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Association between ambient temperature and sex offense: A case-crossover study in seven large US cities, 2007–2017

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ABSTRACT

There is an increasing interest in the link between ambient temperature and sexual crime in the context of climate change. However, existing studies are limited in evaluating the acute effect of temperature and rarely estimate the attributable burden. Here, we show that in seven large US cities, every 5 °C rise in daily mean temperature was associated with a 4.5 % [95 % confidence interval (CI): 2.8–6.3 %] increase in sex offenses in the following 0–8 days. The associations were stronger in hot and cold season compared to moderate season, and could be enhanced by higher relative humidity and precipitation. The associations were only significant for sodomy, fondling and rape, and for sex offenses happened in certain locations (open space, education, street but not residence). We estimated that 2.6 % (95 %CI: 1.7–3.6 %) sex offenses were attributable to temperatures above city-specific median temperatures, corresponding to a mean annual sex offense rate of 2.9/100,000 (95 % CI: 1.9–4.0/100,000). Our findings highlight the potential rising sexual crime along with climate change and provide useful information for targeted preventions.

1. Introduction

Sexual violence is the dark side of human civilization. The “Me Too” movement, a movement against sexual harassment and sexual assault beginning to spread virally on social media since October 2017, is driving more and more public attention to this issue (Caputi, Nobles, & Ayers, 2019). More than 90 % of victims of sexual assault are women (Welch & Mason, 2007). According to the World Health Organization, globally 7.2 % of women aged 15 or above would experience at least one non-partner sexual violence during their life course (World Health Organization, 2013). Sexual assault causes major acute physical and mental injury to the victims, such as unwanted pregnancies, sexually transmitted infections (including HIV) and post-traumatic stress disorder (Welch & Mason, 2007). A recent study also showed that sexual assault could have a long-term impact on women’s mental health, increasing their risk of depressive symptoms, clinically relevant anxiety and poor sleep (Thurston, Chang, Matthews, von Känel, & Koenen, 2019).

In the context of climate change, the increasing global mean temperature is posing great threat on human health and well-beings (Guo et al., 2018; Mora et al., 2017), such as increased heat-related mortality/morbidity/injuries and reduced labour productivity (Liu et al., 2021; Watts et al., 2021). Growing evidence also suggests that temperature rise may result in more violent crime (Berman, Bayham, & Burkhardt, 2020; Cohn, 1990; Gamble & Hess, 2012; Mares, 2013; Ranson, 2014; Stevens, Beggs, Graham, & Chang, 2019), including sexual crime. Ambient temperature may increase sexual crime by increasing people’s aggression level (Cohn, 1990) or sexual desire (Demir, Uslu, & Arslan, 2016), or by altering people’s routine behaviors (e.g., outdoor social activities, alcohol use) associated with sexual crime (Johnson, Ju, & Wu, 2016; Knudsen & Skogen, 2015; Monk & Jones, 2014; Rotton & Cohn, 2003; Seto, 2017).

Several studies have suggested a positive association between ambient temperature and sexual crime (Cohn, 1993; Gamble & Hess, 2012; Mares, 2013; McLean, 2007; Michael & Zumpe, 1983; Ranson, 2014; Rotton, 1993; Rotton & Cohn, 2003). However, most of them were based on monthly (Mares, 2013; Ranson, 2014; Rotton, 1993) or even yearly (Michael & Zumpe, 1983; Rotton & Cohn, 2003) sexual crime data. Such designs cannot account for variations within a month, making it impossible to evaluate acute effects of temperature on sexual crime. Few studies used daily crime data to evaluate the association, and they were all based on a single city and did not account for the potential

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lagged effects of temperature on sexual crime (Cohn, 1993; Gamble & Hess, 2012; McLean, 2007). As observed in recent studies, the impacts of ambient temperature on violent crime last for several days and have a clear harvesting effect or temporal displacement (i.e., some violent crimes were displaced to earlier days due to temperature rise) (Berman et al., 2020; Xu, Xiong, Abramson, Li, & Guo, 2020). Due to the generally violent nature of sex offenses, its association with ambient temperature may show a similar lag pattern, but no previous study has accounted for this.

