlation between NO_2 and $PM_{2.5}$ (coefficient = 0.31) and between $PM_{2.5}$ and O_3 (coefficient = 0.1), which are expected to be related to the sources and dynamics of pollutants.

Suicide deaths averaged 9.9 per day over the study period and this mean increased over time from 8.7 per day in 2003 to 11.4 per day in

Table 1
Descriptive statistics of suicide deaths, Canada, 2002–2015.

Variable	Number of suicide deaths	
	n = 50,800	%[a]
Suicide death type		
Non-violent	12,296	24.2
Violent	38,504	75.8
Age group (years)		
<25	6813	13.4
25–44	17,163	33.8
45–64	20,019	39.4
65+	6805	13.4
Sex		
Female	8658	17.0
Male	42,142	83.0
Season		
Cold	24,246	47.7
Warm	26,554	52.3
Year		
2002–2003	6501	12.8
2004–2005	6799	13.4
2006–2007	6726	13.2
2008–2009	7461	14.7
2010–2011	7538	14.8
2012–2013	7521	14.8
2014–2015	8254	16.2
Province		
Alberta	6199	12.2
British Columbia	6608	13.0
Manitoba	2095	4.1
New Brunswick	1385	2.7
Newfoundland and Labrador	691	1.4
Nova Scotia	1348	2.6
Ontario	14,379	28.3
Prince Edward Island	166	0.3
Quebec	15,836	31.2
Saskatchewan	1648	3.2
Yukon/Nunavut/Northwest Territories	445	0.8

[a] Percentages may not add to 100% due to rounding.

2015. Over the course of a year, the number of suicide deaths tended to be higher in the first half of the year and also around the beginning of each month, with lower numbers observed during the latter half of the year and each month (Fig. 1). These variations were largely driven by violent suicide deaths, as non-violent suicide deaths tended to remain stable throughout the year.

3.1. Air pollution and suicide

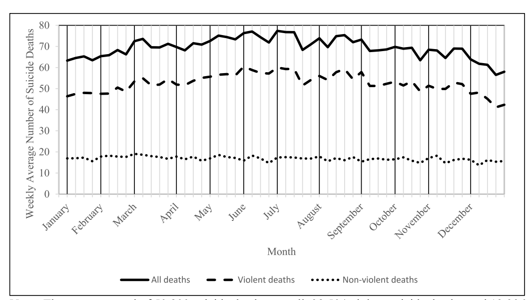
Overall, IQR increases of NO_2 were positively associated with suicide when examined overall and at different lags. The strongest associations with suicide deaths were observed during the 2-day lag (OR:1.023, 95% CI: 1.017–1.030) (Fig. 2). These effects differed by sex, with a strong positive association among females particularly in the cumulative lag up to two days prior to the suicide date (02lag-difference female-male OR: 0.107, 95% CI: 0.082; 0.131). By age-group, there was an inverse association for those less than 25 years of age for most day lags (same day OR: 0.941, 95% CI: 0.927, 0.958). Among adults over 25 years, higher associations were observed for the group between 45 and 64 years and in cumulative day lags (02lag OR: 1.051, 95% CI: 1.037, 1.066). Effects of NO_2 were marginally higher during the warm season with the strongest associations observed during the cumulative 02-day lag (OR:1.033, 95% CI: 1.017–1.050) without statistical significance (02lag-difference warm-cold OR: 0.019, 95% CI: −0.000; 0.039).

Overall, IQR increases in O_3 showed a slightly higher magnitude of the association with suicide deaths than that observed with the other pollutants. These associations were higher during the 2-day cumulative lag prior to suicide date (OR: 1.047, 95% CI: 1.039, 1.056), without substantive differences by type of suicide, sex, and age groups (Fig. 3). There were differences in the direction and magnitude of associations by season with higher effects of O_3 on suicide deaths during the warm season, particularly during the cumulative 02-day lag (OR warm:1.091, 95% CI: 1.080–1.102; difference warm-cold OR: 0.107, 95% CI: 0.089; 0.124).

IQR increases in $PM_{2.5}$ were positively associated with overall suicide deaths across for all lag days structures analyzed. The greatest effects were observed during the 2-day cumulative lag prior to suicide date (OR: 1.034, 95% CI: 1.030, 1.038), with no major differences by suicide type and age groups (Fig. 4). Females appeared to be at an elevated air pollution-suicide risk compared to males (02 lag difference female-male OR: 0.03, 95% CI: 0.019, 0.041). Furthermore, the effects on suicide were higher during the warm season (02 lag warm season OR: 1.045, 95% CI: 1.040, 1.050; difference warm-cold OR: 0.031, 95% CI: 0.022; 0.040).

