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Impact of Heatwave Events on Ozone Pollution and Its Health Effects in Southern Canada

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Abstract: *In order to study the impact of heat waves on ozone in southern Canada, this paper analyzes the ground-level and tropospheric ozone pollution in the heat wave impact and non-impact periods in this region, and uses multivariate data and BenMAP-CE software to compare the correlation between ground-level ozone and temperature, ozone and relative humidity, and their impacts on human health during the impact and non-impact periods of the heat wave in the southern region of Canada. The study shows that: (1) the overall spatial distribution patterns of tropospheric ozone and ground-level ozone concentrations in southern Canada are high in the southeast and low in the northwest, and the ozone concentrations are significantly higher during the heatwave-affected period than during the non-heatwave-affected period. (2) Temperature-ozone correlations were mainly uncorrelated in the eastern and western parts of the study region during non-heatwave-affected periods. The occurrence of summer heat waves enhanced the positive temperature-ozone correlation in most areas. (3) The negative correlation between relative humidity and ozone in the study area during the heatwave-affected period accounted for a smaller percentage of the area than in the non-affected period. The presence of heat waves weakened the negative correlation between relative humidity and ozone. (4) The occurrence of heat waves in the study area led to an increase in the number of deaths due to ozone exposure, with growth rates ranging from 22.6% to 23.2%, and there were significant gender and geographic differences in the number of deaths due to ozone exposure. It was concluded that ozone pollution in the region is closely related to the occurrence of heat waves, and that the strengthening of integrated research on air pollution and climate change will be a major task for the future.*

Keywords: *Heatwave, Temperature, Ozone, Ozone health effects, Southern Canada*

1. Introduction

Ozone is a highly oxidizing secondary pollutant produced by nonlinear and complex photochemical reactions between nitrogen oxides (NOx) and volatile organic compounds (VOCs) in the atmosphere [1-2]. Ozone benefits from participation in other chemical reactions in the atmosphere and is characterized by short survival times and high activity[3]. In recent years, urbanization and industrialization are changing the supply of volatile organic compounds (VOCs) and rapidly increasing concentrations of nitrogen oxides (NOx) and ozone (O_3)[4-5]. The global population-weighted mean ozone concentration (PWC) is estimated to have risen by 7.2% from 1990 to 2015[6]. In recent years, near-surface ozone has been trending upward in many parts of the world, including Canada[7].

Air pollution has become a significant problem in many Canadian cities, posing a serious threat to both the environment and health, which has prompted government regulatory action[8]. In order to improve air quality, Canada initiated the National Air Pollution Surveillance (NAPS) program in 1969 [10]. Based on the monitoring data, data on more than 300 trace pollutants in ambient air are collected, compiled and analyzed, along with Canadian health assessments.

In recent years, health impact assessments in Canada have identified air pollution as one of the greatest risk factors for premature death and disability[8]. There have been numerous analyses of ozone pollution and health in Canada. A previous study conducted in 24 Canadian cities reported on the association between ozone and various health risks, noting that ozone was a risk factor for hospitalization and death from all causes and that ozone showed a significant seasonal risk of death[9-10]. A cohort study found that simultaneous exposure to ozone and $PM_{2.5}$ significantly increased the risk of death from ischemic heart disease, and that this risk varied spatially across climate zones [11]. A national time-stratified case-crossover study found that increases in NO_2, $PM_{2.5}$, and O_3 were associated with higher rates of suicide mortality, and that higher levels of $PM_{2.5}$ and O_3 in particular may amplify the temperature-suicide association[12]. Studies in recent years have also shown that mortality due to respiratory and neurological diseases is positively correlated with ozone exposure, and the degree of correlation varies across large areas of Canada[13-14]. This shows that ozone pollution in Canada has significant negative health effects.

In recent years, the frequency, severity, and duration of heat waves in Canada have increased [15-17]; In particular, Canada experienced a record-breaking heat wave in 2021[17]. At the same time, heat waves are closely related to ozone. Meehl et al.[18]examined the relationship between heat waves and global land surface ozone levels using a global Earth system model and found that, in most regions, ozone concentrations on future heat wave days will be significantly higher than ozone concentrations on non-heat wave days. A study in Barcelona also found that the occurrence of heat waves can lead to abnormally high ozone concentrations[19]. A study in the Beijing-Tianjin-Hebei urban agglomeration found that excessive ozone concentrations were associated with increased heat waves[20]. However, a study in 2022 found that not all heat waves exacerbated ozone pollution in the Beijing-Tianjin-Hebei region[21].

Temperature and ozone have synergistic acute effects on premature mortality, especially during extreme heat waves. A time-series investigation in France reported that extreme heat and air pollution have a significant impact on mortality risk[22]. A study in the Madrid region explored the combined effects of extreme temperatures and air pollution on neuroendocrine diseases[23]. An ecological retrospective time-series study reported that extreme heat exacerbates hospitalization rates for kidney disease, with ozone levels also playing a role [24].

In summary, previous studies on temperature and air pollution during heat waves have only explored the relationship between heat waves and ozone concentrations and the synergistic effects of heat waves and ozone concentrations on premature mortality. However, few studies have examined the role of heat waves in modifying the effects of ozone on human health. In addition, there appear to be no studies that have analyzed the effects of heat waves on air pollution and the effects of ozone on life and health under heat wave conditions, using Canada as the study area. Based on this, the objectives of this study were to (1) assess the effects of heat waves on ozone, (2) assess the effects of heat waves on the correlation between ozone and natural factors, and (3) assess the role of heat waves in modifying the effects of ozone on human health, using southern Canada as the study region. The results of these studies will complement and extend research on the health hazards of air pollution caused by extreme events, providing assistance to governments in environmental management decisions and to people in adapting to climate change.

2. Overview of the Study Area

Canada is located in the northern half of North America, occupying most of the northern part of North America, with latitude and longitude positions between approximately 41 °N -83 ° N and 52 ° W-141 ° W (Fig. 1). The land area is 998.5 million square kilometers, and as of January 2023, the total population of Canada was 39.5 million. The study area is divided into two geographic regions, the Eastern Region and the Western Region. The Eastern Region includes Newfoundland and Labrador, Nova Scotia, Prince Edward Island, New Brunswick, Quebec, and Ontario, and the Western Region includes British Columbia, Alberta, Saskatchewan, and Manitoba.