Time-stratified case-crossover design is a widely used standard epidemiological approach to evaluate the association between acute environmental exposure and health outcomes based on daily data of single or multiple cities (Carracedo-Martinez, Taracido, Tobias, Saez, & Figueiras, 2010; Fu, Gasparrini, Rodriguez, & Jha, 2018; Guo, 2017; Xu et al., 2019; Zhang et al., 2020). This design could well account for the short-term effects and adjust for time-dependent confounders (e.g., temporal trend, seasonality and day of the week) and time-constant confounders (i.e., variables remains stable within one month, such as individuals' and cities' characteristics) (Janes, Sheppard, & Lumley, 2005a; Janes, Sheppard, & Lumley, 2005b). Despite its intensive usage in epidemiological studies, its application in crime research remains quite limited (Gates, Klein, Acquaotta, Garland, & Scovronick, 2019; Xu et al., 2020). Moreover, distributed lag models could be integrated with this design and has widely been used to evaluate the potential lag effects (Fu et al., 2018; Gasparrini, 2011; Guo, Barnett Adrian, Pan, Yu, & Tong, 2011). It is worthwhile to introduce these mature epidemiological methods into the research on the impacts of environmental factors such as ambient temperature on sexual crime, given the aforementioned limitations of existing studies on this topic.

In the present study, using a time-stratified case-crossover design and distributed lag model based on a multi-city daily sex offense dataset from the US, we aimed to evaluate the short-term effect of daily ambient temperature on sex offenses and to quantify the fractions of sex offenses that were attributable to temperature.

2. Methods

2.1. Data collection

2.1.1. Sex offense data

Data on sex offenses were gathered from the municipal websites of 10 large US city governments, as detailed by (Ashby, 2019). The data and its technical documents are publicly available from the Open Science Framework (https://osf.io/zyaqn/). In the present analysis, we only included data from 7 cities (Chicago, Kansas City, Los Angeles, Louisville, San Francisco, Tucson and Virginia Beach). Other 3 cities were excluded, because they either did not open the record of sex offenses (Fort Worth) or their date records of sex offenses were problematic (New York and Detroit, see Data quality check, Figs. A1 and A2 in the Appendix). The study period was defined as the period with crime data available (Ashby, 2019). Among the seven cities selected, the study period started from 2007 to 2013 and all ended in 2017. The dataset recorded the type, location, date, and exact time (to minutes) of each sex offense case. We included six main types of sex offenses including sodomy, fondling, rape, nonforcible sex offenses, sexual assault with an object, and other sex offenses. They were categorized according to the definitions published by the Federal Bureau of Investigation (FBI) (see Table A1 in Appendix for details) (Federal Bureau of Investigation, 2015). Data from Chicago did not have records specifically for rape but records of a similar category called "sexual assault by penetration (including rape)". To make the results easier to follow, we simply recoded "sexual assault by penetration" in Chicago as rape defined by the FBI.

2.1.2. Weather and other data

The daily weather data during the study period, including daily mean temperature, daily mean dewpoint temperature and daily precipitation was obtained from a national meteorological dataset (4 km × 4 km resolution) created by PRISM Climate Group (http://www.prism.oregonstate.edu/) (PRISM Climate Group, 2018). City-specific weather was represented by the average weather data from all grids within the city's officially defined boundary. The average bias of daily mean temperature from PRISM compared to meteorological station records was less than 0.2℃, and the precipitation and daily mean dewpoint temperature were also highly consistent with weather station records (Di Luzio, Johnson, Daly, Eischeid, & Arnold, 2008). The daily mean relative humidity was calculated from daily mean temperature and daily dewpoint temperature using the R package developed by Cai (2018). The population data for each city in each year were gathered from the US census bureau (https://www.census.gov/).

2.2. Statistical analyses

2.2.1. Assessing the temperature-sex offenses association

The association between ambient temperature and sex offenses was evaluated by a time-stratified case-crossover design (Levy et al., 2001; Li, Guo, & Williams, 2016). For each sex offense case, the daily mean temperatures during the risk period (i.e., the time window during which exposure is likely to affect the outcome) were compared with those during control periods (i.e., the periods with usual levels of exposure) in the same city. The essence of this design is to evaluate whether the exposure levels during the risk periods is systematically "unusual", i.e., systematically higher or lower than usual levels during control periods (Maclure, 1991; Maclure & Mittleman, 2000). Control periods were the same days of the week in the same calendar month and year for each sex offense case. This self-matching design could adjust for time-dependent confounders (e.g., temporal trend, seasonality and day of the week) and time-constant confounders (e.g., type, location, cause of the sex offense cases, city's socioeconomic and climatic characteristics) (Janes et al., 2005a, 2005b).

