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UV, ozone, and COVID-19 transmission in Ontario, Canada using generalised linear models

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ABSTRACT

Background: Quantifying the impact of environmental factors on COVID-19 transmission is crucial in preventing more cases. Ultraviolet (UV) radiation and ozone (O3) have reported antimicrobial properties but few studies have examined associations with community infectivity of COVID-19. Research suggests UV light can be preventative while the effect of O3 is contested. We sought to determine the relationship between UV, O3, and COVID-19 incidence in Ontario, Canada.

Methods: In our time series analyses, we calculated daily incidence rates and reproductive number (Rt) from 34,975 cases between January and June 2020 across 34 Ontario Public Health Units. We used generalised linear models, adjusting for potential confounders, to calculate point estimates (PE) and 95% confidence intervals (CI) for UV and O3. Analyses were further stratified by age groups and outbreaks at institutions versus community.

Results: We found that 1-week averaged UV was significantly associated with a 13% decrease (95% CI: 0.80–0.96) in overall COVID-19 Rt per unit increase. A negative association with UV was also significant among community outbreaks (PE: 0.88, 95% CI: 0.81–0.96) but not institutional outbreaks (PE: 0.94, 95% CI: 0.85–1.03). A positive association of O3 with COVID-19 incidence is strongly suggested among institutional outbreak cases (PE: 1.06, 95% CI: 1.00–1.13).

Conclusion: Our study found evidence to support the hypothesis that higher UV reduced transmission of COVID-19 and some evidence that ground-level O3 positively influenced COVID-19 transmission. Setting of infection should be strongly considered as a factor in future research. UV and O3 may explain some of COVID-19’s seasonal behaviour.

1. Introduction

The novel coronavirus disease (COVID-19), caused by Severe Acute Respiratory Syndrome Coronavirus-2 (SARS-CoV-2), is a highly infectious disease (basic reproductive number – 3–5) (Sanche et al., 2020) with high incubation time (up to 14 days) (Lauer et al., 2020). Asymptomatic and pre-symptomatic transmission is possible and can make up 40% of transmitted cases (He et al., 2020). SARS-CoV-2 is transmitted through droplets or aerosol secreted by an infected person (Morawska and Milton, 2020), can remain on surfaces for up to 72 h (van Doremalen et al., 2020), and can travel up to 8 m in the air (Guenther et al., 2020).

COVID-19 was declared a global pandemic on March 11, 2020 with over 115,000 cases, four months after the first reported cases in Wuhan, China (Dong et al., 2020). By August 17, 2020, over 21 million cases and 770,000 deaths have been counted globally (Dong et al., 2020). While the pandemic continues to spike in several countries, many others, which had suppressed the virus earlier, have begun to prepare for or are already experiencing second and third waves.

Given its novelty and infectivity, it is crucial to understand factors that effect COVID-19 transmission to prevent more cases. The role of the environment in COVID-19 transmission, especially with the easing of lockdowns globally and warmer weather in the northern hemisphere, is
important to consider. It has been observed that countries with lower air temperature and humidity (e.g. Korea, Japan, and Iran) have experienced more severe outbreaks compared to warmer and more humid countries (e.g. Singapore, Malaysia, and Thailand). These early observations sparked speculations that COVID-19, like other coronaviruses (SARS and MERS), may survive longer in colder environments than warmer ones (Nicholls, 2020). It has also been suggested that strong ultraviolet light (UV) may diminish COVID-19 and other human coronavirus strains, such as SARS and MERS, and natural UV light is estimated to be able to inactivate 90% of SARS-CoV-2 (Sagripani and Lytle, 2020). More specifically, UVC, a type of UV, is a strong disinfectant, destroying genetic material including viral particles and SARS-CoV-2 (Heilingloh et al., 2020). Some suggest that where and when UV light is high, the pandemic may decline (Tsunetsugu-Yokota, 2008). Similarly, ozone (O$_3$) is formed in presence of UV radiation in the Earth’s atmosphere and is known to have antiviral and antimicrobial effects. Given these sanitizing properties, O$_3$ has been used in therapeutics, can disrupt viral reproduction cycles, and has been suggested as a therapeutic treatment for COVID-19 (Martinez-Sanchez et al., 2020; Jerrett et al., 2009). However, high amounts of O$_3$ in humans can cause adverse health effects including respiratory damage and diseases such as asthma (Jerrett et al., 2009).