The study area is characterized by an uneven distribution of population, with a clear concentration in the south. Topographically, the eastern part of the area is dominated by the low Labrador Plateau, the central part by the Great Plains and the Lorentigen Plateau, and the western part by the Rocky Mountains of the Cordillera. The vast majority of the study area has a temperate continental climate with cold winters and hot summers. During the summer months, temperatures in the study area are high, sometimes exceeding 30 °C. The temperature in the study area is high. Most of the Study Area has a wide range of seasonal temperatures. Precipitation in the western part of B.C. is quite high, with Vancouver receiving about 1,200 millimeters of annual precipitation, while the interior prairies in the western part are quite dry, with annual precipitation ranging from 250 millimeters to 500 millimeters. The eastern region receives relatively little precipitation. The study area is richly forested, with most of the area covered by forests and only the southern portions of Alberta, Manitoba, and Saskatchewan being prairie.

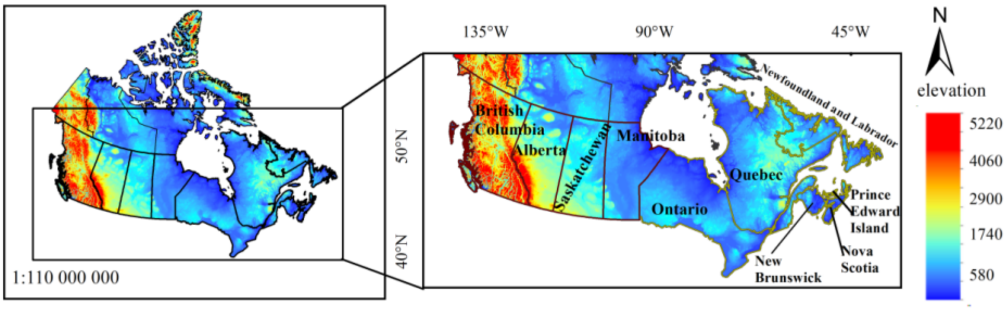

Figure 1: Geographical location of research area in southern Canada.

3. Materials and Methods

3.1. Data Sources

Data sets on air pollution, temperature, relative humidity and mortality were used in this study. Daily data on ozone column concentrations in southern Canada for May to August 2019 and 2021 were obtained from the OMI on the Aura satellite and downloaded from the Goddard Center for Earth Science Data and Information Services on the official NASA website. The data have a spatial resolution of 13 km × 24 km, a sensor field of view of 114 °, a wavelength range of 270 to 500 nm, an average spectral resolution of 0.5 nm, and a swath width of 2600 km[25]. In this paper, 1000hpa relative humidity and 2m temperature were obtained from the NCEP/DOE Reanalysis II dataset from NOAA Physical Sciences Laboratory (PSL).

Hourly air pollution ground station data from the National Air Pollution Monitoring Program (NAPS) maintained by Environment and Climate Change Canada were also used. The rolling 8-hour maximum daily average (8h max) of ozone was used in the study. Population data were obtained from Statistics Canada census data. Mortality data were obtained from month-by-month data from the National Vital Statistics administered by Statistics Canada using the International Classification of Diseases, Tenth Edition (ICD-10). All-cause mortality includes all diseases defined in the International Classification of Diseases, Tenth Edition (ICD-10). Deaths were identified as circulatory if the primary cause of death was categorized by ICD-10 as I00-I99, and as respiratory if categorized by ICD-10 as J00-J99.

3.2. Definition of Heat Wave

Environment Canada defines a "heat wave" as "three or more consecutive days of maximum temperatures greater than or equal to 32°C/90°F"[26]. However, temperature is only one component of defining a heat wave; it also depends on humidity, wind speed and radiative load. Heat wave periods in this paper are subject to humidity values greater than 40%, afternoon temperatures greater than 30%, and nighttime temperatures greater than 20%.2021 Four major heat waves occurred in eastern and western Canada. To facilitate the counting of fatalities and to consider the temporal requirements of short-term exposures, the heatwave impact period for this study was specified as the month in which the heatwave occurred, i.e., May to August 2021 for the heatwave impact period and May to August 2019 for the non-heatwave impact period.

The 2021 heatwave was one of the longest-lasting and hottest heatwaves in Canadian history, and ranked first on Environment and Climate Change Canada's list of top weather events for 2021. The southern region was chosen as the study area because it had the highest temperatures during the 2021 heatwave (June through August) and because it is where the absolute majority of Canada's population is located. From June through August 2019, there were no significant extreme heat wave events in southern Canada[27], so this year will serve as the control group for the heat wave study.

3.3. Research methods

3.3.1. Processing of Ozone Data

The daily concentration data of tropospheric ozone column referred to Peng et al.,[28]s' processing method. Firstly, Python software was used to extract latitude and longitude, ozone column concentration, and cloud cover data. Finally, the obtained data was processed in ArcGIS to obtain a spatiotemporal distribution map of tropospheric ozone concentration. Processing of daily ground ozone concentration data: Firstly, the hourly ozone data is processed to obtain daily data, and then the obtained data is processed in ArcGIS to obtain a spatiotemporal distribution map of ground ozone concentration.

3.1.2. The Pixel Space Analysis Method

Both natural factors and pollutant concentrations rarely exhibit a linear trend. Pearson correlation analysis is an indicator that measures the degree of linear dependence between two random values. The Pearson coefficient, also known as the coefficient of product-moment correlation, is usually represented by r. When r>0, it indicates a positive correlation between the two sets of data, and when r<0, it indicates a negative correlation. The larger the absolute value of r, the more pronounced the linear trend. This article uses Pearson correlation method to analyze the relationship between station ozone data and temperature, relative humidity, and understand the spatial distribution of the correlation between ozone and various influencing factors. The calculation formula related to Pearson is as follows:

$$r_{xy} = \frac{\sum_{i=1}^{n}\left[\left(x_i - \overline{x}\right)\left(y_i - \overline{y}\right)\right]}{\sqrt{\sum_{i=1}^{n}\left(x_i - \overline{x}\right)^2 \sum_{i=1}^{n}\left(y_i - \overline{y}\right)^2}} \tag{1}$$

r_{xy} is the correlation coefficient between variable x and variable y; x_i is the average ozone value on day i ; $\overline{x}$ is the total mean of ozone; y_i is the mean value of a certain influencing factor on day i ; $\bar{y}$ is the total mean of a certain influencing factor.