The relationship between sex offenses and temperature was fitted by a conditional logistic regression model, with R codes detailed previously (Guo, 2017). In this regression model, the dependent variable is a binary variable indicating whether an observation is a case or control (1=case, 0=control). Daily mean temperature was added to the model as an independent variable using a cross-basis function (Guo, 2017). Our initial analyses showed that the association was linear (see Fig. A3 in Appendix) and lasted for 8 days. Thus, we used a linear function for the exposure-response dimension and a natural cubic spline with three degrees of freedom (df) for the lag-response dimension (lag 0–8 days). We chose a three df because it resulted in best model fit with the lowest value of Bayesian information criterion (BIC = 259446.0), compared with model with four (BIC = 259457.3) or five (BIC = 259464.9) df. The holiday effect was controlled by adding a dichotomous variable (whether that date was a public holiday) to the model. We also adjusted for the daily relative humidity and daily precipitation in lag 0–8 days by adding them to the model as cross-basis functions, using a natural cubic spline with three df for both exposure-response and lag-response dimension (lag 0–8 days), respectively.

Stratified analyses were conducted by city, time (00:00–05:59, 06:00–11:59, 12:00–17:59, and 18:00–23:59), day of week (weekday versus weekend), type of sex offenses, location of the offense (street, residence, open space, vehicle and transportation, healthcare, education, leisure, hotel, retail and commercial, other, and uncoded places), season (hot, cold or moderate), daily mean relative humidity (<median versus ≥ median), and daily precipitation (0 mm/d, <10 mm/d, ≥10 mm/d). The hot and cold seasons were defined by the hottest and coldest four months for each city, respectively. The other four months were coded as a moderate season (Guo et al., 2016).

The temperature-sex offenses association was represented by odds ratio (OR) and its 95 % confidence interval (CI) of a sex offense occurrence for every 5℃ increase in daily mean temperature. We used