To date, there is limited published peer-reviewed research examining how UV and other meteorological factors affect SARS-CoV-2 transmission in human populations. Recently, Yao et al. measured the association between UV radiation and COVID-19 cases (from 224 Chinese cities from January to March 9, 2020), while adjusting for temperature and relative humidity, and found no statistically significant associations (Yao et al., 2020). In contrast, Guasp et al. studied various climate and demographic factors from 359 countries and regions; they reported an independent negative association between UV radiation and COVID-19 cases (Guasp et al., 2020). Similarly, Gunthe et al. examined meteorological data from 85 locations between January and February 2020 and found a dose-response relationship between UV index and COVID-19 incidence, where COVID-19 incidence peaked at UV index 2.5 and decreased dramatically after UV index 5 (Gunthe et al., 2020). Despite its antimicrobial properties, increased ground-level O$_3$ often a contributor to air pollution, has been recently associated with increased COVID-19 incidence. However, research on the association of O$_3$ and COVID-19 is limited and findings have been mixed. For example, a study on 120 cities in China found a positive association, while another study in 154 Chinese cities found an inverse association between UV radiation and COVID-19 cases (from 224 Chinese cities from January to March 9, 2020), while adjusting for temperature and relative humidity, and found no statistically significant associations (Yao et al., 2020). In contrast, Guasp et al. studied various climate and demographic factors from 359 countries and regions; they reported an independent negative association between UV radiation and COVID-19 cases (Guasp et al., 2020). Similarly, Gunthe et al. examined meteorological data from 85 locations between January and February 2020 and found a dose-response relationship between UV index and COVID-19 incidence, where COVID-19 incidence peaked at UV index 2.5 and decreased dramatically after UV index 5 (Gunthe et al., 2020). Despite its antimicrobial properties, increased ground-level O$_3$ often a contributor to air pollution, has been recently associated with increased COVID-19 incidence. However, research on the association of O$_3$ and COVID-19 is limited and findings have been mixed. For example, a study on 120 cities in China found a positive association, while another study in 154 Chinese cities found an inverse association between ambient O$_3$ and COVID-19 (Zhu et al., 2020; Ran et al., 2020). In Italy, both Fattorini et al. and Zoran et al. found positive associations between O$_3$ and COVID-19 (Fattorini and Regoli, 2020; Zoran et al., 2020). Zoran et al. also suggested that O$_3$ may act as a virus incubator (Zoran et al., 2020). In contrast, Semple et al. commented that high concentrations of O$_3$ in high altitude areas may have a protective effect on high altitude communities against SARS-CoV-2 with its reactive properties (Semple and GWK, 2020).

The mixed and contrasting evidence among observational studies warrants further population-based investigation. Thus, it is the objective of this study is to use data from Ontario, Canada to examine the association of UV radiation, O$_3$, and incidence of COVID-19 from January to June 2020.

2. Methods

2.1. COVID-19 case data

Epidemiologic data on positive cases of COVID-19 in Ontario, Canada were obtained for January to June 2020 from an open dataset compiled by the Ontario Ministry of Health and Long-Term Care based on information reported by local public health agencies (Ontario Ministry of Health, 2020). Provincially data provided a report date for each case. For this study, we aggregated the COVID-19 incidence data by report date, Ontario Public Health Unit (PHU), age group, gender, transmission source, and outbreak relation. Ontario PHUs are administrative geographical units defined by the provincial health ministry to facilitate the delivery of health care to communities within the regions. Outbreak relation was defined as whether the case was connected to an outbreak in an institutional setting (e.g. long-term care home, hospital, correctional facility, etc.) (Ontario Ministry of Health, 2020).

2.2. Exposure data

Daily UV and O$_3$ data were obtained for January to June 2020 and averaged across each Ontario PHU (n = 34). Maximum UV index data were obtained from Environment and Climate Change Canada (Environment Canada. Histo, 2019). Daily O$_3$ data were obtained from the Ontario Ministry of the Environment, Conservation and Parks (Air Quality Ontario. Curr, 2020).