The pooled effect estimates for the 12 CMA with 500 or more suicide deaths also shows positive and statistically significant effect of the three air pollutants, particularly al 3-day cumulative lag, with high heterogeneity across CMA (89.9% for NO_2, 96.3% for O_3, and 93.2 for $PM_{2.5}$). (See supplementary material Figure S1-S2).

The association of air pollutants with suicide deaths changed slightly when a second pollutant was added to the models (Table 3). More specifically, associations of suicide with $PM_{2.5}$ increased when NO_2 was included in the model, and conversely, associations with NO_2 lost statistical significance. On the other hand, in the two-pollutant model including $PM_{2.5}$ and O_3, the $PM_{2.5}$ associations decreased slightly and O_3 associations decreased about 30% compared to single-pollutant models, but both pollutants kept their lag-structure pattern and statistical



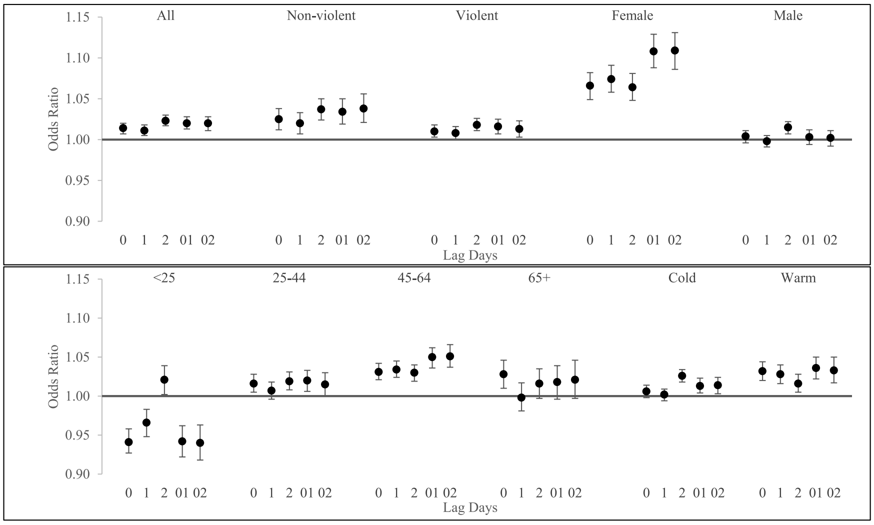
Note: There were a total of 50,800 suicide deaths overall, 38,504 violent suicide deaths, and 12,296 non-violent suicide deaths.

Fig. 1. Trends in suicide deaths over the course of a year by type of death, Canada, 2002–2015.
Note: There were a total of 50,800 suicide deaths overall, 38,504 violent suicide deaths, and 12,296 non-violent suicide deaths.

Table 2
Descriptive statistics for air pollution and meteorological variables for cases and control days, Canada, 2002–2015.