3.1.3. BenMAP-CE

BenMap is a computer program based on the Windows system, mainly used to evaluate the human health effects and economic value caused by changes in surrounding air pollution. BenMAP estimates the health benefits associated with changes in air quality by creating population exposure surfaces and estimating changes in a range of health outcomes related to air pollution [29].

This model uses population data, ozone station data, and mortality rate data. The health impact function used by map is as follows:

$$\vartriangle Y = Y_0 * \left(1 - e^{-\beta * \vartriangle \rho}\right) * Pop \tag{2}$$

Where, ΔY is the estimation of the health impact of the change of pollutant concentration, Y_0 is the baseline incidence of the health terminal (i.e. mortality or incidence rate), *Pop* is the population affected by the change of air quality, $\Delta\rho$ is the change of air quality, βand is the relationship coefficient between pollution concentration and health impact (i.e. exposure response relationship coefficient).

4. Results

4.1. The Overall Pattern of Ozone Spatial Distribution

By processing ground station ozone data and tropospheric ozone concentration data from May to August 2019 and 2021 in southern Canada, a spatial distribution map of overall ozone concentration was obtained (Fig. 2). The ground ozone concentration in the study area ranges from 24.2 to 45.7 pbb, showing an overall distribution pattern of high in the south and low in the north.Ozone shows two high values in the western grasslands (mainly concentrated in Alberta, Saskatchewan, and southern Manitoba) and southwestern Ontario, respectively. The range of tropospheric ozone concentration is 26.3-46.4 DU. From a spatial perspective, the overall spatial distribution patterns of tropospheric ozone and ground-level ozone concentrations show some similarity: high in the southeast and low in the northwest.

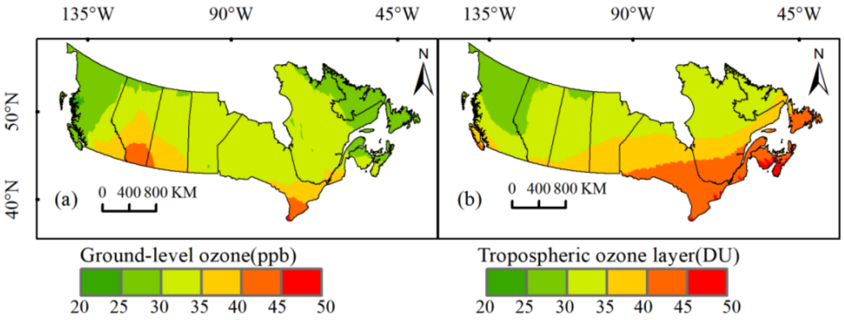

Figure 2: General spatial distribution of ground-level ozone (a) and tropospheric ozone (b) concentrations in southern Canada.

4.2. Comparison of Ozone Concentration Between the Affected Period and the Unaffected Period of Heat Wave

Figure 3 shows the spatial distribution of ground and tropospheric ozone concentrations during the heat wave impact and non impact periods in southern Canada, in order to investigate whether the occurrence of heat waves has an impact on ozone concentration and spatial distribution. The ozone concentration on the ground in the study area can be divided into six levels. The ozone concentration in the troposphere can also be divided into six levels.

Compared with the nonimpact period (Fig. 3a), the ground ozone concentration during the heatwave impact period (Fig. 3b) shows a significant increase in the proportion of areas occupied by levels three, four, five, and six, while the proportion of areas occupied by levels two and one decreases significantly. Compared with the non impact period (Fig. 3c), the concentration of tropospheric ozone during the heat wave impact period (Fig. 3d) shows a significant increase in the proportion of the total area occupied by the third, fourth, fifth, and sixth orders, while the proportion of the area occupied by the second order significantly decreases.

In summary, whether it is tropospheric ozone or ground ozone, the ozone concentration and high ozone value areas during the heat wave impact period are higher than those during the non impact period.

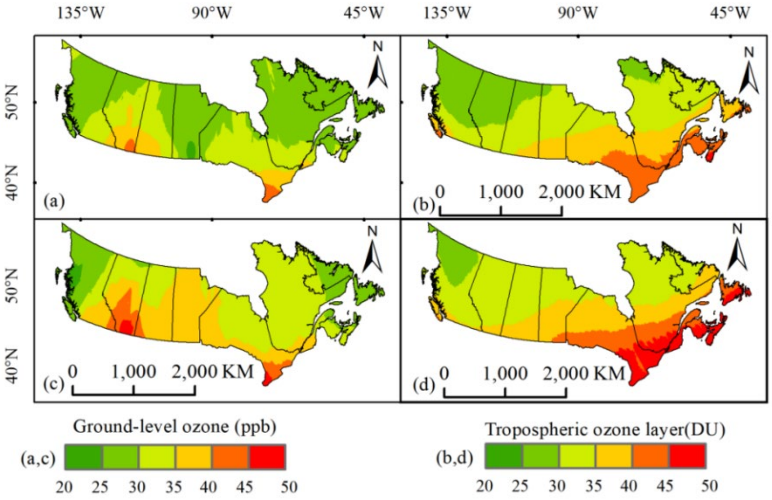

Figure 3: Spatial distribution of ground-level ozone and tropospheric ozone concentrations during heat wave impact and non-impact periods. (a) (b) are the spatial distributions of Ground-level ozone and tropospheric ozone during non-heatwave-affected periods, respectively. (c) (b) are the Ground-level ozone and tropospheric ozone during heat wave impact periods, respectively.

4.3. Correlation Analysis Between Ozone Concentration and Natural Factors

Ozone concentration is influenced by a combination of natural and anthropogenic factors. Natural factors include the amount of air pollutants released by the source, the distance between the source and the observation site, and meteorological conditions such as temperature and relative humidity[30]. Since ground-level ozone concentrations and meteorological factors come from different types of monitoring stations-air quality monitoring stations and meteorological stations, respectively-and the spatial distributions of these two types of stations are not exactly the same, this leads to the possibility of introducing large errors when using these two types of data for kriging interpolation followed by Pearson correlation analysis. In addition, due to the difficulty in obtaining anthropogenic data, this paper focuses on investigating the interrelationships between tropospheric ozone concentration, temperature and relative humidity. By using correlation analysis, the correlations between tropospheric ozone concentration, temperature and relative humidity during heat waves in eastern and western Canada are analyzed.