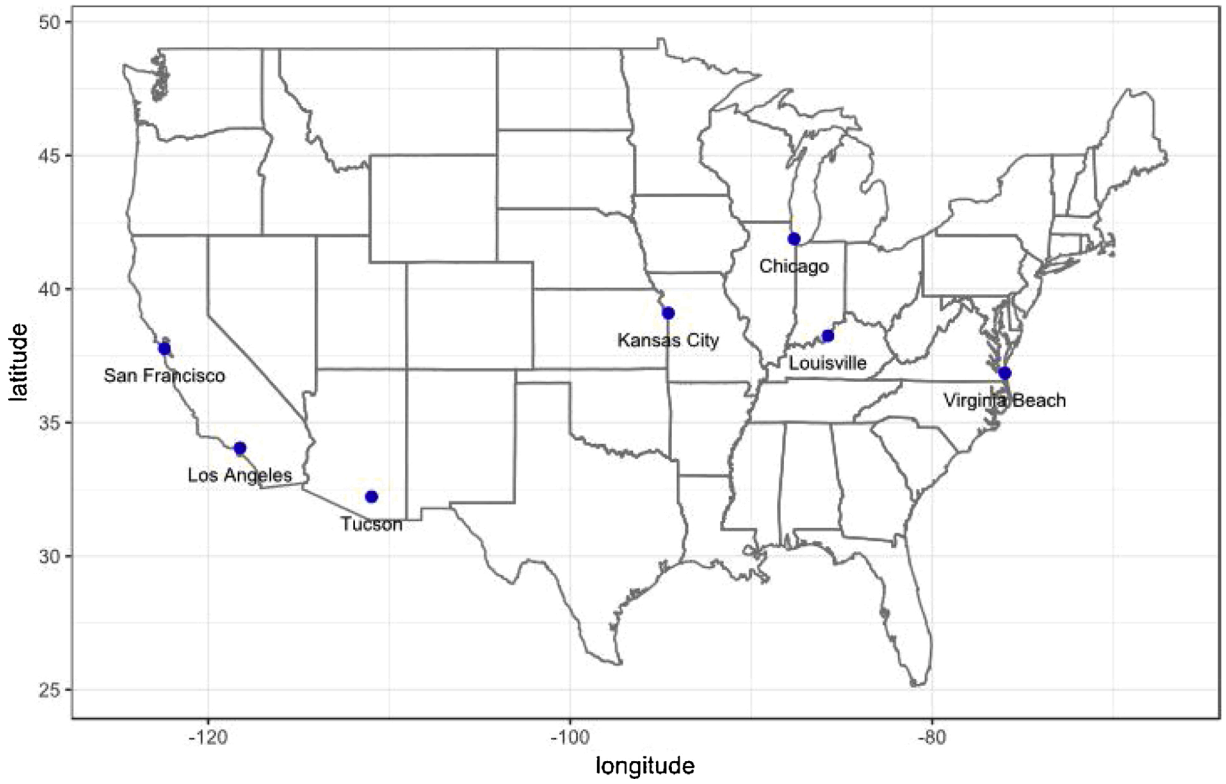

Fig. 1. The locations of the seven large US cities included in the present study.

univariate fixed effect meta-regression to check the statistical differences in the ORs between strata. Briefly, we modelled the effect estimates of different strata with standard error (e.g., seven city-specific effect estimates) against the meta-predictors (e.g., city as a categorical variable with seven levels), then the meta-regression model will test the inter-stratum (e.g., inter-city) difference in effect estimates with likehood ratio test (Guo, 2017; Xu et al., 2019; Yang et al., 2015; Zhang et al., 2020).

We conducted several sensitivity analyses to check the robustness of our results, including altering maximum lag of daily mean temperature from 8 days to shorter (6 and 7) or longer (9 and 10) days; changing the df of lag days from 3 to 4 or 5 that with more model flexibility; removing precipitation and/or relative humidity from the model; and using daily minimum or daily maximum temperature rather than daily mean temperature as the exposure variable. We used meta-regression to test whether these models were statistically different from the primary model.

2.2.2. *Calculating the attributable fraction of sex offenses due to temperature*

For each city, three steps were used to calculate attributable fraction (AF) and its 95 % CI. At the first step, the city-specific median daily mean temperatures during the study period were chosen as reference temperatures for each city. Although the city-specific minimum daily mean temperature during the study period was the temperature with lowest risk of sex offense given the linear relationship, it could be easily

Table 1
Basic characters of sex offenses and climate parameters for the seven cities during the study period.

City	Study period	No. of cases	Area size of city (km^2)	Mean population	Mean annual sex offenses rate (1/100,000)	Daily mean climate parameters, mean ± sd			
						Mean temp (°C)	Temp range (°C)	RH (%)	Precipitation (mm)
Chicago	2007–2017	26620	606	2749282	88.0	11.0 ± 11.1	−23.9 to 33.2	63.3 ± 12.2	3.1 ± 8.3
Kansas City	2009–2017	11336	826	470308	267.8	13.3 ± 10.9	−18.3 to 34.3	63.9 ± 13.1	3.1 ± 9.6
Los Angeles	2010–2017	40593	1302	3903613	130.0	18.5 ± 4.1	7.4–32.2	56.6 ± 17.1	0.8 ± 4.4
Louisville	2009–2017	2669	1030	605528	49.0	14.5 ± 10.1	−17.6 to 33.3	63.4 ± 12.2	3.7 ± 9.6
San Francisco	2007–2017	6892	121	824868	76.0	14.4 ± 3.2	5.0–30.8	68.8 ± 12.4	1.5 ± 5.3
Tucson	2009–2017	8052	587	528798	169.2	21.3 ± 7.8	−2.8 to 37.1	30.7 ± 15.6	0.7 ± 3.1
Virginia Beach	2013–2017	938	1289	450057	41.7	16.5 ± 9.0	−9.4 to 32.5	64.7 ± 12.5	3.9 ± 11.9
Total	2007–2017	97100	NA	9532453	111.3	15.4 ± 9.2	−23.9 to 37.1	58.9 ± 18.2	2.3 ± 7.8

Note: sd, standard deviation; temp, daily mean temperature; RH, relative humidity; NA, not applicable; mean population represents the average population during the study period; the total mean annual sex offenses rate was the weighted average (by population) of city-specific rates.