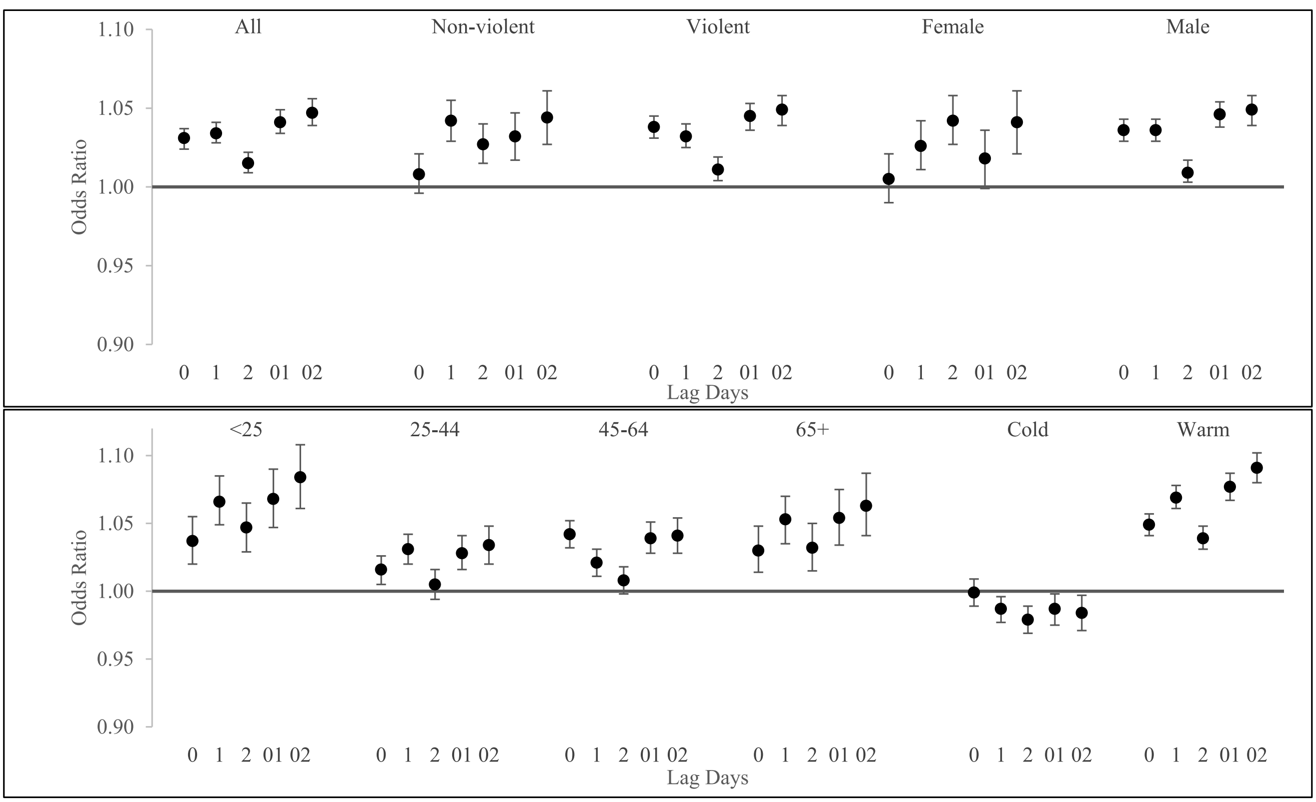
Variable	No. days	Minimum	P25	Median	P75	Maximum	IQR	Mean (SD)
NO_2 (ppb)	5113	−0.9	4.5	8.3	14.2	77.1	9.7	10.3 (7.8)
O_3 (ppb)	5113	0	16.8	23.7	30.9	82.7	14.1	24.0 (10.3)
$PM_{2.5}$ (μg/m^3)	5113	0	3.3	5.5	8.9	204.2	5.6	6.9 (5.9)
Temperature (°C)	5110	−40.5	−4.75	0.4	4.85	29.4	9.6	0.0 (7.9)
Precipitation (mm)	5110	0	0	0	2	113.9	2	2.3 (5.2)
Relative humidity (%)	5113	10	64	72	80	100.5	16	71.6 (12.3)

Note: IQR= Interquartile range; P = percentile; ppb = parts per billion; SD = standard deviation.



Note: Single pollutant models. Lag days represent the number of days before the suicide death. Single day lag (0, 1, and 2) models are adjusted for average daily temperature and public holidays. Multi-day lag models (01 and 02) are adjusted for 2- and 3- day moving averages of average daily temperature, respectively. Estimations of Odds Ratio per interquartile range increase in pollutant concentration (9.7 ppb of NO_2).

Fig. 2. Lagged effects of the association between an interquartile range increase in nitrogen dioxide (NO_2) and suicide deaths by type of death, sex, age group, and season, Canada 2002–2015.
Note: Single pollutant models. Lag days represent the number of days before the suicide death. Single day lag (0, 1, and 2) models are adjusted for average daily temperature and public holidays. Multi-day lag models (01 and 02) are adjusted for 2- and 3- day moving averages of average daily temperature, respectively. Estimations of Odds Ratio per interquartile range increase in pollutant concentration (9.7 ppb of NO_2).



