







# Short-term temperature and precipitation patterns associated with firearm discharge incidents in Detroit, MI, USA 2021–2025: A time-stratified case-crossover study

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## ABSTRACT

**Background:** Firearm violence is a leading cause of injury and death in U.S. cities. Weather may shape firearm discharge risk by altering outdoor activity and social contact, yet evidence on lagged effects and on the relative importance of daytime versus nighttime temperatures is limited. This research tests lag-associations of precipitation and temperature with firearm-related incidents in Detroit, Michigan.

**Methods/Approach:** We studied firearm discharge incidents in Detroit, Michigan from 2021 to 2025 using police records with geocoded locations. We paired incident dates and matched control dates using a time-stratified case-crossover design and assigned daily precipitation and maximum/minimum temperature for the incident day and for each of the prior 7 days. We estimated exposure–lag associations using distributed lag non-linear models and evaluated whether neighborhood ecological characteristics modified weather effects.

**Results/Outcome:** Among 4062 firearm discharge incidents between 2021 and 2025, higher temperatures were associated with increased odds of incidents in cumulative models. Associations with minimum temperature remained elevated across lag windows up to 7 days. Cumulative exposure to precipitation at the upper end of the distribution (95th percentile = 0.54 inches (13.7 mm)) was associated with reduced odds of gunfire incidents over short accumulation windows (0–1 days and 0–3 days), with attenuation and imprecision when cumulated through 7 days. Weather associations were generally consistent across neighborhood characteristics.

**Conclusions/Implications:** In this urban setting, warmer conditions, especially warmer nights, were associated with higher odds of firearm discharge incidents, while higher precipitation was associated with lower odds of incidents over short lag windows. These patterns suggest that weather-sensitive opportunity structures may be important for anticipating short-term risk periods.

## 1. Introduction

Firearm violence remains a major public health crisis in the United States, resulting in  $\approx 45,000$  deaths and  $\approx 85,000$  emergency department visits each year (Kaufman et al., 2021; Schnippel et al., 2021; Centers for Disease Control and Prevention, 2024). While nearly half of all firearm deaths annually are suicides, firearm homicides have increased in recent years and appear to be driving overall trends in firearm mortality (Kaufman et al., 2021; Centers for Disease Control and Prevention, 2024). Firearm-related incidents are distinguished by their

high lethality and their dependence on situational opportunity (Center for Gun Violence Solutions, 2024). The importance of situational opportunity suggests that firearm violence may be uniquely shaped by environmental and climatic conditions that influence human activity patterns and social interaction, and short-term physiological or neurobiological states.

Shootings, in contrast to many other forms of violence, frequently occur in outdoor or semi-public spaces (Bureau of Justice Statistics,

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2024), making them especially sensitive to environmental conditions that shape where and when people congregate (Kieltyka et al., 2016; Klerman et al., 2024). Warmer temperatures can increase outdoor social activity and heighten physiological stress and aggression (Hsiang et al., 2013), whereas precipitation can deter street presence, alter routine activities, and change opportunities for interpersonal encounters in ways that may influence the incidence of firearm-related injuries and crime (Kieltyka et al., 2016; Goin et al., 2018). These mechanisms suggest that weather may influence firearm violence through a combination of behavioral and neurobehavioral pathways, although the relative importance of these pathways may differ from other forms of violence. Although prior research has linked weather and climate patterns to violent crime, less is known about how specific weather exposures influence firearm violence, particularly within urban settings such as Detroit, where distinctive spatial and structural factors may alter these relationships.

Extreme temperatures and precipitation are increasingly recognized as determinants of population health, contributing to excess mortality and a range of adverse outcomes (Ban et al., 2024). Elevated heat and cold stress have been associated with multiple physical and mental health outcomes (Alahmad et al., 2023; Zhang et al., 2018; Huang et al., 2023), while intense rainfall events and heat waves contribute to unintentional injuries, including traffic collisions and accidents during cleanup or reconstruction (Basagaña et al., 2011; Bergel-Hayat et al., 2013; Brijs et al., 2008). Environmental exposure may also shape risk for violence-related injury; for example, spending time outdoors increases the likelihood of firearm victimization among adolescents (Dong et al., 2017). These patterns might reflect the role of ambient environmental conditions in influencing when, where, and to whom violent events occur.

Consistent with these proposed neurobehavioral pathways, population-level studies also show that ambient heat may influence violence risk through neurobehavioral pathways that overlap with mental health, in addition to shifting routine activities. A growing literature links higher temperatures and heat events to worsened mental health, including acute psychological distress and sleep disruption, and some studies report associations with suicide incidence (Liu et al., 2021; Nori-Sarma et al., 2022; Thompson et al., 2023). These heat-related changes could increase irritability, impulsivity, and conflict escalation. In contexts with widespread firearm availability, even modest shifts in these proximate states could plausibly increase the likelihood that encounters culminate in firearm discharge.

A growing body of research indicates that higher ambient temperatures are positively associated with violence, including homicide, assault, and intimate partner violence (Choi et al., 2024; van Daalen et al., 2022; Rahman et al., 2023; Lyons et al., 2022). These population-level findings are broadly consistent with a long-standing behavioral literature suggesting that heat exposure can increase irritability, aggression, and hostile behavior under certain conditions (Hsiang et al., 2013). Some research suggests that temperature exerts a stronger influence on violent crime than other meteorological factors such as precipitation or humidity (Reeping and Hemenway, 2020a; Michel et al., 2016), though the relationship may plateau beyond extreme heat thresholds and vary by geographic context (Lyons et al., 2022; Kim et al., 2023). Despite this evidence, uncertainties remain regarding the short-term, lagged effects of weather exposure (e.g., days or weeks) on incidence of firearm violence. Addressing these gaps is essential for understanding how climate variability affects firearm-related harm in urban settings such as Detroit.

Gun violence shares many social and structural risk factors with other forms of interpersonal violence, but its occurrence often depends heavily on situational conditions (Lantz et al., 2024) and the immediate availability of firearms (Anglemyer et al., 2014). Prior work has explored the association between temperature and aggression/violence (Miles-Novelo and Anderson, 2019) and between weather and aggregated shootings in large cities such as Chicago (Reeping and

Hemenway, 2020b), yet few studies have examined how localized environmental characteristics modify these weather–violence relationships. Urban features such as housing vacancy, population density, and the distribution of commercial and residential land uses may shape both the opportunity for violence and individuals' exposure to environmental stressors.