The analysis of the western region concluded that during the non-heatwave period, temperature in the central part of the western region was weakly positively correlated with ozone (Fig. 4). During the heatwave impact period, temperature and ozone in the western region showed weak positive and moderate positive correlations, and the range of the correlation increased significantly compared to the non-heatwave impact period, in addition to the deepening of the positive correlation. Observing the P-value of the correlation between temperature and ozone during the non-impact period in the eastern region, it can be seen that the correlation between temperature and ozone did not pass the significance test. During the heatwave impact period, temperature and ozone were positively correlated in the southern and western parts of the eastern region. The northern part of the eastern region showed a negative correlation.

Overall, there was no correlation between temperature and ozone mainly in the eastern and western parts of the study area during non-heatwave affected periods. It can be seen that the presence of summer heat waves enhanced the correlation between temperature and ozone in the study area. The positive correlation between temperature and ozone increased in most areas, while the negative correlation increased in northern Quebec, Newfoundland and Labrador.

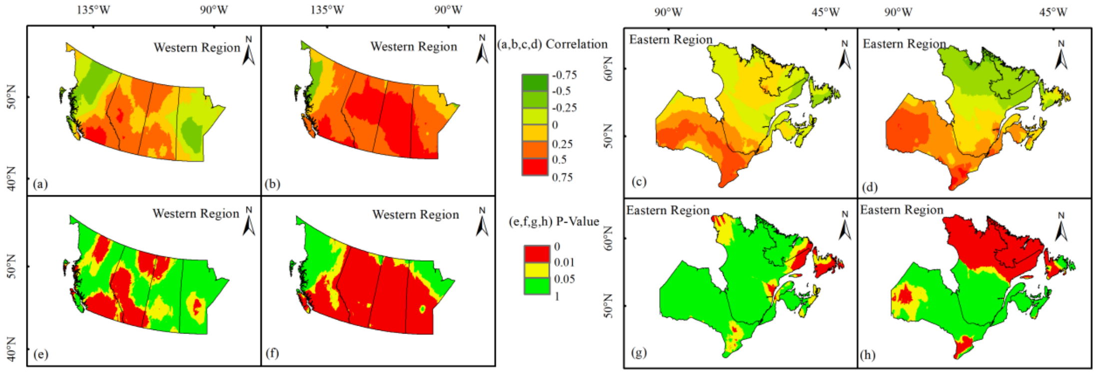

Figure 4: Spatial distribution of ozone-temperature correlations during non-heatwave-affected periods (a)(c) and heatwave-affected periods (b)(d) and p-values of correlations during non-heatwave-affected periods (e)(g) and heatwave-affected periods (f)(h).

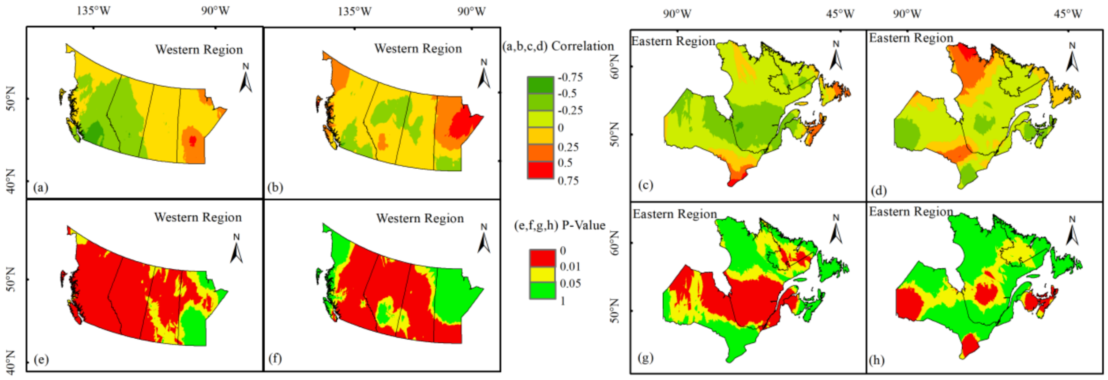

Figure 5: Spatial distribution of ozone-relative humidity correlations during non-heatwave-affected periods (a)(c) and heatwave-affected periods (b)(d) and p-values of correlations during non-heatwave-affected periods (e)(g) and heatwave-affected periods (f)(h).

Figure 5 shows the spatial correlation and P-values between ozone and relative humidity in southern Canada. From the spatial correlation between ozone and relative humidity, both heatwave-affected and non-heatwave-affected periods showed a weak negative correlation in the eastern and western parts of the study region. However, the range of overall negative ozone-relative humidity correlation was smaller in the heatwave-affected period than in the non-affected period. This suggests that the presence of heat waves weakened the negative correlation between relative humidity and ozone.

4.4. Comparison of the Health Effects of Ground-level Ozone Pollution during Heat Waves and Non-heat Waves

High temperatures and sunlight are key factors in ozone production, and extreme heat conditions help accelerate ozone production through photochemical reactions. As a result, ozone concentrations tend to increase during heat waves, which puts populations at higher risk of ozone exposure during heat waves. The research in this paper utilizes the BenMAP model, whose core strength is its ability to quantify the independent health effects of air pollution (particularly ozone). The model combines air quality data, meteorological data, and health data to estimate the effects of changes in ozone concentrations on population health by modeling exposure-response relationships. Exposure-response modeling allows BenMAP to accurately analyze the independent effects of elevated ozone concentrations on the number of deaths during a given period of time, excluding the interference of other potential factors. In this way, the BenMAP model can analyze premature deaths due to ozone exposure in isolation, without confounding the effects of other factors such as heat.

This paper analyzes the number of premature deaths due to ozone exposure in populations during heatwaves and non-heatwaves separately from a study in southern Canada, and further compares and analyzes the differences in health risks associated with short-term exposure to ambient ozone in populations during heatwaves versus non-heatwaves, and explores the impact of gender differences. Given that human exposure to ground-level ozone is more direct and sustained than that to tropospheric ozone, the impact of ground-level ozone on human health is more significant. For this reason, this study chose to use ground-level ozone data for health risk assessment. Table 1 provides reference data from mortality health studies used in this analysis.