2.3. Covariate climate and regional data

Climate data, encompassing daily meteorological data and daily nitric oxide (NO), nitrogen dioxide (NO$_2$), and fine particulate matter of <2.5 μm diameter (PM$_{2.5}$) data, were obtained from January to June 2020 and averaged across each Ontario PHU. Daily meteorological data (mean ambient temperature, mean relative humidity, mean wind speed, mean air quality health index (AQHI), and total precipitation) were obtained from Environment and Climate Change Canada (Environment Canada. Histo, 2019). Daily NO, NO$_2$, and PM$_{2.5}$ data were obtained from the Ontario Ministry of the Environment, Conservation and Parks (Air Quality Ontario. Curr, 2020).

Regional data by Ontario PHU were also obtained. PHU-level rates of self-rated physical health, prevalence of asthma, chronic obstructive pulmonary disease (COPD), hypertension, smoking, and obesity were obtained from the Canadian Community Health Survey 2017/2018 cycle from Statistics Canada (Statistics Canada, 2020). Data on population densities, average ages, and population counts for each PHU were obtained from the 2016 Canadian census from Statistics Canada (Statistics Canada, 2019). Data on marginalization indices by PHU were obtained from the Canadian Urban Environmental Health Research Consortium (Matheson et al., 2012).

In Ontario, full lockdown restrictions (except for essential services) began on March 23, 2020 and were slowly eased in the following weeks on a case-by-case basis by PHU. Ontario follows a stage framework for reopening where stage 1 allows selected workplaces to open and some small gatherings; stage 2 open more workplaces and outdoor spaces, allow some larger gatherings; and stage 3 further relaxes the restrictions on public gatherings, opening all workplaces responsibly (Go, 2020a). Among the three stages of public health measures and restrictions, where higher stages allowed for more businesses and areas to reopen, the first PHUs were moved to stage 1 restrictions on May 19, 2020 and stage 2 restrictions began on June 8, 2020. The last PHUs were moved to stage 2 by July 7, 2020 (Go, 2020b). PHUs were assigned a categorical indicator based on what stage they were in by date for this work’s analyses.

2.4. Statistical analysis

In this time series study, point estimates (PE) and 95% confidence intervals (CI) for associations between COVID-19 activity (daily incidence or time-varying reproductive number R$_t$) and UV and O$_3$ were estimated with generalised linear models using the restricted maximum likelihood method, accounting for clustering within PHUs and repeated date measures. Both incidence and R$_t$ models used first-order autoregressive covariance structures. Daily incidence rates were modelled in a negative binomial distribution and calculated from the gender-age group-PHU specific case count with an at-risk population offset that was gender-age group-PHU specific. R$_t$, a metric for estimating the
expected number of additional cases each positive case will result in, was estimated from the number of cases at each time point, distinguishing between locally spread and imported cases, and the serial interval, the estimated time between two symptomatic cases. Daily R\textsubscript{t} was calculated from daily case data for each PHU (Thompson et al., 2019) and modelled with a gamma distribution. UV exposure was measured using the UV index (ranging from 0 to 11\textsuperscript{+}). O\textsubscript{3} exposure was measured in parts per billion (ppb). Cases were linked to climate variables by report date and regional variables by PHU. To estimate the climate around time of infection, UV, O\textsubscript{3}, and covariate climate data were averaged one week prior to the report date.

Covariates for models were selected a priori and assessed using a forward building method. Only statistically significant covariates were included in analyses in models. Incidence models had log-transformed outcomes and all models were adjusted for mean temperature (°C), mean relative humidity (%), mean wind speed (km/h), total precipitation (mm), NO (ppb), NO\textsubscript{2} (ppb), PM\textsubscript{2.5} (μg/m\textsuperscript{3}), COPD (%), hypertension (%), daily smokers (%), adults who are obese (%), population density (person/km\textsuperscript{2}), lockdown stage (pre-restriction, full lockdown, stage 1, stage 2), deprivation index (quintile), and ethnic concentration index (quintile). Incidence models were further adjusted for gender (male, female), age group (<20, 20–29, 30–39, 40–49, 50–59, 60–69, 70–79, 80–89, 90+), good physical health (%), poor physical health (%), asthma (%), and adults who are overweight (%). R\textsubscript{t} models were also adjusted for mean age (years) and gender (%). Male and female incidence models were subsequently stratified by age group and gender and all models were stratified by outbreak relation (institutional, community) for subgroup analyses.