This study extends prior work on weather and violence in three important ways. First, we analyze incident-level firearm discharge events identified using police administrative records with precise spatial and temporal resolution, allowing weather exposure to be assigned at a scale at which both human activity and local environmental conditions might vary. This focus on discrete discharge events captures a highly lethal, opportunity-dependent form of violence that is plausibly sensitive to short-term changes in outdoor and ambient conditions. Second, we apply a distributed lag non-linear modeling framework within a time-stratified case-crossover design to explicitly characterize nonlinear exposure response relationships and temporal lag structure. This approach distinguishes immediate from delayed associations and moves beyond same day or long term average assumptions. Third, we directly compare daytime heat (maximum temperature) and nighttime warmth (minimum temperature) as competing predictors of firearm discharge risk. By contrasting these exposure windows, we evaluate whether observed associations are more plausibly consistent with physiological heat stress pathways or with routine activity mechanisms that operate through increased evening and nighttime social interaction. We additionally assess whether fine-scale ecological features related to heat exposure and violence modify these short-term associations.

## Methods

### Study setting: Detroit, MI

Detroit, MI, is a resilient and vibrant city with a long history of prosperity, loss, and neglect. Once the center of the automotive industry in the United States, Detroit has suffered economic downturn from factors including de-industrialization, suburbanization, and government mismanagement (Herbert, 2021). In the 1960s, a majority of Detroit's highest earners moved to the now-sprawling metro area, bringing with them much of the city's taxable income (Herbert, 2021). As of 2023, the city's median household income was \$38,100; \$31,100 less than the state's median household income, and \$39,600 less than the nation's (Gandhi, 2025). Recent census data places Detroit's population around 645,000, demonstrating a loss of approximately a million residents since 1960 (U.S. Census Bureau, 2025; Citizens Research Council of Michigan, 2021). Due to Detroit's history of population loss, the city has hundreds of abandoned properties, and one in five homes remains vacant (Bureau, 2022). Detroit's economic struggles have created conditions in which crime is pervasive, and the city ranked among the top 5 U.S. cities for gun violence, homicide, and overdose in 2023 (BCHC, 2023). Though Detroit's economic and social struggles are ongoing, recent years have shown improvements in housing vacancy, income, and population size (Gandhi, 2025; U.S. Census Bureau, 2025; Bureau, 2022). This context of economic challenge, spatial disinvestment, and endemic violence provides a critical setting in which to study how acute environmental exposures intersect with an urban environment to influence patterns of firearm violence.

### Crime data

Data for all reported crimes occurring within the City of Detroit between 2021 and 2025 were obtained from the Detroit Police Department Records Management System (RMS) through the City of Detroit Open Data Portal (City of Detroit, 2025). RMS entries include the incident date, offense description, Michigan Incident Crime Reporting (MICR) offense code, and the latitude and longitude of the nearest street intersection.

For the primary analysis, firearm discharge incidents were defined as those records that both (1) had a MICR code indicating a firearm-related violent offense; and (2) contained narrative text keywords unambiguously indicating a firearm discharge (e.g., “shots fired,” “gunshot”). The MICR firearm codes used were 1301, 1304, 1307, 1310, 0901, 0903, 0905, 0907, and 0911, representing aggravated assault with a firearm, discharge of a firearm at a dwelling or vehicle, firearm-related homicide categories, and attempted murder offenses (Michigan State Police, 2024). The offense code 1301 as used in the RMS is non-specific regarding weapon use. We additionally generated an indicator variable identifying incidents whose text descriptions unambiguously referenced a fatal or non-fatal firearm discharge. A full table listing the MICR codes used are shown in Supplementary Table A.1.

#### Weather data

We obtained daily meteorological data from the NOAA nClimGrid-Daily dataset, which provides gridded fields of daily maximum temperature, minimum temperature, and precipitation for the contiguous United States at 5 km spatial resolution (for Environmental Information, 2022). The dataset is generated from station observations in the Global Historical Climatology Network–Daily (GHCN-D) and interpolated using a thin-plate spline (TPS) climatological interpolation procedure to ensure spatial and temporal consistency over areas of variable elevation and topographic complexity. For each incident, we identified the event date and geographic location. Using the latitude and longitude coordinates, we assigned daily maximum temperature, minimum temperature, and precipitation from the corresponding grid cell. While the dataset is optimized for aggregated or regional use, its daily resolution, fine gridding, and completeness make it sufficiently precise for assigning climate exposures to incident locations (Thornton et al., 2021). We considered the grid-cell value as a proxy for local ambient conditions at the block level. Although microclimatic conditions can vary within grid cells, particularly in highly heterogeneous urban environments (Kianmehr et al., 2023) and the accuracy of nClimGrid-Daily for individual points and days can be sensitive to localized spatial variability (for Environmental Information, 2022), Detroit’s narrow geographic extent reduces the likelihood of meaningful exposure misclassification.

#### Ecological variables

Ecological data at the ZCTA level were obtained from the National Neighborhood Data Archive (NaNDA) (ICPSR, 2024). NaNDA is a publicly available data repository that provides measures of the physical, economic, demographic, and social environment across multiple spatial scales, including census tract, ZIP Code Tabulation Area, and county. Each NaNDA dataset covers all or most of the United States, both rural and urban, and contains a focused set of measures on a single topical domain such as socioeconomic disadvantage, healthcare access, housing characteristics, partisanship, or public transit. Using the geocoded location of each gunfire incident, we linked measures of racial segregation, social advantage, and social disadvantage at the ZCTA level and appended these variables to the main analytic dataset.

We also selected three spatial environmental variables based on their theoretical and empirical links to heat exposure and interpersonal violence. Percent tree canopy cover was obtained from the 2023 National Land Cover Database (NLCD) Tree Canopy product, produced jointly by the U.S. Geological Survey and the U.S. Forest Service (U.S. Geological Survey and U.S. Forest Service, 2023). Urban tree canopy has been shown to mitigate ambient temperatures through shading and evapotranspiration (Alonzo et al., 2025), and increasing evidence suggests that greener environments may also reduce violent crime (Troy et al., 2012; Kondo et al., 2017).

We additionally incorporated indicators of neighborhood physical disorder and alcohol availability. Vacant residential properties have

well-documented criminogenic effects (Porter et al., 2019), and remediation of abandoned buildings has been associated with subsequent reductions in violent crime (Locke et al., 2023). Alcohol retail outlets, particularly bars and off-premise stores, have consistently been linked to elevated risks of violence and assault (Gruenewald et al., 2023). Geocoded data on vacant properties (City of Detroit, Buildings, Safety Engineering, and Environmental Department (BSEED), 2025b) and licensed alcohol establishments (City of Detroit, Buildings, Safety Engineering, and Environmental Department (BSEED), 2025a) were obtained from the Detroit Open Data Portal.