Table 1: Exposure-response coefficients for health effects.

Healthy Endpoint	Beta			
	total number of people	Males	Females	C-R Function
All due to death.	0.00054 (0.0002,0.00085)	0.00087 (0.00036,0.00135)	0.0002 (-0.00028,0.00065)	Hwashin et al. 2021
cardiovascular death	0.0007 (0.00022,0.0011)	0.0011 (0.00031,0.00171)	0.0003 (-0.00046,0.00096)	Hwashin et al. 2020
Respiratory death	0.0011 (0.0001,0.0022)	-	-	Hwashin et al. 2022

4.4.1. All-cause Mortality Risk Assessment of Ozone Concentration Increases during Heatwave-affected and Non-heatwave-affected Periods

The geographical differences in the number of premature deaths caused by short-term ozone exposure are significant (Table 2). The ozone pollution mortality risks in the eastern region is higher than that in the western region, with Ontario and Quebec having the highest risk of ozone pollution death. These two provinces have the highest population and are also provinces with higher levels of ozone pollution, reflecting a combination of high population density and air pollution levels. Saskatchewan, Manitoba, Finland and Labrador, Prince Edward Island, New Brunswick, and Nova Scotia have the lowest death toll. Saskatchewan and Manitoba provinces have high levels of ozone pollution and low deaths, reflecting that the risk of death in these two provinces is mainly limited by population density.

Through gender comparison, it can be seen that there is a significant gender difference in the number of premature deaths caused by short-term ozone exposure (Table 2). Whether it is during the heat wave impact period or non impact period, the ozone pollution mortality risks for women is much higher than that for men.

Figure 6 shows the results of subtracting the number of premature deaths caused by short-term ozone exposure during the heat wave impact period from the number of deaths caused by non heat wave impact periods, resulting in an estimated number of all cause deaths caused by increased ozone due to heat waves (The number of people in the table is presented as the maximum, minimum, and average values). It can be seen that heat waves significantly increase ozone pollution mortality risks, especially in Ontario and Quebec, where the impact is most profound. The total number of premature deaths during the heat wave impact period was approximately 298.3 more than during the non impact period, with a growth rate of approximately 22.8%. There is a similar pattern in different categories (whether it is a group of people or a group of people divided by gender): the higher the ozone pollution mortality risks in a region or province, the higher the difference between the number of all cause deaths during the heat wave impact period and the non impact period.

Table 2: Health effects of ozone in southern Canada during heat wave impact and non-impact periods.

Region—population	Heatwave non-impact period(In persons, 95% CI)			Heatwave non-impact period(In persons, 95% CI)		
	All	Male	Females	All	Male	Females
Southern Canada—36,873,821	1307(486,2048)	239(-334,772)	1063(444,1640)	1605(597,2511)	294(-138,949)	1303(403,2008)
Alberta—4,262,635	132(49,206)	25(-34,91)	106(44,163)	159(59,249)	30(-41,95)	128(53,196)
British Columbia —5,000,879	154(57,242)	28(-39,91)	126(53,195)	177(66,277)	32(-45,104)	144(60,222)
Manitoba—1,342,153	46(17,73)	9(-12,28)	38(16,58)	64(24,100)	12(-17,38)	52(22,80)
New Brunswick—775,610	37(14,58)	7(-9,22)	30(13,46)	40(15,62)	7(-10,24)	32(14,50)
Newfoundland and Labrador—510,550	20(8,32)	4(-5,12)	17(7,26)	25(9,39)	5(-6,15)	20(8,31)
Nova Scotia—969,383	47(17,73)	8(-12,27)	39(16,59)	51(19,79)	9(-13,30)	42(17,64)
Ontario—14,223,942	503(187,787)	82(-128,295)	410(171,633)	613(228,957)	112(-156,360)	500(209,770)
Prince Edward Island—154,331	6(1,9)	1(-2,4)	5(2,8)	7(3,10)	1(-2,4)	6(2,8)
Québec—8,501,833	314(117,49)	58(-81,186)	255(106,393)	417(155,653)	77(-107,248)	337(141,520)
Saskatchewan—1,132,505	48(18,75)	9(-12,29)	38(16,59)	53(20,84)	10(-14,32)	43(18,66)

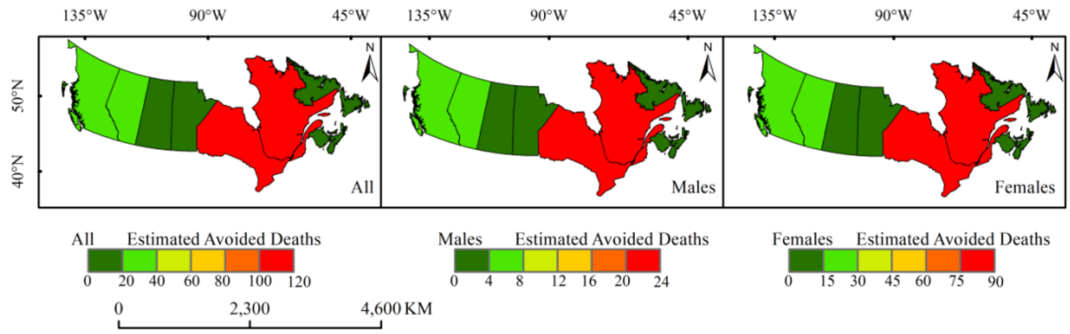

Figure 6: Estimated number of all-cause deaths due to increased ozone during heatwaves (minus non-heatwave effects.

4.4.2. Risk Assessment of Cardiovascular Disease Mortality Due to Ozone Concentrations during Heatwave-affected and Non-heatwave-affected Periods

The geographic and gender difference in premature deaths in the circulatory system due to short-term ozone exposure are similar to the pattern of all-cause mortality (Table 3). Circulatory deaths due to short-term ozone exposure accounted for about 25% of all-cause deaths.

By comparing the number of premature deaths in the circulation system caused by ozone during the heat wave impact period and the non heat wave impact period (Table 3 and Fig. 7), it can be seen that the number of people in the heat wave impact period is about 84.6 more than that in the non heat wave impact period, with a growth rate of about 22.6%. The heatwave significantly increases the risk of circulatory system death due to ozone pollution, especially in Ontario and Quebec, which are most affected. And similar to the risk pattern of all cause premature death, regions and provinces with a higher risk of ozone pollution death have a higher ozone pollution mortality risks caused by heat waves.