UV was tested for an interaction with temperature and UV and O\textsubscript{3} were each assessed for a non-linear relationship using a 5-knot restricted cubic spline for each model. Model differences were assessed using statistical significance was defined where p-values were <0.05. All regression analyses were performed in SAS software (v9.4; SAS Institute Inc., Cary, NC). Data cleaning, model building, and graphics were performed in R software (v4.0.2) (R Foundation, 2020) with the packages: zoo (v1.8-8), tidyverse (v1.3.0), EpiEstim (v2.2-3), incidence (v1.7.1), ggrepack (v1.3–1), forestplot (v1.10), and MuMln (v1.43.17).

3. Results

3.1. Descriptive results

Our study included 34,975 COVID-19 cases in Ontario, Canada across 34 PHUs reported between January 1st and June 28th, 2020. This represented 100% of Ontario’s confirmed cases and 33.6% of Canada’s cases to date. The mean ± standard deviation and range (min-max) for daily incidence and R\textsubscript{t} were (13.08 ± 33.6, 0.184–682.2) and (1.43 ± 1.83, 0.09–30), respectively. The mean ± standard deviation and range for UV and O\textsubscript{3} were (5.90 ± 1.71, 1–12) and (32.02 ± 3.32, 8.25–58.0).

Table 1 shows a summary of characteristics by covariates used in multivariate models. Fig. 1 and Fig. 2 show the distributions of UV and O\textsubscript{3} averages by PHU from January to June 2020, respectively. Mean, standard deviation, and ranges of UV and O\textsubscript{3} by PHU are in Table S1.

### Table 1

| Case Variables | All | Community | Institutional |
|----------------|-----|-----------|--------------|
| Age            | 1668 | 1498 (7.1) | 170 (1.2) |
|                | 20–29| 5306 (15.2) | 4079 (19.5) |
|                | 30–39| 4873 (13.9) | 3350 (16.0) |
|                | 40–49| 4964 (14.2) | 3345 (16.0) |
|                | 50–59| 5652 (16.1) | 3878 (18.5) |
|                | 60–69| 3994 (11.4) | 2695 (12.9) |
|                | 70–79| 1333 (6.4) | 1317 (9.4) |

(continued on next page)
Ontario with individuals aged over 80 experiencing the highest rates. Institutional outbreak-related cases were more likely to be female and were over 80 years old than community-related cases.

3.2. Regression results

Univariate analysis of averaged UV and O$_3$ found significant correlations with daily incidence and R$_t$ (Table 2). After adjusting for covariates, 1-week averaged UV was not significantly associated with daily COVID-19 incidence rate overall (PE: 1.00, 95% CI: 0.95–1.06) or after outbreak stratification (Fig. 3a, Table 3). When stratified by age group, all age groups did not show significant associations between UV and COVID-19 incidence rates (Fig. 3c, Table 4).

UV was associated with overall R$_t$. Averaged 1 week prior to report date, adjusting for covariates, a per unit increase in UV was significantly associated with a 13% decrease (95% CI: 0.80–0.96) of overall R$_t$ (Fig. 3b, Table 5). When stratified by age group, all age groups did not show significant associations between UV and COVID-19 incidence rates (Fig. 3c, Table 4).

O$_3$ was not found to have significant associations. However, some associations are suggested. A per unit increase in 1-week averaged O$_3$ was not associated in the overall incidence rate (PE: 1.02, 95% CI: 0.998–1.04), adjusting for covariates. When stratified by outbreak relation and adjusted for covariates, a positive association of incidence with O$_3$ approached significance for institutional outbreaks (PE: 1.06, 95% CI: 1.00–1.13) unlike community outbreaks (PE: 1.00, 95% CI: 0.98–1.03) (Fig. 4a, Table 3). When stratified by age group and controlling for other variables, individuals in age group 20–29 had an associated increase in incidence rate ratio by a factor of 1.04 (95% CI: 1.01–1.07) per unit increase in O$_3$. No other age group had significant associations (Fig. 4c, Table 4). O$_3$ was not associated with R$_t$ overall or when stratified by outbreak relation but suggested a negative association (Table 5).

Gender stratification did find any meaningful difference. Findings of associations with other air pollutants (NO, NO$_2$, PM$_{2.5}$) are shown in Table S2. No significant interaction between UV and temperature was found in any of the models. Non-linear UV and O$_3$ models were not found to be a better fit than the linear models in full multivariate analysis (Table S3). Sensitivity analyses showed our findings to be robust.