For the point-based environmental variables, we counted the number of features located within concentric radial buffers (100 m and 250 m) around each shooting incident. We appended these spatial measures to the incident-level dataset and used them as ecological effect-modification variables in the distributed lag models.

#### Statistical methods

We used a time-stratified case-crossover design, where each firearm incident (case) was matched to control days on the same day of the week within the same month and year (Janes et al., 2005; Mittleman, 2005). The case-crossover design is well-suited for evaluating acute-onset outcomes in relation to short-term environmental exposures (Lewer et al., 2022; Maclure, 1991; Jaakkola, 2003), and firearm incidents, specifically, are sudden, discrete events that happen at specific points in time and space (Lewer et al., 2022). This design controls for all time-invariant confounders (e.g., location, long-term socioeconomic factors) (Maclure, 1991), minimizes confounding by season, and helps control for short-term temporal autocorrelation by restricting comparisons to narrow time windows (Guo et al., 2011). Because this is an observational, case-crossover study, we interpret estimates as associations between short-term weather variation and incident occurrence within matched strata, not as causal effects.

Associations between environmental exposures and firearm incidents were estimated using conditional logistic regression within the distributed lag non-linear model (DLNM) framework (Gasparrini, 2014). In this study, conditional logistic regression is implemented as a stratified Cox proportional hazards model, which yields identical estimates under the time-stratified case-crossover design (Wang et al., 2011). For each exposure (daily maximum temperature, minimum temperature, and precipitation), we specified a cross-basis function comprising two components: (1) an exposure–response function capturing potential nonlinearity across exposure levels, and (2) a lag–response function describing how associations are distributed over lag days. Together, these components define an exposure–lag–response surface. The DLNM framework allows estimation of both lag-specific associations and cumulative effects that summarize exposure impacts across multiple lag days. In this analysis, we focus on cumulative exposure–lag associations, which capture the net short-term effect of weather across the full lag window and reduce the risk of over-interpretation of isolated lag-specific estimates for temporally correlated environmental exposures. To account for potential residual seasonality, models included sine and cosine terms to adjust for residual seasonal variation in firearm incidents, allowing for smooth annual cyclic patterns independent of short-term exposure effects.

To test for effect modification by neighborhood ecological factors, we added interaction terms between the exposure–lag cross-basis and binary indicators (high vs. low) for each ecological modifier (e.g., vacant structures, liquor outlets, tree cover). To set “high” and “low” categories, we dichotomized each modifier at the median value calculated at the incident-level (i.e., based on the value for the census tract where the incident occurred). Evidence for effect modification was evaluated using a joint Wald test of the interaction coefficients.

**Table 1**  
Final DLNM cross-basis specifications used in primary models.

Exposure	Exposure-response	Lag-response	Lag window	Center
Precipitation	Linear	Strata (0, 1–2, 3–6, 7)	0–7 days	0 in
Maximum temperature	Natural spline (df = 5)	Natural spline (df = 4)	0–7 days	70°F
Minimum temperature	Natural spline (df = 5)	Natural spline (df = 4)	0–7 days	32°F

### Primary model and DLNM specification

We estimated short-term associations between weather exposures and firearm incidents using distributed lag non-linear models (DLNMs) within a time-stratified case-crossover design. Each incident day was matched to control days occurring on the same day of the week within the same month and year. Let  $i$  index matched case-control sets and  $t$  denote the day within each set. For each exposure  $x \in \{\text{precipitation}, T_{\max}, T_{\min}\}$ , we modeled the exposure-lag relationship using a DLNM cross-basis function over lags 0 through  $\ell$  days (primary analyses:  $\ell = 7$  days).

Associations were estimated using conditional logistic regression implemented as a stratified Cox proportional hazards model:

$$\log \lambda_{it} = \alpha_i + \mathbf{cb}_x(x_{it,0:\ell})^\top \boldsymbol{\beta} + \delta_1 \sin\left(\frac{2\pi \text{doy}_t}{365.25}\right) + \delta_2 \cos\left(\frac{2\pi \text{doy}_t}{365.25}\right),$$

where  $\lambda_{it}$  denotes the conditional hazard (or instantaneous risk) for incident occurrence on day  $t$  within matched set  $i$ ,  $\alpha_i$  is a stratum-specific intercept representing the matched case-control set,  $\text{doy}_t$  is the day of year, and  $\mathbf{cb}_x(\cdot)$  denotes the DLNM cross-basis describing nonlinear exposure-response and lag-response relationships. The sine and cosine terms adjust for residual seasonal variation not captured by the case-crossover matching.

### Final cross-basis parameterization (AIC-selected)

We evaluated a grid of alternative parameterizations for the cross-basis functions, varying the flexibility of the exposure-response and lag-response dimensions, and considered AIC (Burnham and Anderson, 2002) together with parameter stability in selecting the final specifications. For precipitation, we specified a linear exposure-response function and a stratified lag-response function over lags 0–7 days, with lag strata corresponding to days 0, 1–2, 3–6, and 7. Precipitation models were centered at 0 inches. For maximum and minimum temperature, we specified natural spline functions for both the exposure-response and lag-response dimensions, using 5 degrees of freedom for the exposure basis and 4 degrees of freedom for the lag basis over lags 0–7 days. Knot placement was determined implicitly by the spline basis parameterization in the dlnm framework through the specified degrees of freedom. Maximum temperature models were centered at 70°F and minimum temperature models were centered at 32°F. We additionally confirmed that estimated regression parameters were stable across neighboring model specifications. We assessed residual temporal dependence by visually inspecting autocorrelation plots and calculating the Box-Ljung statistic (see Table 1).

### Single-exposure primary models and sensitivity analyses

Primary analyses were conducted as single-exposure DLNM models (separately for precipitation, maximum temperature, and minimum temperature) to characterize the exposure-lag structure for each metric and to examine daytime versus nighttime temperature indicators. As a sensitivity analysis, we fit mutually adjusted models including precipitation and temperature in the same conditional logistic regression, and we evaluated longer maximum lags (e.g.,  $\ell = 14$  days) to assess whether estimated exposure-response patterns returned toward baseline over a longer window (Supplementary Tables A.2 and A.3).

## Results

### Descriptive statistics

There were 67,965 violent incidents recorded from January 1, 2021 to June 3, 2025. Among these there were 4062 lethal and non-lethal events which unambiguously involved a firearm discharge. In this dataset, there was a median of 43 violent incidents per day (IQR 37–50) and 2 gunfire-related incidents per day (IQR 1–4). When standardized by population, there are 6.72 violent incidents per 100,000 residents per day (IQR 5.78–7.81) and 0.31 gunfire-related incidents per 100,000 per day (IQR 0.16–0.62). Firearm violence occurs throughout the city (Fig. 1). Both violent incidents and firearm discharge incidents follow seasonal patterns, peaking in the Summer months and declining through midwinter. The pattern of violent incidents have been trending downward since 2021, though the highest single-week counts are observed in Summer 2022 and Summer 2023 (See Fig. 2). Firearm discharge incidents primarily occur on weekends and in the hours around and just following midnight (Supplementary Fig. A.1).