Note: Single pollutant models. Lag days represent the number of days before the suicide death. Single day lag (0, 1, and 2) models are adjusted for average daily temperature and public holidays. Multi-day lag models (01 and 02) are adjusted for 2- and 3- day moving averages of average daily temperature, respectively. Estimations of Odd Ratio per interquartile range increase in pollutant concentration (14.1 ppb of O_3)

Fig. 3. Lagged effects of the association between an interquartile range increase in ozone (O_3) and suicide deaths by type of death, sex, age group, and season, Canada 2002–2015.
Note: Single pollutant models. Lag days represent the number of days before the suicide death. Single day lag (0, 1, and 2) models are adjusted for average daily temperature and public holidays. Multi-day lag models (01 and 02) are adjusted for 2- and 3- day moving averages of average daily temperature, respectively. Estimations of Odd Ratio per interquartile range increase in pollutant concentration (14.1 ppb of O_3).

significance. For the two-pollutant models including NO_2 and O_3, the associations of suicides with NO_2 increased more than 70% and with O_3 about 30% compared to single-pollutant models, and both pollutants kept their lag-structure pattern and statistical significance.

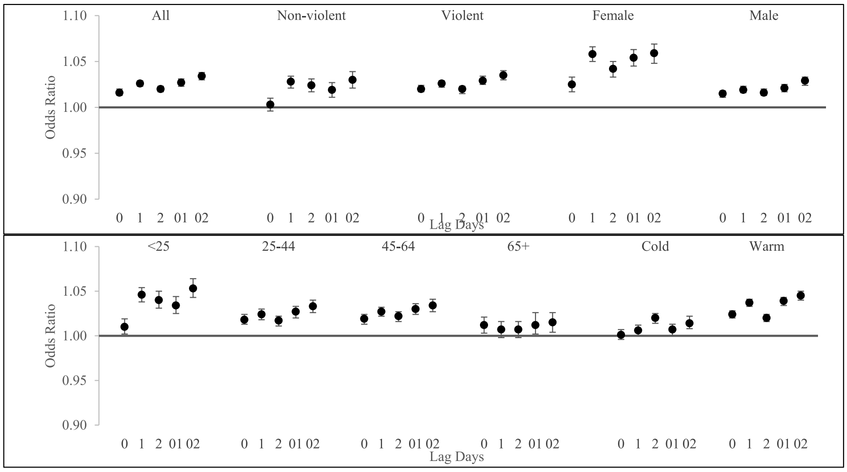


Fig. 4. Lagged effects of the association between an interquartile range increase in fine particulate matter ($PM_{2.5}$) and suicide deaths by type of death, sex, age group, and season, Canada 2002–2015.
Note: Single pollutant models. Lag days represent the number of days before the suicide death. Single day lag (0, 1, and 2) models are adjusted for average daily temperature and public holidays. Multi-day lag models (01 and 02) are adjusted for 2- and 3- day moving averages of average daily temperature, respectively. Estimations of OR per interquartile range increase in pollutant concentration (5.6 μg/$m^3$of $PM_{2.5}$).

Note: Single pollutant models. Lag days represent the number of days before the suicide death. Single day lag (0, 1, and 2) models are adjusted for average daily temperature and public holidays. Multi-day lag models (01 and 02) are adjusted for 2- and 3- day moving averages of average daily temperature, respectively. Estimations of OR per interquartile range increase in pollutant concentration (5.6 μg/m^3 of $PM_{2.5}$)

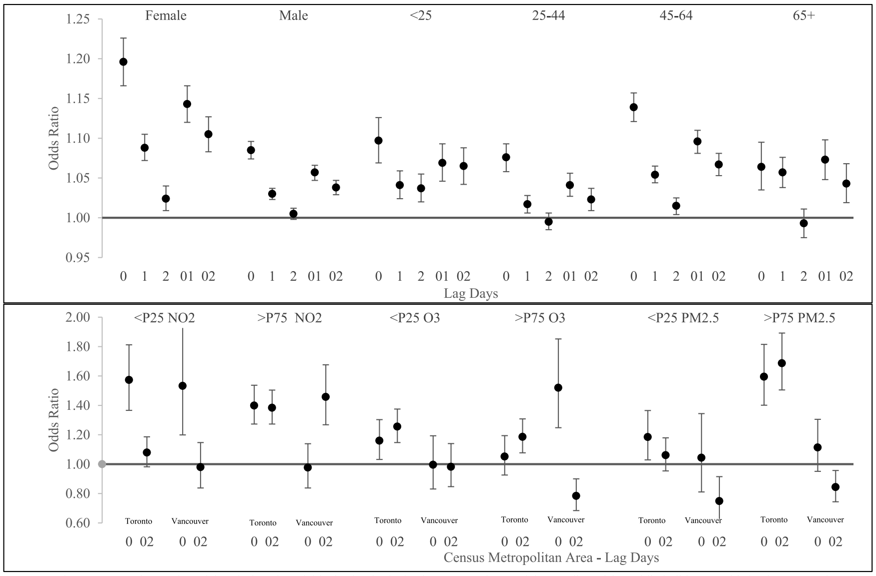
Table 3
Associations between concentrations of air pollutants in two-pollutant models for all suicide deaths by season, Canada 2002–2015.