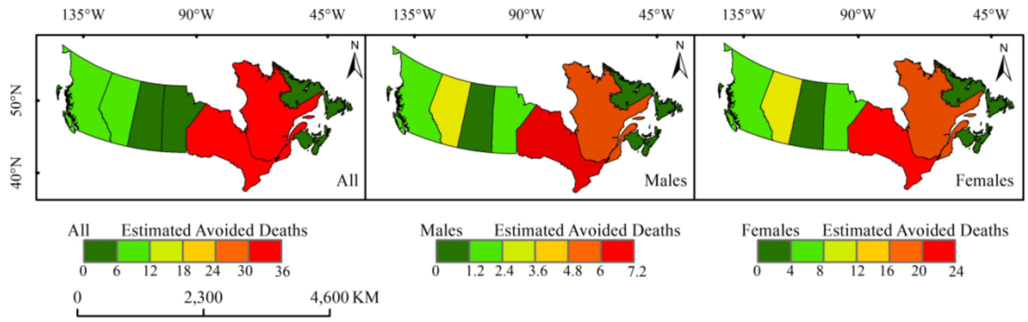

Figure 7: Estimated number of cardiovascular disease deaths due to increased ozone during heatwaves (less non-heatwave effects).

Table 3: Ozone health effects on cardiovascular disease during heatwave-affected and non-heatwave-affected periods in southern Canada.

Region—population	Heatwave non-impact period(In persons, 95% CI)			Heatwave non-impact period(In persons, 95% CI)		
	All	Male	Females	All	Male	Females
Southern Canada—36,873,821	375(119,586)	80(-121,257)	297(85,458)	460(146,716)	98(-149,315)	363(104,560)
Alberta—4,262,635	55(18,86)	12(-18,39)	43(12,67)	66(21,104)	14(-22,46)	52(15,80)
British Columbia —5,000,879	42(13,66)	9(-14,29)	34(10,52)	48(15,76)	10(-16,33)	38(11,59)
Manitoba —1,342,153	15(5,23)	3(-5,10)	12(3,18)	20(6,32)	4(-7,14)	16(5,25)

New Brunswick —775,610	9(3,14)	2(-3,6)	7(2,11)	9(3,14)	2(-3,3)	7(2,11)
Newfoundland and Labrador —510,550	6(2,9)	1(-2,4)	5(1,7)	7(2,11)	1(-2,5)	6(2,9)
Nova Scotia —969,383	12(4,19)	3(-4,8)	10(3,15)	13(4,20)	3(-4,9)	11(3,16)
Ontario —14,223,942	143(45,224)	30(-46,98)	113(33,176)	174(55,272)	37(-56,119)	139(40,214)
Prince Edward Island—154,331	2(1,3)	1(-1,1)	2(1,2)	2(1,3)	1(-1,1)	2(1,3)
Québec—8,501,833	77(24,120)	16(-25,53)	61(17,94)	102(32,159)	22(-33,70)	81(23,124)
Saskatchewan—1,132,505	14(4,22)	3(-5,10)	11(3,17)	16(5,25)	3(-5,11)	12(4,19)

4.4.3. Risk Assessment of Respiratory Mortality Due to Ozone Concentrations during Heatwave-affected and Non-heatwave-affected Periods

In Canada, there is no significant gender difference in the risk of death from ozone exposure in the respiratory system[15], so this article only studies the overall population's risk of death from ozone pollution. The ozone pollution mortality risks of respiratory system death in the eastern region is higher than that in the western region (Table 4).

Table 4: Ozone health effects on respiratory disease during heat wave impact and non-impact periods in southern Canada.

Region—population	Heatwave non-impact period	Heat wave impact periods
	All mortality(In persons, 95% CI)	All mortality(In persons, 95% CI)
Southern Canada—36,873,821	207(19,409)	255(24,500)
Alberta—4,262,635	28(3,54)	33(3,65)
British Columbia — 5,000,879	22(2,43)	25(2,50)
Manitoba —1,342,153	7(1,14)	10(1,19)
New Brunswick —775,610	5(1,11)	6(1,11)
Newfoundland and Labrador —510,550	3(0,7)	4(0,8)
Nova Scotia —969,383	7(1,13)	7(1,15)
Ontario —14,223,942	76(7,149)	92(9,181)
Prince Edward Island—154,331	1(0,2)	1(0,3)
Québec—8,501,833	51(5,100)	68(6,132)
Saskatchewan—1,132,505	7(1,15)	9(1,17)

Figure 8 shows the results of subtracting the number of premature deaths from the respiratory system caused by short-term ozone exposure during the heat wave impact period from the number of people during the non heat wave impact period. The number of people in the heat wave affected period in southern Canada increased by approximately 47.2 people compared to the non heat wave affected period, with a growth rate of approximately 23.2%. The heatwave significantly increases the risk of cycling system death due to ozone pollution during the heatwave period, especially in Ontario and Quebec, which are most profoundly affected, and this is roughly consistent with the results of the all-cause analysis.

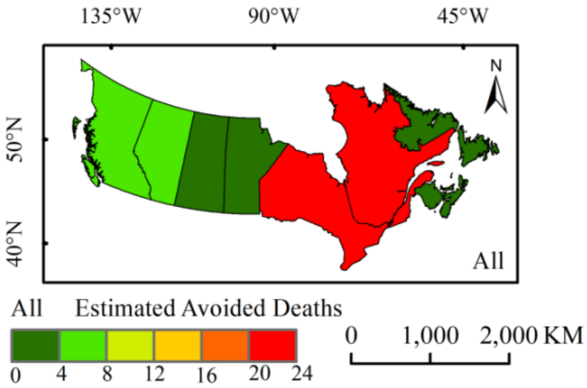

Figure 8: Estimated number of deaths from respiratory diseases due to increased ozone during heatwaves (less non-heatwave effects.