Detroit, MI has a temperate climate typical of the Great Lakes Region of the United States, with cold winters and relatively hot summers. See Table 2 for summary statistics of temperature and precipitation by season.

### Model results

Across the full study period, cumulative associations were observed between all three weather exposures (precipitation, maximum temperature, and minimum temperature) and the odds of both overall violent incidents and incidents confirmed to involve gunfire. Results are presented as cumulative odds ratios corresponding to exposure at the 95th percentile, aggregated over lag windows of increasing duration (0, 1, 3, and 7 days). Cumulative odds ratios summarize the aggregate association of exposure at a given level across lag days 0 through  $k$ , relative to the reference exposure. Numerical results are shown in Table 3 and Fig. 3.

Cumulative exposure to precipitation at the upper end of the distribution (95th percentile = 0.54 inches (13.7 mm)) was associated with reduced odds of gunfire-related incidents over short lag-accumulation windows. Specifically, cumulative precipitation exposure through the same day (lag 0) was associated with lower odds of gunfire incidents (OR = 0.35, 95% CI [0.17, 0.73]). Inverse associations persisted when exposure was cumulated through 1 day (OR = 0.16, 95% CI [0.04, 0.60]) and 3 days (OR = 0.07, 95% CI [0.01, 0.62]). When cumulative exposure was extended through the full 7-day window, the association was imprecise (OR = 0.34, 95% CI [0.02, 6.56]), indicating that the association of higher precipitation with gunfire is concentrated within short time windows. In contrast, evidence suggested that cumulative precipitation exposure showed little evidence of association with overall violent incidents within any lag-accumulation window.

Cumulative exposure to high maximum temperatures was positively associated with both outcomes, although the pattern across lag windows differed between overall violent incidents and gunfire-confirmed incidents. For overall violent incidents, cumulative exposure to extreme maximum temperatures was associated with increased odds across all accumulation windows, including the full 7-day window (OR = 1.09,

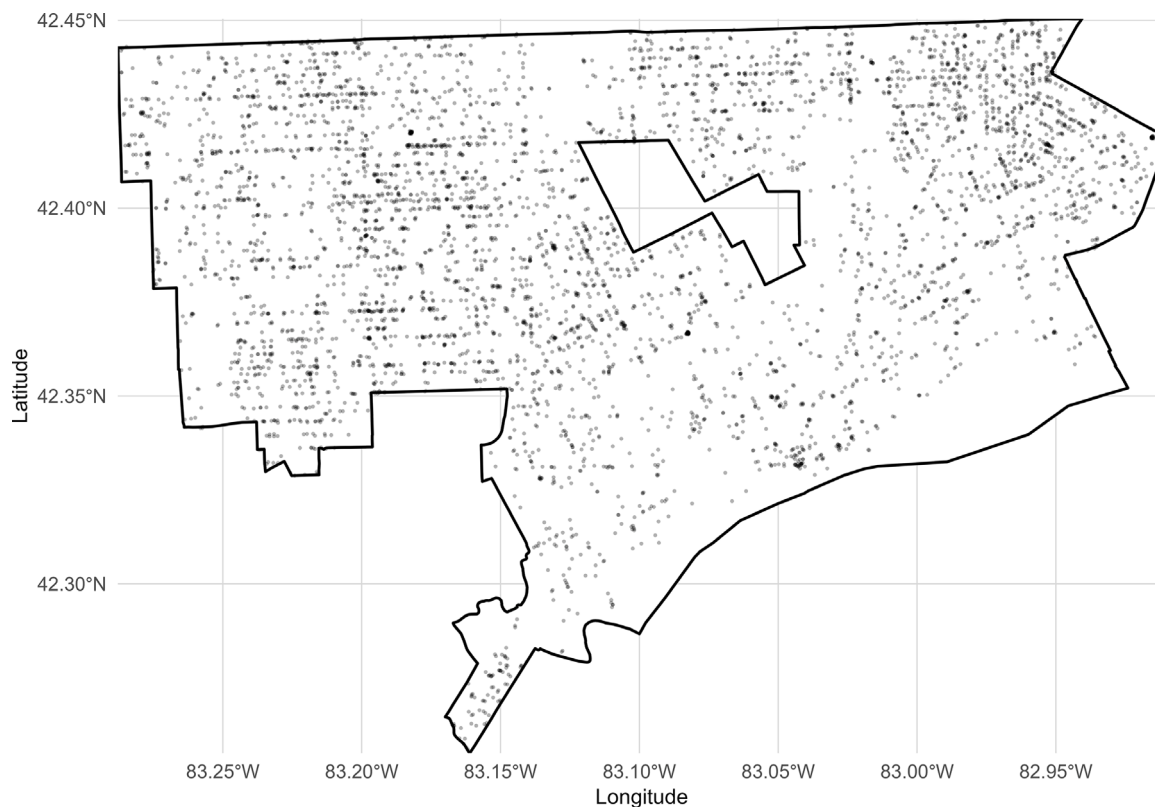


Fig. 1. Locations of all firearm discharge related incidents in Detroit, MI 2021–2025.

**Table 2**  
Overall and seasonal summary of daily precipitation and temperature in Detroit.

Season	Variable	Median (IQR)	Min–Max
Overall	Precipitation (in)	0.0 (0.0–0.1)	0.0–6.5
	Max temperature (° F)	66.9 (46.9–79.9)	9.7–96.5
	Min temperature (° F)	47.7 (33.1–61.5)	–1.8–79.7
Winter	Precipitation (in)	0.0 (0.0–0.1)	0.0–1.3
	Max temperature (° F)	37.1 (30.1–43.3)	9.7–72.7
	Min temperature (° F)	26.8 (18.5–32.6)	–1.8–53.7
Spring	Precipitation (in)	0.0 (0.0–0.1)	0.0–2.2
	Max temperature (° F)	60.1 (49.6–71.0)	22.4–89.5
	Min temperature (° F)	42.0 (33.0–50.1)	14.5–72.1
Summer	Precipitation (in)	0.0 (0.0–0.1)	0.0–6.5
	Max temperature (° F)	82.5 (77.8–86.7)	64.9–96.5
	Min temperature (° F)	65.4 (60.4–69.8)	45.2–79.7
Fall	Precipitation (in)	0.0 (0.0–0.0)	0.0–2.9
	Max temperature (° F)	67.4 (55.2–77.0)	28.3–89.6
	Min temperature (° F)	49.2 (40.4–58.5)	16.9–74.1

95% CI [1.01, 1.17]). For gunfire-confirmed incidents, cumulative associations were strongest when exposure was cumulated over shorter windows, including 1 day (OR = 1.20, 95% CI [1.06, 1.36]) and 3 days (OR = 1.33, 95% CI [1.10, 1.61]), but were attenuated and no longer clearly elevated when cumulated through 7 days (OR = 1.28, 95% CI [0.98, 1.68]). This pattern suggests that the influence of high daytime temperatures on gunfire risk is acute rather than sustained.