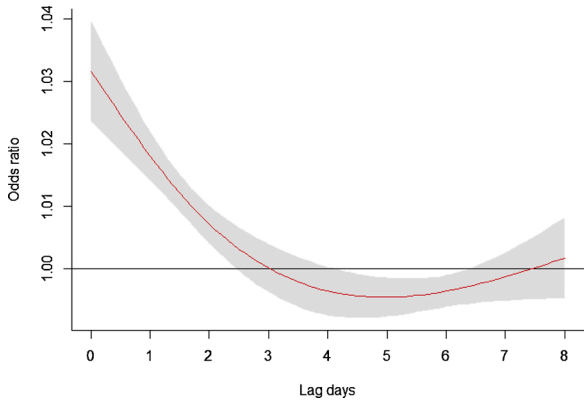

Fig. 2. The lag structure of the association between current day ambient temperature (every 5 °C increase in daily mean temperature) and sex offenses during the following lag 0–8 days.

affected by extreme weather observations. By contrast, city-specific median daily mean temperatures are more stable and can hardly be affected by extreme observations, thus AFs in relative to median temperature tend to be more robust than AF in relative to the minimum temperature (Xu et al., 2020).

At the second step, the attributable number of sex offense cases caused by temperature above reference temperature on day i were calculated using the formula $AC_i = C_i \times (RR_i - 1)/RR_i$, with RR_i being the city-specific overall cumulative OR over lag 0–8 days associated with the increase in temperature above reference temperatures on day i, and Ci the city-specific averages of sex offense cases from day i to day i+8 (Gasparrini & Leone, 2014; Hu et al., 2018). We used ORs deriving from regression analyses based on all included cities to represent city-specific RR, because the inter-city differences in effect estimates were not statistically significant (see Fig. A4 in Appendix). We got the total AC by summing the AC_i during the study period. Finally, the AFs were calculated by dividing the total AC by total sex offense cases. We also calculated the annual attributable sex offense rate by dividing the total AC by the city-specific mean population and the number of years during the study period. The 95 % CI of AC, AF and attributable rates were calculated by applying the 95 %CI of OR to the above algorithm following the same procedures.

We used R software (version 3.3.2) to perform all data analyses. We used packages "survival" (Therneau, 2020), "dlnm" (Gasparrini, 2011) and "mvmeta" (Gasparrini & Armstrong, 2013) to fit conditional logistic regression, distributed lag linear or non-linear model, and meta-regression, respectively. The package "humidity" was used to calculate the daily mean relative humidity (Cai, 2018). A two-side *p* value less than 0.05 was considered as being statistically significant.

3. Results

3.1. Descriptive results

The present study included seven large US cities (Chicago, Kansas City, Los Angeles, Louisville, San Francisco, Tucson and Virginia Beach) (Fig. 1). The average daily mean temperature for all observed days in the seven cities was 15.4 ± 9.2 ℃, varying from 11.0 ± 11.1℃ in Chicago to 21.3 ± 7.8℃ in Tucson. A total of 97,100 sex offenses were recorded in all observed cities during the study periods, among them 90,182 (92.9 %) cases with proper date records were included in the regression analyses. The mean annual sex offense rate ranged from 41.7/100,000 in Virginia Beach to 267.8/100,000 in Kansas City (Table 1).

3.2. The association between temperature and sex offenses

The association between daily mean temperature and sex offenses in lag 0–8 days was generally linear (Fig. A3). This linear association was significant and positive [odds ratio (OR)>1] in lag 0–2 days, then diminished and followed by a temporal displacement until lag 8 days. In other words, there were some sex offense cases supposed to happen in lag 3–8 days but happened in advance at lag0–2 days due to the temperature rise in lag 0 day (Fig. 2).

The cumulative effect of temperature on sex offenses during lags 0–8 days is shown in Fig. 3. Overall, every 5 °C increase in daily mean temperature was associated with a 4.5 % [95 % confidence interval (CI): 2.8–6.3 %; OR = 1.045, 95 %CI: 1.028–1.063)] increase in sex offense cases in lag 0–8 days. The effect estimates did not show a significant difference between different times (00:00–05:59, 06:00–11:59, 12:00–17:59 and 18:00–23:59), weekday and weekend, and different cities (*P*-values for difference all >0.05) (Fig. A4).