5. Discussion

From the overall spatial distribution of ozone in the study area, according to the ground ozone spatial distribution map and the tropospheric atmosphere spatial distribution map, the ground and tropospheric ozone concentrations show a distribution pattern of high in the south and low in the northwest. This distribution pattern is not only affected by the temperature brought by latitude, but also by cross-border ozone. The southern part of the region is susceptible to the impact of cross-border air pollution, especially in the southern and southwestern regions of Ontario[31-32]. The inland areas of the western grasslands have low precipitation and very dry air masses, which is very beneficial for the growth of ozone concentration. In the eastern region, southern Ontario belongs to the Great Lakes Industrial Zone, which supports many heavy industries and has developed trade and transportation, making the area a high ozone.

As many previous studies have revealed, there is a strong positive correlation between ozone and temperature, while there is a strong negative correlation between ozone and relative humidity[33]. The occurrence of the vast majority of heat waves increases ozone concentration[34-36]. In terms of the relationship between ozone and temperature, the appearance of heat waves has enhanced the positive correlation between temperature and ozone in most regions, while the negative correlation has increased in northern Quebec, Newfoundland, and Labrador provinces. This is because the increase in temperature directly affects the chemical kinetic rate and mechanism pathways of ozone production, leading to an increase in ozone in most regions. However, this is not always effective, as the rate of increase also depends on the concentration levels of volatile organic compounds and nitrogen oxides. Each variable leads to a unique nonlinear reaction to ozone through its specific mechanism, which may affect the chemical reactions of ozone formation or depletion[37]. In terms of the relationship between relative humidity and ozone, heat waves weaken the negative correlation between relative humidity and heat waves. During the heat wave, ozone and relative humidity are negatively correlated only in the central, southwestern, and southeastern parts of the western region, as well as in the central and southern parts of the eastern region. This indicates that different regions require different environmental management measures during heatwaves, providing targeted measures to reduce ozone, and providing training to adapt to climate change.

As previous research has revealed, ozone can have an impact on human life and health. However, there is a lack of research on the impact of ozone pollution on life and health under heatwave conditions, with only one study on deaths related to air pollution during the 2003 Dutch heatwave [38]. On this basis, this article compares the impact of ozone on health during the heat wave impact period and non heat wave impact period. The results indicate that (1) there are strong regional and gender differences in the number of premature deaths caused by ozone. In terms of geographical differences, the patterns of all-cause, circulatory, and respiratory mortality risks are the same. Compared to the western region, the eastern region has a higher mortality risk from ozone pollution, while Ontario and Quebec have the highest mortality risk. According to previous analysis, geographical differences may be due to the combined effects of population density and ozone pollution levels. In terms of gender differences, compared to men, women have significantly higher ozone pollution mortality rates in terms of cyclic and all-cause mortality rates. This is mainly because in Canada, regardless of cyclic and all-cause mortality rates, women have higher mortality rates from exposure to ozone[13]. (2) Whether it is all-cause death or death in the circulatory or respiratory systems, the growth rate of ozone exposure death caused by heat waves ranges from 22.6% to 23.2%. This indicates that ozone pollution under heat wave conditions has a more significant impact on life and health. The synergistic effects of ozone and temperature on mortality are complex, and this study only explores ozone concentrations, mortality, and population data based on heatwave-impacted versus non-impacted periods; further unraveling of the relationship between ozone and temperature and mortality under heatwave conditions may require the application of methodologies such as generalized additivity models (GAMs) to control for confounding effects.

6. Conclusion

This article finds that the appearance of heat waves has a significant impact on the growth of ground and tropospheric ozone concentration; Enhanced the correlation between temperature and ozone, weakened the negative correlation between relative humidity and ozone; The appearance of heat waves leads to an increase in the number of deaths caused by ozone exposure, and there are significant gender and geographical differences in the number of deaths caused by ozone exposure. These findings are crucial for the government to develop long-term preventive measures in heatwave plans, which can help people better manage the environment and adapt to climate change. Overall, these findings have played an important role in preventing environmental pollution, strengthening weather forecast management, promoting sustainable urban-rural development, and helping people adapt to climate change.

Statement

Declaration of Competing Interest: The authors report no declarations of interest.

References

[1] Atkinson R. Atmospheric chemistry of VOCs and NOx[J]. Atmospheric environment, 2000, 34(12-14): 2063-2101.

[2] Lacis A A, Wuebbles D J, Logan J A. Radiative forcing of climate by changes in the vertical distribution of ozone[J]. Journal of Geophysical Research: Atmospheres, 1990, 95(D7): 9971-9981.

[3] Qin L, Gu J, Liang S, et al. Seasonal association between ambient ozone and mortality in Zhengzhou, China[J]. International journal of biometeorology, 2017, 61: 1003-1010.

[4] Huang J, Zhou C, Lee X, et al. The effects of rapid urbanization on the levels in tropospheric nitrogen dioxide and ozone over East China[J]. Atmospheric environment, 2013, 77: 558-567.

[5] Huryn S M, Gough W A. Impact of urbanization on the ozone weekday/weekend effect in Southern Ontario, Canada[J]. Urban Climate, 2014, 8: 11-20.

[6] Cohen A J, Brauer M, Burnett R, et al. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015[J]. The lancet, 2017, 389(10082): 1907-1918.

[7] Brauer M, Freedman G, Frostad J, et al. Ambient air pollution exposure estimation for the global burden of disease 2013[J]. Environmental science & technology, 2016, 50(1): 79-88.

[8] Public Health Agency of Canada.(2021).Health Impacts of Air Pollution in Canada: Estimates of morbidity and premature mortality outcomes – 2021 Report.Retrieved fromhttps://www.canada.ca/en/health-canada/services/publications/healthy-living/health-impacts-air-pollution-2021.html#a3.1. Accessed September 13, 2024

[9] Shin H H, Gogna P, Maquiling A, et al. Comparison of hospitalization and mortality associated with short-term exposure to ambient ozone and PM2. 5 in Canada[J]. Chemosphere, 2021, 265: 128683.30

[10] Environment and Climate Change Canada .(2013). National Air Pollution Surveillance Program: NAPS Program Information.Retrieved from https://www.canada.ca/en/environment-climate-change/search.html?q=NAPS&wb-srch-sub=#wb-land. Accessed September 13, 2024

[11] Cakmak S, Hebbern C, Pinault L, et al. Associations between long-term PM2. 5 and ozone exposure and mortality in the Canadian Census Health and Environment Cohort (CANCHEC), by spatial synoptic classification zone[J]. Environment international, 2018, 111: 200-211.