Minimum temperature exhibited the most consistent cumulative associations. For overall violent incidents, cumulative exposure to high minimum temperatures was associated with increased odds across all accumulation windows, including the 7-day window (OR = 1.28,

95% CI [1.16, 1.41]). Similarly, for gunfire-confirmed incidents, cumulative associations with minimum temperature persisted through 7 days (OR = 1.50, 95% CI [1.03, 2.19]). These findings are consistent with associations between elevated nighttime temperatures and higher odds of violence across longer lag windows.

Sensitivity analyses including both precipitation and temperature in the same distributed lag model produced results similar to those observed in the single-exposure models reported in the main text (Supplementary Table S1). Extending the lag window to 14 days did not materially alter the exposure-response patterns.

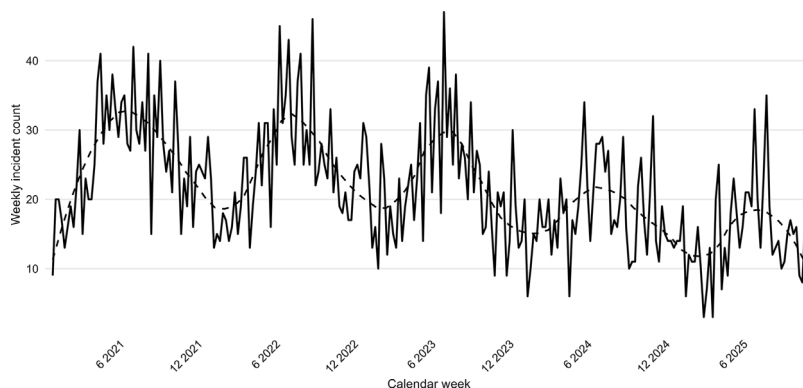


Fig. 2. Time series of weekly firearm discharge incidents.

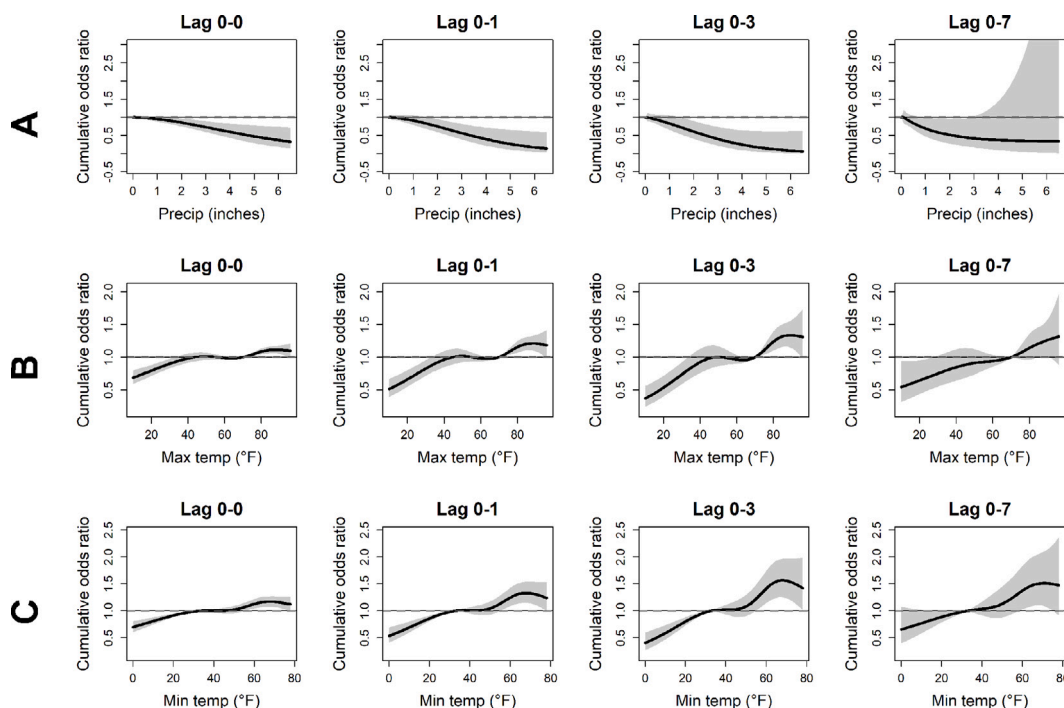


Fig. 3. Exposure-lag-response associations between A) daily precipitation, B) maximum temperature, and C) minimum temperature and firearm incident risk. Panels display cumulative odds ratios across exposure levels, cumulated from lag day 0 through the indicated lag day (0, 1, 3, and 7), from distributed lag non-linear models. Solid lines indicate point estimates and shaded regions represent 95% confidence intervals, with odds ratios referenced to the exposure-specific centering value.

Effect modification by ecological variables

Among most potential modifiers we tested – including vacant parcels, liquor outlets, tree canopy, socioeconomic indices, and population size – there was little evidence that neighborhood characteristics meaningfully altered weather and violence associations. Stratified odds ratios at same day lag exposures were generally similar and Wald tests provided little evidence for interaction. One exception was that of maximum temperature, where the heat–violence association was slightly stronger in lower-population ZIP codes. In addition, tree canopy within 100–250 m modestly modified the lag structure of the minimum-temperature effect, although same-day estimates were nearly identical.

See Table 4 for full results and Supplementary Fig. A.2 for same day exposure, stratified odds ratios.

Discussion

Our findings suggest that short-term exposure to elevated temperatures are associated with increased risk of firearm discharge incidents, whereas precipitation was associated with reduced odds of incidents in the short term. Associations with minimum temperature remained elevated across longer lag windows, and firearm discharge incidents occurred disproportionately during nighttime hours (after 11 pm) and

**Table 3**

Odds ratios (95% confidence intervals) for cumulative exposure to the 95th percentile of each weather variable, cumulated over lag days 0 through the specified lag, for outcomes of all violent incidents and firearm-related incidents only. For precipitation, the 95th percentile corresponded to 0.54 inches (13.7 mm).