Across different types of sex offenses, sodomy had the strongest association with temperature rise (OR = 1.098, 95 %CI: 1.039–1.162), followed by fondling (OR = 1.066, 95 %CI: 1.037–1.097) and rape (OR = 1.030, 95 %CI: 1.007–1.055). The effect estimate was weaker for rape compared to sodomy (*P*-values for difference<0.05). Nonforcible sex offenses and sexual assault with an object showed a non-significant association with temperature. As for different locations, sex offenses happened on open space (green space, vehicle parking, etc.) showed the strongest association with temperature rise (OR = 1.174, 95 %CI: 1.047–1.317), followed by healthcare, education (school, childcare and

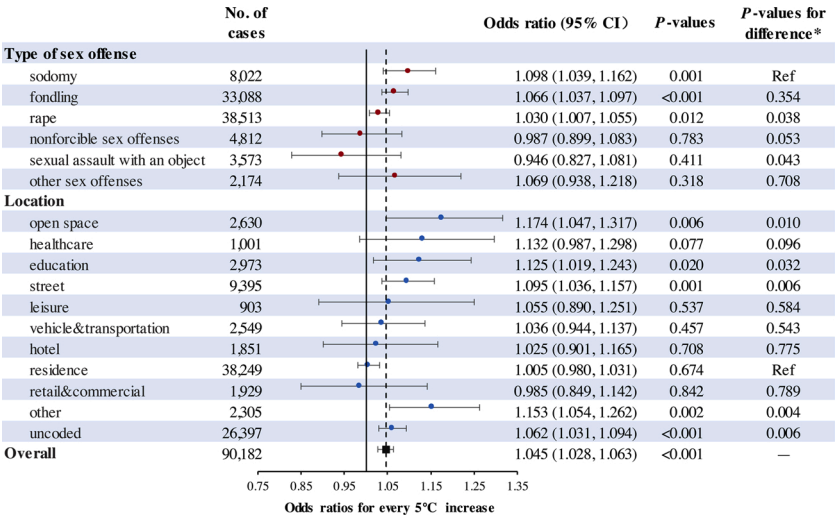

Fig. 3. The cumulative association between ambient temperature and sex offenses during lag 0–8 days, stratified by type and location.
Note: **P*-values for testing the difference between subgroups, estimated by meta-regression. CI = confidence interval. The vertical dashed line represents the overall effect size. Statutory rape was not included in rape. Nonforcible sex offenses include statutory rape (5511 cases) and incest (81 cases). Open space includes green space, vehicle parking and other open space.

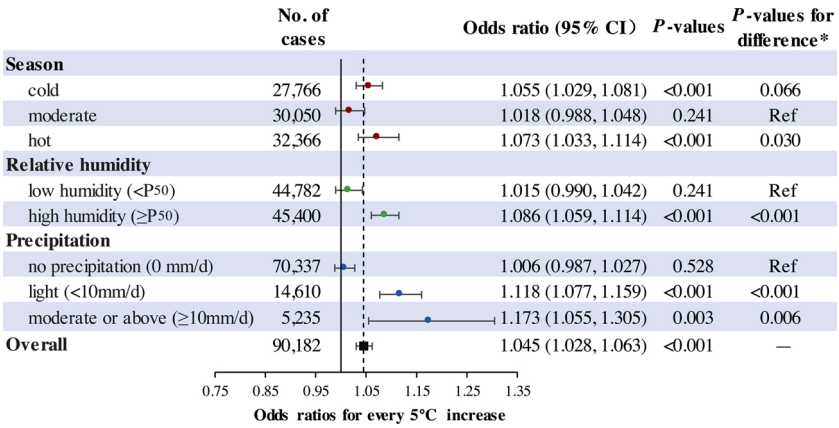

Fig. 4. The cumulative association between ambient temperature and sex offenses during lag 0–8 days, stratified by season, relative humidity and precipitation. Note: *P-values for testing the difference between subgroups, estimated by meta-regression. P50 represents the median relative humidity for all included observed days. CI = confidence interval. The vertical dashed line represents the overall effect size.

Table 2
The number, fraction and annual rate of sex offenses that could be attributed to temperature above city-specific median temperature during the study period.

City	Reference temperature (°C)	Attributable cases (95 %CI)	Attributable fraction (95 %CI), %	Attributable annual rate (95 %CI), 1/100,000
Chicago	11.9	1076 (688, 1451)	4.0 (2.6, 5.5)	3.6 (2.3, 4.8)
Kansas City	14.3	444 (283, 599)	3.9 (2.5, 5.3)	10.5 (6.7, 14.1)
Los Angeles	18.7	591 (374, 805)	1.5 (0.9, 2.0)	1.9 (1.2, 2.6)
Louisville	15.8	93 (59, 126)	3.5 (2.2, 4.7)	1.7 (1.1, 2.3)
San Francisco	14.3	78 (49, 106)	1.1 (0.7, 1.5)	0.9 (0.5, 1.2)
Tucson	21.4	231 (147, 313)	2.9 (1.8, 3.9)	4.9 (3.1, 6.6)
Virginia Beach	17.8	25 (16, 34)	2.7 (1.7, 3.6)	1.1 (0.7, 1.5)
Overall	NA	2551 (1625, 3450)	2.6 (1.7, 3.6)	2.9 (1.9, 4.0)

Note: city-specific median temperatures were selected as the reference temperature. CI = confidence interval. NA, not applicable.

college), and street. Interestingly, although about 60 % of sex offense cases with location code occurred in residence, these cases had a weak and non-significant association with temperature (OR = 1.005, 95 %CI: 0.980–1.031) (Fig. 3).