Lag structure	Model $PM_{2.5}$ and NO_2		Model $PM_{2.5}$ and O_3		Model NO_2 and O_3	
	OR (95% CI)		OR (95% CI)		OR (95% CI)	
	$PM_{2.5}$	NO_2	$PM_{2.5}$	O_3	NO_2	O_3
Overall						
Same day	1.018 (1.014–1.021)	0.990 (0.983–0.998)	1.015 (1.011–1.018)	1.022 (1.015–1.029)	1.027 (1.019–1.034)	1.042 (1.035–1.049)
1 day	1.028 (1.025–1.032)	0.984 (0.976–0.991)	1.024 (1.020–1.027)	1.028 (1.021–1.034)	1.021 (1.015–1.029)	1.040 (1.033–1.047)
2 day	1.020 (1.016–1.023)	1.007 (0.999–1.015)	1.019 (1.016–1.023)	1.008 (1.002–1.015)	1.030 (1.024–1.038)	1.024 (1.017–1.030)
0–1 days	1.030 (1.025–1.034)	0.983 (0.974–0.992)	1.024 (1.020–1.028)	1.030 (1.022–1.038)	1.033 (1.024–1.041)	1.053 (1.048–1.061)
0–2 days	1.039 (1.034–1.044)	0.977 (0.967–0.987)	1.031 (1.026–1.035)	1.032 (1.024–1.041)	1.034 (1.024–1.043)	1.058 (1.049–1.067)
Cold season						
Same day	0.999 (0.992–1.007)	1.001 (0.991–1.011)	1.001 (0.994–1.007)	1.002 (0.991–1.014)	1.008 (0.999–1.018)	1.007 (0.995–1.019)
1 day	1.007 (1.000–1.015)	0.999 (0.989–1.009)	1.003 (0.997–1.009)	0.988 (0.977–0.999)	0.996 (0.986–1.005)	0.987 (0.975–0.999)
2 day	1.017 (1.010–1.024)	1.018 (1.008–1.029)	1.016 (1.010–1.022)	0.985 (0.974–0.996)	1.024 (1.015–1.034)	0.994 (0.982–1.007)
0–1 days	1.005 (0.997–1.014)	1.005 (0.993–1.018)	1.004 (0.997–1.011)	0.993 (0.980–1.006)	1.011 (1.000–1.023)	0.998 (0.984–1.012)
0–2 days	1.015 (1.006–1.024)	1.003 (0.989–1.017)	1.010 (1.002–1.018)	0.987 (0.973–1.001)	1.011 (0.998–1.023)	0.992 (0.977–1.007)
Warm season						
Same day	1.024 (1.019–1.028)	0.994 (0.981–1.007)	1.019 (1.015–1.024)	1.023 (1.014–1.032)	1.034 (1.023–1.047)	1.055 (1.047–1.064)
1 day	1.037 (1.033–1.042)	0.976 (0.964–0.989)	1.027 (1.023–1.032)	1.046 (1.036–1.055)	1.028 (1.017–1.041)	1.067 (1.058–1.076)
2 day	1.021 (1.016–1.026)	0.984 (0.971–0.997)	1.016 (1.011–1.020)	1.025 (1.016–1.035)	1.017 (1.005–1.029)	1.040 (1.032–1.049)
0–1 days	1.039 (1.034–1.045)	0.972 (0.957–0.988)	1.029 (1.024–1.035)	1.042 (1.031–1.053)	1.031 (1.017–1.046)	1.079 (1.069–1.089)
0–2 days	1.050 (1.044–1.055)	0.959 (0.942–0.975)	1.035 (1.029–1.041)	1.052 (1.039–1.064)	1.028 (1.012–1.044)	1.095 (1.012–1.044)

Note: Single day lag (0, 1, and 2) models are adjusted for average daily temperature and public holidays. Multi-day lag models (01 and 02) are adjusted for 2- and 3-day moving averages of average daily temperature, respectively. Estimations are reported by increase of interquartile range of each pollutant.