Exposure	Lag (days)	All violent	Firearm
		OR (95% CI)	OR (95% CI)
Precipitation	0	0.89 (0.75, 1.07)	0.35 (0.17, 0.73)
	1	0.83 (0.59, 1.15)	0.16 (0.04, 0.60)
	3	0.77 (0.45, 1.31)	0.07 (0.01, 0.62)
	7	0.96 (0.42, 2.18)	0.34 (0.02, 6.56)
Temperature (max)	0	1.06 (1.04, 1.08)	1.11 (1.03, 1.18)
	1	1.11 (1.07, 1.15)	1.20 (1.06, 1.36)
	3	1.17 (1.11, 1.23)	1.33 (1.10, 1.61)
	7	1.09 (1.01, 1.17)	1.28 (0.98, 1.68)
Temperature (min)	0	1.12 (1.09, 1.15)	1.15 (1.05, 1.27)
	1	1.23 (1.17, 1.28)	1.29 (1.09, 1.53)
	3	1.37 (1.27, 1.47)	1.51 (1.15, 1.97)
	7	1.28 (1.16, 1.41)	1.50 (1.03, 2.19)

on weekends. The consistency of associations with nighttime warmth, the timing of incidents, and the inverse association with precipitation suggest that extended outdoor opportunity windows and increased social activity, in addition to physiologic heat-related aggression, may be stronger drivers of violence in this context. Although reliance on administrative incident data limits our ability to directly isolate behavioral opportunity from other pathways, the observed timing, accumulation-window patterns, and weather metric specific findings are most consistent with routine activity mechanisms linking weather conditions to firearm violence. The timing and weather-related patterns are consistent with routine activity mechanisms in this context, although neurobehavioral pathways linked to heat exposure may also contribute to escalation conditional on social contact.

Our work is similar to other studies on temperature and violence, but contrary to some prior work (Xu et al., 2020), we found that temperature was strongly associated with violence in Detroit, MI. Although the RMS incident data contain limited contextual information, as in other cities, shootings in Detroit likely occur primarily outdoors and are therefore likely to be influenced by weather and seasonal conditions. Detroit, relative to comparably sized U.S. cities, differs from many large U.S. cities in its relatively low population density and abundance of open spaces, which provide numerous settings for outdoor social interaction. In addition, firearm possession in Detroit is believed to be widespread, with a substantial number of illegal weapons in circulation (Headd et al., 2023). The combination of high levels of weapon availability, socioeconomic disadvantage, and gang activity, together with seasonal weather-related shifts in outdoor activity, could contribute to heterogeneity in observed associations across settings. These associations should be evaluated across multiple cities using similar data in future research.

We found that most firearm-related violent incidents occur at night, consistent with prior research (Klerman et al., 2024). Maximum temperatures primarily occur during the day. Although maximum temperatures peak during daytime hours and are correlated with nighttime temperatures, minimum temperature may be a more relevant indicator of people's willingness to socialize outdoors during late-evening and nighttime periods, i.e. times when most violent incidents occur. As a result, nighttime and minimum temperatures may better capture the environmental conditions that influence routine activities and increase opportunities for violent encounters.

Prior research suggests that ambient temperature can influence mental and behavioral health through short-term neurobehavioral pathways. Studies have linked higher temperatures to increases in psychological distress, sleep disruption, and other mental health outcomes, and some analyses report associations with suicide risk and mental health-related emergency visits (Liu et al., 2021; Nori-Sarma et al.,

2022; Thompson et al., 2023). These findings provide biological plausibility for temperature-related increases in irritability, impulsivity, or conflict escalation. However, in the present study firearm discharge incidents occurred predominantly at night, and we observed associations with minimum (nighttime) temperature that remained elevated across longer lag windows. Further, precipitation was associated with reduced incidents over short lag windows. These patterns are most consistent with temperature and rainfall altering routine activities and opportunities for interpersonal encounters, while not excluding additional neurobehavioral pathways.

We found very little evidence to suggest that factors such as tree cover, vacant housing and social disadvantage/affluence modified the relationship of temperature and violence. Other research has suggested, for example, that urban heat islands (UHI) raise risk for outdoor violence, but have no effect on indoor violence and that urban green space may reduce the likelihood of violent events (Stevens et al., 2024). The absence of an observable modifying effect of social disadvantage or affluence in our analysis may reflect the relatively limited socioeconomic variation within the city of Detroit; the more affluent segments of the Detroit metropolitan population largely reside outside the city limits. Future analyses should extend beyond the city limits to the broader Detroit metropolitan area, where greater demographic, socioeconomic, infrastructural and environmental diversity may clarify how climate and neighborhood factors jointly shape gun violence risk.

While previous research has established a link between higher temperatures and increased violence, to our knowledge few studies have directly compared whether daytime maximum temperatures or nighttime/early-morning minimum temperatures are stronger predictors of violent incidents. Our results indicate that associations with minimum temperature remained elevated across longer lag windows, which might suggest a higher temperature "floor" may predict violence. Theoretical considerations suggest that minimum temperatures may better capture social behavior (outdoor evening/overnight exposure) and microclimatic conditions conducive to violence. Future work might compare various weather metrics to determine which is most informative in specific contexts.

#### Strengths and limitations

A strength of this study is that incident-level timestamps and coordinates permitted linkage to daily gridded meteorological fields and estimation of nonlinear exposure-lag relationships. The 5 km resolution of the weather data cannot capture hyperlocal changes in temperature patterns, but it is well-suited to capturing day-to-day variation across Detroit and supports internally consistent comparisons between incident and matched control days.

The RMS data lack contextual details about each gunfire incident, such as whether it occurred indoors or outdoors, the social setting, or the circumstances leading to the event. Demographic information on the perpetrator or victim if the incident would also provide valuable context for the social and demographic context of the incident and show whether certain groups are more sensitive to weather factors than others. In addition, although we would have preferred to examine pre-pandemic trends, RMS data prior to 2021 did not reliably distinguish firearm-related assaults or homicides from simple assaults, preventing us from constructing consistent and valid historical datasets specific to gun discharge events. Time-varying factors correlated with weather, such as holidays, special events, or changes in policing practices, could contribute to residual confounding, although the case-crossover design mitigates many such concerns.

Although we believe that certain aspects of the results of this work are generalizable to other, similar post-industrial cities in the Midwestern United States, the factors which contribute to violence might be specific to these areas. Future work might explore the same questions over multiple cities, both in and outside the United States.

**Table 4**

Effect modification of weather–violence associations. Odds ratios (ORs) represent the 95th percentile exposure at lag 0, stratified by low vs high levels of each modifier.