4. Discussion

This study correlated Ontario provincial data of COVID-19 cases and meteorological and air pollution data from January to June 2020. To our knowledge, this is the first Canadian study that has investigated the association between O$_3$ and COVID-19 and the first study that has investigated the association between UV and COVID-19 at a sub-national level within Canada. Our study found an overall negative association between ambient UV and COVID-19 activity in R$_t$, while adjusted for climate and demographic factors. When stratified by institutional outbreak relation, adjusting for covariates, the associations between UV and COVID-19 R$_t$ remained statistically significant for institutional outbreak cases but not community outbreak cases. Our
study found no statistically significant associations between $O_3$ and COVID-19 incidence, overall and by outbreak relation, though a positive association is suggested. When stratified by institutional outbreak relation, the positive association between $O_3$ and COVID-19 incidence was strongly suggested for institutional outbreak cases but not for community outbreak cases. When stratified by age groups, the association between $O_3$ and COVID-19 incidence remained statistically significant for individuals aged 20–29. UV radiation is a natural environmental antimicrobial. Previous studies have shown that climate variables such as temperature, sunlight, or UV light may affect the transmission of influenza and other viruses.

Table 2
Expontiated point estimates, 95% CIs, and p-values for univariate analysis of 1-week averaged UV and $O_3$ for daily incidence and $R_t$.

|           | Daily Incidence | Effective $R_t$ |
|-----------|-----------------|-----------------|
|           | Estimate | 95% CI  | p-value | Estimate | 95% CI  | p-value |
| UV        | 0.97     | (0.88–0.98) | 0.01    | 0.97     | (0.89–1)   | 0.051   |
| $O_3$     | 1.00     | (0.88–0.99) | 0.03    | 0.99     | (0.94–0.99) | <0.01   |

Fig. 2. Daily 1-week averaged $O_3$ between January to June 2020 by Ontario PHU.

Fig. 3. A) Percent change per unit increase in UV for COVID-19 incidence rate overall and by outbreak subgroup. B) Percent change per unit increase in UV for COVID-19 $R_t$ overall and by outbreak subgroup. C) Percent change per unit increase in UV for COVID-19 incidence rate overall and by age group.
therefore hypothesized that COVID-19 transmission may behave similarly to previous positive immune effects (Grant et al., 2020; McCartney and Coulthard 2020). UV may inactivate COVID-19 as it does with coronaviruses (Tsasetsugu-Yokota, 2008) and MERS-CoV (Tsunetsugu-Yokota, 2008). UV also helps generate vitamin D in the body through skin exposure. Given the reports of O3 detrimental to human health. It is well-documented that inhalation of high levels of O3 can increase epithelial permeability in the lungs and may disturb local biota, increasing susceptibility to respiratory infection (Kehrl et al., 1987; Niu et al., 2020). Relatedly, O3 may disturb local biota, increasing susceptibility to respiratory infection (Kehrl et al., 1987; Niu et al., 2020).



Table 3

| Overall | Community Outbreak | Institutional Outbreak |
|---------|-------------------|-----------------------|
|         | Estimate<sup>a</sup> | 95% CI | p-value | Estimate<sup>b</sup> | 95% CI | p-value | Estimate<sup>b</sup> | 95% CI | p-value |
| UV      | 1.00 (0.95-1.06)   | 0.93     |         | 1.01 (0.93-1.11)   | 0.78     |         | 0.98 (0.84-1.15)   | 0.79     |         |
| O3      | 1.02 (0.998-1.04)  | 0.08     |         | 1.00 (0.98-1.03)   | 0.99     |         | 1.06 (1.00-1.13)   | 0.05     |         |

<sup>a</sup> Adjusted for for age group, lockdown stage, outbreak relation, gender, deprivation, ethnic concentration, NO<sub>2</sub>, NO, precipitation, population density, wind speed, temperature, humidity, COPD, hypertension, adults who are overweight, daily smokers, asthma, good physical health, PM<sub>2.5</sub>, adults who are obese, and poor physical health.

<sup>b</sup> Adjusted for the above variables, excluding outbreak relation.