3.2. Temperature and suicide

Overall, IQR increases in temperature showed a stronger association with suicide deaths than that observed with the air pollutants. Compared to the single-day and moving average lag periods, the associations were strongest during the same day of the suicide death (OR: 1.101, 95% CI: 1.090, 1.112). All other lag day structures had statistically significant positive associations. Temperature same-day effect on violent deaths (OR: 1.099, 95% CI: 1.087, 1.111) was slightly lower compared to non-violent deaths (OR: 1.108, 95% CI: 1.086, 1.130). Females appeared to be at elevated risk particularly at the same day of the suicide compared to males (same-day difference female-male OR: 0.111, 95% CI: 0.079, 0.143) (Fig. 5). The age group between 25 and 44 years was at lower risk compared to other age groups with an inverse association in the 2-day lag prior to the suicide death (OR: 0.995, 95% CI: 0.985, 1.006). The effect of same-day temperature on suicide was



Note: Lag days represent the number of days before the suicide death. Single day lag (0, 1, and 2) models are adjusted for public holidays. Multi-day lags (01 and 02) represent 2- and 3- day moving averages, respectively. <P25 represent daily temperature below percentile 25 and >P75 represent daily temperature above percentile 75 for each census metropolitan area during the study period. Estimations of Odds Ratio per 9.6°C increase in average daily temperature.

Fig. 5. Lagged effects of the association between an interquartile range increase in average daily temperature and suicide deaths by sex and age group for all cities, and air pollutant percentile concentrations for selected census metropolitan areas, Canada 2002–2015.

Note: Lag days represent the number of days before the suicide death. Single day lag (0, 1, and 2) models are adjusted for public holidays. Multi-day lags (01 and 02) represent 2- and 3- day moving averages, respectively. <P25 represent daily temperature below percentile 25 and >P75 represent daily temperature above percentile 75 for each census metropolitan area during the study period. Estimations of Odds Ratio per 9.6 °C increase in average daily temperature.

higher during the warm season (OR: 1.131, 95% CI: 1.111, 1.150) compared to the cold season (OR: 1.087, 95%CI: 1.074, 1.100). The effect of temperature on suicide deaths in the CMA of Toronto seems to be modified by the concentrations of $PM_{2.5}$, with higher effect of temperature on days with concentrations of $PM_{2.5}$ above the percentile 75 (same-day lag difference P75–P25 OR: 0.41, 95% CI: 0.14–0.68; 3-day cumulative lag difference P75–P25 OR: 0.63, 95% CI: 0.40–0.85). Similar statistically significant effect modification was found for 3-day cumulative lag for NO_2 in Toronto and Vancouver metropolitan areas, and for the same day lag for O_3 in Vancouver. The pooled effect estimates for the 12 CMA with 500 or more suicide deaths also shows positive and statistically significant effect of temperature, particularly during the same day, with high heterogeneity across CMA (93.4%). (See supplementary material Figure S1-S2).

3.3. Sensitivity analyses

While there were modest increases in effect sizes for O_3 and $PM_{2.5}$ when adding average daily relative humidity and precipitation to the models, there was no overall change in the statistical significance of the results for all air pollutant analyses (See Supplementary material Table S1). The risk estimates of the association between average daily temperature and suicide deaths adjusted by holidays and other meteorological conditions were all higher compared to the main model controlling for holidays only and follow the same lagged effects with the highest risks for the same-day effect. The risk estimates adjusted by the air pollutant concentrations were lower compared to estimations from the main model. With the exception for the 2-day lag risk estimate, the other lag structures did not change their direction (See Supplementary material Table S2).

The estimations of association between air pollutants and suicide deaths using time-stratified Poisson conditional models showed on average 6% higher risk estimations for all pollutants and lag structures compared to conditional logistic models. Estimates kept the pattern and statistical significance with higher effect estimates for moving average lag structures and highest to lowest risk estimates for O_3, $PM_{2.4}$, and NO_2, respectively (See Supplementary material Table S3).

4. Discussion

In this Canadian study of more than 50,000 suicides over a 14-year period, we found positive associations between daily increases of O_3, NO_2, $PM_{2.5}$ and temperature and death from suicide. While positive associations were observed across different exposure lags, the strongest estimate was observed with a 3-day moving average for all pollutants. In contrast, for temperature, the strongest association was found with the same day average. The associations between increases in NO_2, $PM_{2.5}$, and temperature and suicide deaths were higher among females. Furthermore, we found that the associations for each pollutant and temperature were stronger during the warm season.