EM variable	Low OR (95% CI)	High OR (95% CI)	<i>P</i> <sub>Wald</sub>
<b>Precipitation</b>			
Vacant parcels within 300 m	0.76 (0.60, 0.98)	1.14 (0.87, 1.50)	0.395
Liquor outlets within 300 m	0.77 (0.60, 1.00)	1.08 (0.83, 1.40)	0.361
Tree canopy 0–100 m	0.97 (0.76, 1.25)	0.83 (0.64, 1.08)	0.649
Tree canopy 100–250 m	0.96 (0.74, 1.24)	0.84 (0.65, 1.10)	0.194
Total population (ZCTA)	0.89 (0.69, 1.14)	0.89 (0.68, 1.16)	0.630
Neighborhood affluence index	0.85 (0.65, 1.10)	0.94 (0.73, 1.22)	0.766
Neighborhood disadvantage index	0.87 (0.67, 1.13)	0.92 (0.71, 1.19)	0.663
Median family income	0.87 (0.67, 1.13)	0.92 (0.71, 1.19)	0.711
<b>Max temperature</b>			
Vacant parcels within 300 m	1.07 (1.05, 1.10)	1.05 (1.02, 1.08)	0.674
Liquor outlets within 300 m	1.06 (1.04, 1.09)	1.06 (1.03, 1.09)	0.527
Tree canopy 0–100 m	1.07 (1.04, 1.10)	1.04 (1.01, 1.08)	0.157
Tree canopy 100–250 m	1.07 (1.04, 1.10)	1.04 (1.01, 1.07)	0.260
Total population (ZCTA)	1.09 (1.06, 1.11)	1.04 (1.01, 1.06)	0.008
Neighborhood affluence index	1.05 (1.02, 1.08)	1.07 (1.04, 1.10)	0.695
Neighborhood disadvantage index	1.08 (1.05, 1.10)	1.05 (1.02, 1.07)	0.790
Median family income	1.05 (1.02, 1.08)	1.07 (1.04, 1.10)	0.253
<b>Min temperature</b>			
Vacant parcels within 300 m	1.12 (1.08, 1.16)	1.11 (1.07, 1.15)	0.434
Liquor outlets within 300 m	1.11 (1.08, 1.15)	1.12 (1.08, 1.16)	0.326
Tree canopy 0–100 m	1.11 (1.07, 1.16)	1.10 (1.06, 1.14)	0.386
Tree canopy 100–250 m	1.10 (1.06, 1.14)	1.11 (1.07, 1.15)	0.040
Total population (ZCTA)	1.14 (1.11, 1.18)	1.08 (1.05, 1.12)	0.164
Neighborhood affluence index	1.12 (1.08, 1.16)	1.11 (1.07, 1.15)	0.548
Neighborhood disadvantage index	1.13 (1.09, 1.17)	1.10 (1.06, 1.14)	0.756
Median family income	1.12 (1.08, 1.16)	1.11 (1.07, 1.15)	0.306

## Conclusions

Short-term variation in temperature and precipitation was associated with measurable changes in firearm discharge risk in Detroit. Warmer conditions, particularly elevated nighttime temperatures, were linked to increased odds of incidents, whereas precipitation at the upper end of the observed distribution was associated with short-term reductions in risk. The stronger and more persistent associations observed for minimum temperature, together with the concentration of incidents during nighttime hours, suggest that weather may influence firearm violence primarily through changes in routine activities and opportunities for interpersonal encounters, while not excluding possible neurobehavioral responses to heat exposure. Although these associations should not be interpreted as causal effects, they suggest that short-term environmental conditions may act as contextual factors shaping when and where firearm violence occurs. As climate change increases the frequency of extreme heat and precipitation events, understanding how weather patterns shape violence risk may help inform situational prevention strategies and improve short-term risk awareness for communities and public safety systems.

## CRedit authorship contribution statement

**Peter S. Larson:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jason E. Goldstick:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Jack Kappelman:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Sawyer L. Stribley:** Writing – review & editing, Writing – original draft, Investigation, Data curation. **Jaemin Jeon:** Writing – review & editing, Writing – original draft, Data curation. **Douglas J. Wiebe:** Writing – review & editing, Writing – original draft, Conceptualization.

## Ethical considerations

This study used de-identified, publicly available administrative and environmental data and did not involve interaction with human subjects.

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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.

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## Appendix. Supplementary materials

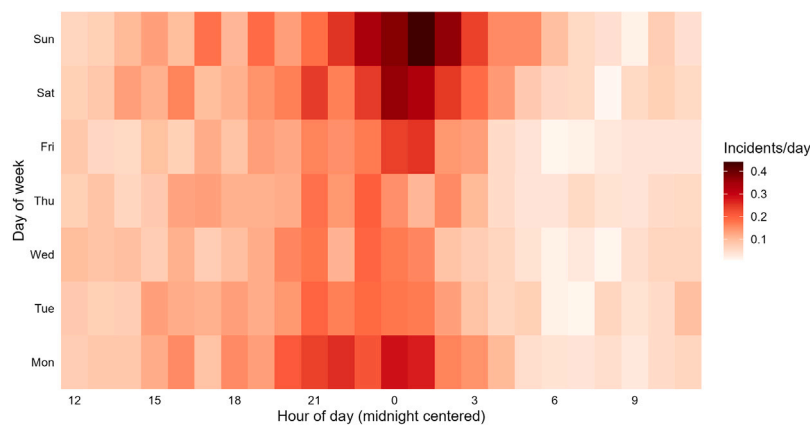
See [Figs. A.1](#) and [A.2](#) and [Tables A.1–A.3](#).

## Data availability

All data sources used in this study are publicly accessible. RMS crime incident data for Detroit are available from the City of Detroit Open Data Portal ([City of Detroit, 2025](#)). Gridded weather data can be obtained from the NOAA nClimGrid-Daily archive ([for Environmental Information, 2022](#)). Neighborhood ecological measures are distributed by the National Neighborhood Data Archive (NaNDA) ([ICPSR, 2024](#)), and tree canopy data are available from the National Land Cover Database tree canopy product ([U.S. Geological Survey and U.S. Forest Service, 2023](#)). Code is available in the GitHub Repository: [https://github.com/kambanane/firearm\\_climate\\_detroit](https://github.com/kambanane/firearm_climate_detroit).

**Table A.1**  
Michigan Incident Crime Reporting (MICR) firearm-related offense codes used to identify firearm-discharge incidents.