[12] Villeneuve P J, Huynh D, Lavigne É, et al. Daily changes in ambient air pollution concentrations and temperature and suicide mortality in Canada: findings from a national time-stratified case-crossover study[J]. Environmental research, 2023, 223: 115477.

[13] Shin H H, Parajuli R P, Maquiling A, et al. Temporal trends in associations between ozone and circulatory mortality in age and sex in Canada during 1984–2012[J]. Science of the Total Environment, 2020, 724: 137944.

[14] Zhao N, Pinault L, Toyib O, et al. Long-term ozone exposure and mortality from neurological diseases in Canada[J]. Environment international, 2021, 157: 106817.

[15] Parajuli R P, Shin H H, Maquiling A, et al. Multi-pollutant urban study on acute respiratory hospitalization and mortality attributable to ambient air pollution in Canada for 2001–2012[J]. Atmospheric Pollution Research, 2021, 12(12): 101234.

[16] Kegel F, Luo O D, Richer S. The impact of extreme heat events on emergency departments in Canadian hospitals[J]. Wilderness & environmental medicine, 2021, 32(4): 433-440.

[17] Environment and Climate Change Canada .(2021).Canada's top 10 weather stories of 2021. Retrieved from https://www.canada.ca/en/environment-climate-change/services/top-ten-weather-stories/2021.html. Accessed September 13, 20247

[18] Meehl G A, Tebaldi C, Tilmes S, et al. Future heat waves and surface ozone[J]. Environmental Research Letters, 2018, 13(6): 064004.

[19] Jaén C, Udina M, Bech J. Analysis of two heat wave driven ozone episodes in Barcelona and surrounding region: Meteorological and photochemical modeling[J]. Atmospheric Environment, 2021, 246: 118037.

[20] Wang R, Bei N, Hu B, et al. The relationship between the intensified heat waves and deteriorated summertime ozone pollution in the Beijing–Tianjin–Hebei region, China, during 2013–2017[J]. Environmental Pollution, 2022, 314: 120256.

[21] Yang X, Zeng G, Iyakaremye V, et al. Effects of different types of heat wave days on ozone pollution over Beijing-Tianjin-Hebei and its future projection[J]. Science of The Total Environment, 2022, 837: 155762.

[22] Pascal M, Wagner V, Alari A, et al. Extreme heat and acute air pollution episodes: A need for joint public health warnings?[J]. Atmospheric environment, 2021, 249: 118249.

[23] Egea A, Linares C, Díaz J, et al. How heat waves, ozone and sunlight hours affect endocrine and metabolic diseases emergency admissions? A case study in the region of Madrid (Spain)[J]. Environmental Research, 2023, 229: 116022.

[24] López-Bueno J A, Díaz J, Padrón-Monedero A, et al. Short-term impact of extreme temperatures, relative humidity and air pollution on emergency hospital admissions due to kidney disease and kidney-related conditions in the Greater Madrid area (Spain)[J]. Science of The Total Environment, 2023, 903: 166646.

[25] Hong H, Lee H, Kim J, et al. First comparison of OMI-DOAS total ozone using ground-based observations at a megacity site in East Asia: Causes of discrepancy and improvement in OMI-DOAS total ozone during summer[J]. Journal of Geophysical Research: Atmospheres, 2014, 119(16): 10058-10067.

[26] Environment Canada.(2011).Adapting to Extreme Heat Events: Guidelines for Assessing Health Vulnerability. Retrieved from https://www.canada.ca/en/health-canada/services/environmental-workplace-health/reports-publications/climate-change-health/adapting-extreme-heat-events-guidelines-assessing-health-vulnerability-health-canada-2011.html#fn7.Accessed September 13, 2024

[27] Environment and Climate Change Canada .(2019).Canada's top 10 weather stories of 2019.Retrieved from https://www.canada.ca/en/environment-climate-change/services/top-ten-weather-stories/2019.html. Accessed September 13, 2024

[28] Peng S, Ju T, Liang Z, et al. Analysis of atmospheric ozone in Fenwei Plain based on remote sensing monitoring[J]. Environmental Monitoring and Assessment, 2022, 194(6): 412.

[29] US EPA．(2023). BenMAP-CE Manual and Appendices．Retrieved from http: / /www2. epa． gov /benmap /manual-and-appendices-benmap-ce.Accessed September 13, 2024

[30] Ju T, Liang Z, Liu W, et al. Monitoring of air pollution by remote sensing in Lanzhou City from 2010 to 2019[J]. Water, Air, & Soil Pollution, 2022, 233(9): 359.

[31] Yap D, Ning D T, Dong W. An assessment of source contributions to the ozone concentrations in southern Ontario, 1979–1985[J]. Atmospheric Environment (1967), 1988, 22(6): 1161-1168.

[32] Leung K H Y. Projecting the Influence of Climate Change on Extreme Ground-level Ozone Events in Selected Ontario Cities[M]. University of Toronto (Canada), 2015.

[33] Liao Z, Pan Y, Ma P, et al. Meteorological and chemical controls on surface ozone diurnal variability in Beijing: A clustering-based perspective[J]. Atmospheric Environment, 2023, 295: 119566.

[34] Pu X, Wang T J, Huang X, et al. Enhanced surface ozone during the heat wave of 2013 in Yangtze River Delta region, China[J]. Science of the Total Environment, 2017, 603: 807-816.

[35] Kalisa E, Fadlallah S, Amani M, et al. Temperature and air pollution relationship during heatwaves in Birmingham, UK[J]. Sustainable cities and society, 2018, 43: 111-120.

[36] Varotsos K V, Giannakopoulos C, Tombrou M. Ozone-temperature relationship during the 2003 and 2014 heatwaves in Europe[J]. Regional Environmental Change, 2019, 19: 1653-1665.

[37] Steiner A L, Davis A J, Sillman S, et al. Observed suppression of ozone formation at extremely high temperatures due to chemical and biophysical feedbacks[J]. Proceedings of the National Academy of Sciences, 2010, 107(46): 19685-19690.

[38] Fischer P H, Brunekreef B, Lebret E. Air pollution related deaths during the 2003 heat wave in the Netherlands[J]. Atmospheric environment, 2004, 38(8): 1083-1085.