Historically, research that has evaluated the effects of daily increases of air pollution on suicide has produced mixed results. However, a meta-analysis of 18 studies published up to May 2021 reported positive and statistically significant associations for suicide with NO_2 and $PM_{2.5}$, and a positive but non-statistically significant association for O_3 (Heo et al., 2021). Most studies included in the meta-analysis were conducted in Asian countries, and only four were conducted North American cities including one study in Vancouver. The combined relative risk estimate reported an average of 2% and 3% increase in suicide risk related to an increase of IQR in $PM_{2.5}$ and NO_2 concentrations, which are similar to our findings for Canada that were 3.7% and 2.4% for the same day of the suicide when using the same IQR ranges, respectively.

Contrary to the findings of the meta-analysis (Heo et al., 2021) and the previous study in Vancouver (Szyszkowicz et al., 2010), we found stronger and statistically significant effects of O_3 compared to other pollutants evaluated. Previous research evaluating the influence of ground level ozone on suicide risk has been mixed for hospital admissions (Szyszkowicz et al., 2010; Yang et al., 2019), but our results are in agreement with Kim et al. (2015) who reported the strongest effects for ozone on mortality in a nationwide study in South Korea. Our findings add to prior evidence of effects of O_3 in a different geographical area while using finer spatially resolved estimates of air pollution exposure.

Overall, the association between air pollutants and suicide increased as the number of lag days or cumulative lags (moving-day average) increased up to 2 days before the suicide death. Our findings of stronger effects within short-day lags are in line with findings of studies conducted in Asia that report higher effects for this lag structure (Lin et al., 2016; Kim et al., 2018), and overall, higher effects for all three pollutants during the same week of the suicide compared to longer lagged effects (Kim et al., 2015). These findings might be explained by a "trigger effect" of the acute change in pollutant concentrations on top of more chronic disorders related to mental health which are mediated by increased neuroinflammation and altered serotonin functioning (Heo et al., 2021).

In our study, all three pollutants showed higher adverse effects during the warm season compared to the cold season and the strongest effects were observed for O_3. Ozone levels tend to be higher on warm days in relation to solar radiation; thus, there might be an increased exposure to air pollutants during these periods as people tend to keep windows open and outdoor activities are increased (Stafoggia et al., 2008). Another potential explanation is that ozone may interact with the adverse effect of maximum temperatures on suicide that have been already reported (Frangione et al., 2022).

Our models revealed that associations between air pollutants and suicide deaths were also modified by sex. Females were at higher risk of suicide in relation with IQR increases of NO_2 and $PM_{2.5}$. Our results differ from those reported by Bakian et al. (2015) in Utah (US), where stronger effects were observed in males for NO_2 and $PM_{2.5}$. Despite males dying by suicide more frequently, females are more vulnerable to the effects of air pollution, and stronger effects on females have been also reported for cerebrovascular disease mortality (Liu et al., 2020). Potential mechanisms for the observed sex difference include a greater susceptibility of females to oxidative stress that has been identified for other air pollutants (Guo et al., 2014).

While the exact causal pathways are not fully understood, previous work has proposed potential mechanisms by which air pollutants may lead to mental illness and suicide (Heo et al., 2021). Specifically, air pollutants may increase pro-inflammatory markers and oxidative stress (Block and Calderón-Garcidueñas, 2009; Power et al., 2015), negatively disturb central nervous system activity (Ng et al., 2016; Bakian et al., 2015), and change how neurotransmitters are metabolized (González-Piña and Paz, 1997), leading to increased susceptibility for mental illness and thus suicide. Specific biological mechanistic pathways for particles and gases are still under study, but there is some evidence that $PM_{2.5}$ might be more related to the neuroinflammatory response derived from microglia (brain macrophages), and O_3 more related to increased oxidative stress (Block and Calderón-Garcidueñas, 2009).

Our findings regarding temperature analyses are consistent with the previous meta-analyses that found evidence of adverse effects of temperature on suicide attempts and deaths, and stronger effects in periods of maximum temperatures (warm season) (Heo et al., 2021; Frangione et al., 2022; Gao et al., 2019). Contrary to the results reported by Frangione et al. (2022), we found that positive associations between suicide and ambient temperature primarily occurred on the day of suicide (OR: 1.097, 95% CI: 1.085, 1.109). Similar findings were reported by Kim et al. (2016) in Asian countries (South Korea OR: 1.068, 95% CI: 1.054, 1.082; Japan OR: 1.045, 95% CI: 1.033, 1.057; Taiwan OR: 1.078, 95% CI: 1.050, 1.108).