MICR Code	Offense Category	Description
1301	Aggravated Assault	Assault and battery — simple assault, also aggravated assault involving a firearm; includes assault with intent to do great bodily harm using a gun.
1304	Aggravated Assault	Assault with other firearm-related weapon types (e.g., unspecified firearm).
1307	Aggravated Assault	Discharge or delivery of a firearm at a dwelling, vehicle, or occupied structure.
1310	Aggravated Assault	Other gun-related aggravated assault not classified elsewhere.
0901	Homicide	Murder or non-negligent manslaughter committed with a firearm.
0903	Homicide	Negligent homicide involving a firearm.
0905	Homicide	Justifiable homicide involving use of a firearm.
0907	Homicide	Manslaughter (involuntary) involving a firearm.
0911	Attempted Murder	Attempted murder committed with a firearm.



**Fig. A.1.** Heatmap of firearm discharge incidents in Detroit by hour of day and day of week. Each cell represents the average number of firearm discharge incidents per day observed within a given hour of the day and day of the week across the study period. Darker colors indicate higher incident frequency. Incidents were most frequent during late-night and early-morning hours, with the highest concentrations on Saturday and Sunday.

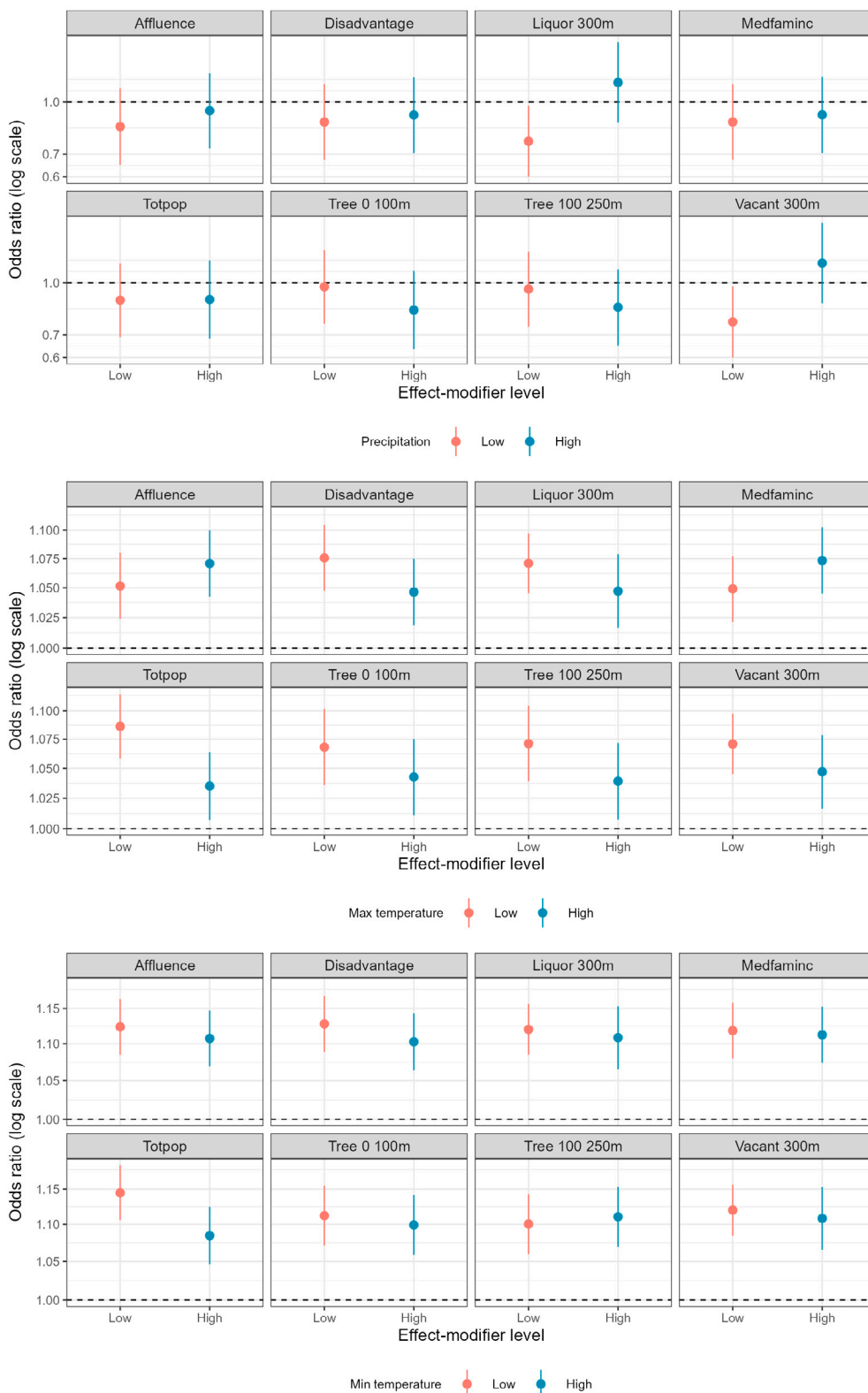
**Table A.2**  
Mutually adjusted distributed lag models including precipitation and maximum temperature. Odds ratios (OR) correspond to the 95th percentile of each exposure relative to the reference value used in the main analysis. Models include precipitation and temperature cross-basis terms simultaneously in the conditional logistic regression with the same adjustment variables as the primary models.

Exposure	Lag (days)	OR (95% CI)
Temperature (max)	0	1.09 (1.05, 1.14)
Temperature (max)	14	1.06 (1.01, 1.10)
Precipitation	0	0.85 (0.79, 0.91)
Precipitation	14	0.89 (0.83, 0.96)

**Table A.3**  
Mutually adjusted distributed lag models restricted to firearm incidents. Odds ratios (OR) correspond to the 95th percentile of each exposure.

Exposure	Lag (days)	OR (95% CI)
Temperature (max)	0	1.14 (1.08, 1.21)
Temperature (max)	14	1.10 (1.03, 1.18)
Precipitation	0	0.58 (0.49, 0.68)
Precipitation	14	0.66 (0.56, 0.77)

### Effect Modification of Weather–Violence Associations Precipitation, Max Temp, and Min Temp | ORs at 95th percentile, lag 0



**Fig. A.2.** Effect modification of weather–violence associations by neighborhood ecological characteristics. Panels show odds ratios (ORs) and 95% confidence intervals for firearm discharge incidents associated with precipitation, maximum temperature, and minimum temperature at the 95th percentile of each exposure (lag 0), stratified by low versus high levels of potential effect modifiers. Modifiers include neighborhood affluence, disadvantage, population size, liquor outlets within 300 m, vacant properties within 300 m, and tree canopy within 0–100 m and 100–250 m buffers. Points represent estimated ORs and vertical lines indicate 95% confidence intervals; the dashed horizontal line denotes the null value (OR = 1).

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