Table 4

| Age Group | UV | 95% CI | p-value |
|-----------|----|--------|---------|
| Overall   | 1.00<sup>b</sup> | (0.95-1.06) |         |
|           | 1.00 | (0.95-1.16) |         |
| <20       | 1.05 | (0.95-1.16) | 0.93     |
| 20–29     | 1.00 | (0.88-1.14) | 0.96     |
| 30–39     | 0.96 | (0.88-1.05) | 0.93     |
| 40–49     | 0.99 | (0.92-1.07) | 0.92     |
| 50–59     | 1.01 | (0.93-1.10) | 0.94     |
| 60–69     | 1.03 | (0.94-1.14) | 0.94     |
| 70–79     | 1.04 | (0.96-1.12) | 0.96     |
| 80–89     | 0.92 | (0.79-1.07) | 0.97     |
| 90+       | 0.91 | (0.73-1.14) | 0.94     |

<sup>a</sup> Adjusted for for age group, lockdown stage, outbreak relation, gender, deprivation, ethnic concentration, NO<sub>2</sub>, NO, precipitation, population density, wind speed, temperature, humidity, COPD, hypertension, adults who are overweight, daily smokers, asthma, good physical health, PM<sub>2.5</sub>, adults who are obese, and poor physical health.

<sup>b</sup> Adjusted for the above variables and age group.

Table 5

| Overall | Community Outbreak | Institutional Outbreak |
|---------|-------------------|-----------------------|
|         | Estimate<sup>a</sup> | 95% CI | p-value | Estimate<sup>b</sup> | 95% CI | p-value | Estimate<sup>b</sup> | 95% CI | p-value |
| UV      | 0.87 (0.80-0.96)   | <0.01  |         | 0.88 (0.81-0.96)   | <0.01  |         | 0.94 (0.85-1.03)   | 0.19     |         |
| O3      | 0.97 (0.95-1.00)   | 0.06   |         | 0.98 (0.95-1.01)   | 0.10   |         | 0.98 (0.96-1.01)   | 0.17     |         |

<sup>a</sup> Adjusted for humidity, average age, population density, lockdown stage, outbreak relation, gender proportion, NO, NO<sub>2</sub>, hypertension, PM<sub>2.5</sub>, deprivation, precipitation, temperature, wind speed, COPD, adults who are obese, and daily smokers.

<sup>b</sup> Adjusted for the above variables, excluding outbreak relation.

such as the respiratory syncytial virus as they tend to be seasonal (Baker et al., 2019; Moore et al., 2014; Obando-Pacheco et al., 2018). It is therefore hypothesized that COVID-19 transmission may behave similarly and may decrease or even disappear when temperature and UV radiation increase in the summer. However, we previously found no association between temperature and COVID-19 incidence (To et al., 2019; Moore et al., 2014; Obando-Pacheco et al., 2018). It is strongly suggested a positive association among institutional outbreaks. Our overall finding of negative association is strongly suggested differing associations. When measuring by COVID R<sub>0</sub>, our overall finding suggested a negative association. However, when measuring by incidence and stratified by outbreak relation, our findings strongly suggested a positive association among institutional outbreaks. Furthermore, when incidence rates were stratified by age group, the age group 20–29 was found to have a significant positive association. While other age groups had no statistically significant association, it should be noted that many point estimates were positive, especially for age groups under 70. Given that individuals in these age groups are working age, it is possible that the effects of O3 are more pronounced given their increased likelihood to be in environments with a higher chance of Ground-level O3 is often created from an interaction between ground-level pollution and sunlight. Previous studies have found O3 detrimental to human health. It is well-documented that inhalation of high levels of O3 can increase epithelial permeability in the lungs and may disturb local biota, increasing susceptibility to respiratory infection (Kehrl et al., 1987; Niu et al., 2020). Relatedly, O3 has also been previously associated with increased hospitalizations of respiratory diseases in Canadian hospitals (Burnett et al., 1997). It is therefore hypothesized that this damage to the lungs by O3 may aid in facilitating COVID-19’s transmission from the air into the human body via the lungs.