The associations between temperature and suicide have been explored more extensively relative to air pollution and suicide. We examined the effect modification by air pollution on temperature-suicide association, a knowledge gap identified in this field (Heo et al., 2021), and found that the association is lower when daily concentrations for NO_2 are below the percentile 25 in 3-day cumulative lag in Toronto and Vancouver metropolitan areas. The effect modification by $PM_{2.5}$ and O_3 differ by city. We found statistically significant increase of temperature effects in Toronto with higher levels of $PM_{2.5}$ and in Vancouver during the same day with higher levels of O_3. These findings suggest a modifying effect of air pollutants concentrations that might be city-specific, and potential synergistic effects of air pollution and temperature should be further explored in future studies.

Our analyses revealed that the direction and effects of lag structures remain similar when two-pollutant models are used. Furthermore, the effect of $PM_{2.5}$ and O_3 seem to be more evident when adjusting for a second pollutant and similar findings related to O3 were reported in Taipei (Yang et al., 2019). The inclusion of other meteorological variables in the sensitivity analysis did not affect the direction of associations and lag structures. Regarding the consistency of results using different statistical approaches, the direction and pattern of lagged effects were similar with conditional logistic or time-stratified Poisson models, but larger estimates were obtained from Poisson models. Poisson conditional models have shown to be a better approach for case-crossover designs when working with time-series data and shared exposures obtained at city level (Armstrong et al., 2014). For the present results, however, the differences between risk estimations from both models might be interpreted as overestimation of the effects of the Poisson model because we used finer exposure data resolution (closest monitoring station by postal code). Therefore, personal exposure is not the same for all individuals within the same city (which is especially true for large cities) and conversion to time series data even at the city level may include an exposure misclassification error of the exposure than in this case led to overestimation of the associations.

Szyszkowicz et al. (2010) found statistically significant associations between NO_2 and emergency department (ED) visits for suicide between 1999 and 2003 in Vancouver. In contrast to our findings, the associations with NO_2 were higher for men, during the cold season, and in a 1-day lagged model (OR: 1.21, 95%CI: 1.03, 1.41). Differences from this study might be related to the use of different outcomes for suicide with potential differential effects of pollutants on suicide attempts and deaths by suicide. Also, local specific weather and air pollution dynamics in Vancouver might differ in relation to suicide effects with nationwide summary estimations. They also found significant associations of ED visits for suicide and other pollutants not evaluated in our study such as carbon monoxide, SO_2, and PM_{10}. They also compared estimations from time-series and case-crossover analysis and found higher estimates using Poisson regression time-series method, which is consistent with our sensitivity analyses.

The main strengths of this study are the large number of suicides that were identified from a national population over a time period that spanned 14 years. We recognize that ascertainment of deaths from suicide may be incomplete due to underreported due stigma (Public Health Agency of Canada, 2016). However, this underreporting is unlikely to be related to daily air pollution concentrations, and therefore we don't believe to be a source of bias.

5. Conclusions

In summary, our study demonstrates that short-term increases in NO_2, O_3, $PM_{2.5}$, and temperature are associated with an increased risk of dying by suicide in Canada. Furthermore, our findings suggest that sex and season act as effect modifiers of theses associations, with higher adverse effects during the warm season and for females. Overall, these findings may provide insight for consideration in developing future suicide prevention strategies.

Authorship contributions

PV: Conceptualization, Methodology, Formal analysis, Writing – review & editing, Supervision, Funding acquisition. DH: Methodology, Formal analysis, Data curation, Writing – original draft. EL: Conceptualization, Methodology, Formal analysis, Data curation, Writing– review & editing. IC: Methodology, Writing– review & editing. HA: Methodology, Writing– review & editing. CP: Methodology, Writing– review &; editing. LR-V: Methodology, Formal analysis, Data curation, Writing – original draft.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Nitrogen dioxide data, ozone, and $PM_{2.5}$ metrics, and weather-related indicators (based on custom data from Natural Resources Canada) were indexed to DMTI Spatial Inc. postal codes and provided by CANUE (Canadian Urban Environmental Health Research Consortium). Air pollutant-related data were prepared by Dr. Eleanor Setton and Sajjad, and weather-related indicators were developed by Dr. Johannes Feddema, Pei-Ling Wang, and Mahdi Shooshtarie for CANUE. Humidity data were provided by Environment and Climate Change Canada.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.envres.2023.115477.

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