While our O3 findings did not find statistically significant evidence of an association with COVID activity by incidence or by R<sub>0</sub>, our findings strongly suggest differing associations. When measuring by COVID R<sub>0</sub>, our overall finding suggested a negative association. However, when measuring by incidence and stratified by age group, our findings strongly suggested a positive association among institutional outbreaks.
accurate climate data drawn from official sources. At a PHU level, this study also contained a low amount of missing data and used information, and stratified cases by outbreak relation, age group, and confirmed provincial cases to date, used accurate case demographic identifiable of this study therefore minimizing confounding and increasing the external generalizability of this study.

To our knowledge, no other COVID-19 study has compared the effect of climate factors in different local settings. We found evidence of no significant negative UV effect and a suggested positive O₃ effect among institutional outbreak cases. This lack of UV effect, as compared to a negative one overall and among community outbreak cases, may be due to reduced exposure to outdoor UV rays for institutional residents such as individuals in long-term care homes, hospitals, and correctional facilities. In contrast to the lack of estimated effect among community outbreak cases, O₃ is strongly suggested to have a positive association with institutional COVID-19 outbreak cases. It is possible that this is due to an accumulation of O₂ in these indoor settings due to their location next to roadside areas, poor ventilation, and confinement to indoor areas (Weschler, 2000; Salonen et al., 2018). During our study period, spikes in COVID-19 incidence were noted in April and May, when outbreaks occurred in a number of long-term care homes in Ontario, which may confound this study’s estimate due to the natural epidemic curve of the outbreak (PHAo, 2020).

4.1. Strengths and limitations

Compared to the previous study conducted by Yao et al., our study has added strength in having a longer observation period that spanned winter, spring, and summer, allowing us to examine a larger UV and O₃ range over multiple months. Furthermore, in an observational time series analysis over a few months, we do not expect individual risk factors like age and location to vary meaningfully over the study period, therefore minimizing confounding and increasing the external generalizability of this study’s results. By using case data provided by the Ontario Ministry of Health and Long-Term Care, we analyzed 100% of confirmed provincial cases to date, used accurate case demographic information, and stratified cases by outbreak relation, age group, and gender. This study also contained a low amount of missing data and used accurate climate data drawn from official sources. At a PHU level, this study was able to accurately represent localized climate patterns.

Our study has limitations. Despite the use of official data, under-reporting throughout the course of the pandemic may have resulted in an undercount of COVID-19 cases, limiting this study’s ability to capture all COVID-19 cases. Furthermore, this study was limited to using regional rates of comorbidities and income measures as case-specific data were not available. Due to COVID-19-related policies like lockdowns and stay-at-home orders, it is possible that there would be lower air pollution, limiting this study’s range of ozone, and lower exposure of UV to individuals. Similarly, despite this study’s best attempts to control for such factors by clustering by PHU, other confounding factors such as mask mandates, mask uptake by the population, and other public health policies may obscure the true magnitude of association described in this study.

5. Conclusion

In summary, our study found evidence to support the hypothesis that higher UV was associated with lower transmission of COVID-19 and some evidence that ground-level O₃ positively influenced COVID-19 transmission. Furthermore, our study found evidence that UV may be a factor for community outbreak cases but not for institutional outbreak cases while the opposite may be true for O₃. These findings indicate the need for further research into the relationship between climate factors and COVID-19 transmission. However, they provide some evidence to the reason behind COVID-19’s seasonal behaviour. Future research should consider factors that influence an individual’s likelihood of exposure to the outdoor environment, such as age or the setting of infection, namely indoor settings such as long-term care homes where outdoor environmental factors may not play as a strong role. As the northern hemisphere approaches winter, lower UV and greater O₃ exposure from increased indoor settings present a risk of further transmission of COVID-19. Meteorological conditions may play a role in reducing COVID-19 transmission, but in order to minimize the risk of resurgence, it is prudent to continue with safety practices such as hand washing and social/physical distancing even during the warmer seasons, where temperature rises and there is plenty of sunlight.
Author contributions

Teruo To: Conceptualization, Supervision, Writing – original draft
Kimball Zhang: Formal analysis, Writing – original draft, Visualization, Project administration Bryan Maguire: Formal analysis, Methodology, Writing – review & editing Emilee Terebessy: Project administration, Data curation, Writing – review & editing Ivy Fong: Data curation, Writing – review & editing Supriya Parakh: Data curation, Writing – review & editing Jingqin Zhu: Methodology, Writing – review & editing Yushan Su: Data curation, Writing – review & editing.

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Declaration of competing interest

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2020.110645.

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