The association between ambient temperature and sex offenses was significantly modified by season, relative humidity, and precipitation. The association was stronger in the hot or cold season and days with high humidity compared to moderate season and days with low humidity. The association was non-significant in days with no precipitation (0 mm/d), but strengthened with the increase of daily precipitation from light (<10 mm/d) to moderate or above (≥10 mm/d) (Fig. 4).

3.3. Sex offenses attributable to temperature

Table 2 shows that 2.6 % (95 %CI: 1.7 %–3.6 %) sex offense cases during the study periods were attributable to temperatures above city-specific median temperatures, corresponding to 2,551 excess cases and 2.9/100,000 average annual sex offense rate in the seven cities. The attributable fractions ranged from 1.1 % in Los Angeles to 4.0 % in Chicago.

3.4. Results of sensitivity analyses

As shown by sensitivity analyses, our results had minimal and non-significant (*P*-values for difference all >0.05) change when altering the maximum lag of daily mean temperature and degrees of freedom (df) of lag days, or removing relative humidity and precipitation from the model (Table A2). The results also changed minimally when we used daily minimum or daily maximum temperature rather than daily mean temperature as the exposure variable (Table A3).

4. Discussion

This is the first multi-city study that has evaluated the short-term impacts of ambient temperature on sex offenses. The case-crossover design with the distributed lag linear model has been introduced into this topic for the first time. We found a significant and linear increase in sex offense cases during lag 0–8 days associated with temperature rise. The associations were only significant for sodomy, fondling and rape, and for sex offenses happened in certain locations (open space, education, street but not residence). The association seemed to be stronger in the hot and cold season compared to the moderate season and was enhanced by higher relative humidity and precipitation. We estimated that 2.6 % of the sex offenses cases could be attributed to temperatures above the city-specific median temperatures during the study periods.

4.1. Comparison with previous studies

Our findings are generally consistent with previous studies (Cohn, 1993; Gamble & Hess, 2012; Mares, 2013; McLean, 2007; Michael & Zumpe, 1983; Ranson, 2014; Rotton, 1993; Rotton & Cohn, 2003) in the positive temperature-sex offense association. Recent studies also found similar positive associations between short-term exposure to ambient temperature and other types of violent crime (e.g. homicide, assault) (Berman et al., 2020; Gates et al., 2019; Stevens et al., 2019; Xu et al., 2020). However, the effect estimates of our study are not comparable with those of most previous studies, mainly due to different study design and statistical model. A recent study using the same case-crossover design and distributed lag model found that every 5 °C increase in daily mean temperature was associated with a 4.2 % (95 % CI:1.1–7.3 %) increase in intentional homicide over lag 0–7 days, based on pooled data of nine US cities (Xu et al., 2020). This effect estimate and lag pattern are quite similar with those of the present study, suggesting

different types of violent crime may show a similar association with ambient temperature.

4.2. Potential mechanisms underlying the temperature-sex offenses association

Theories that could explain the association between ambient temperature and sex offenses could be summarized as two types—biological theory and routine activity theory (Agnew, 2012; Cohn, 1990; Rotton & Cohn, 2003). The biological theory, also known as temperature-aggression theory, takes high temperatures as an environmental stressor that may increase people's aggression by making them uncomfortable (Cohn, 1990; Kenrick & Macfarlane, 1986). With this additional stressor, those who are already highly stressed, or more sensitive to stressors, or with low self-control, may turn to violent behavior such as sexual assault to release the stress (Cohn, 1990). In addition to the direct effect, a high ambient temperature may also increase people's aggression indirectly such as by causing sleep deprivation (Obradovich, Migliorini, Mednick, & Fowler, 2017; Okamoto-Mizuno, Mizuno, Michie, Maeda, & lizuka, 1999). Finally, temperature rise might also provoke human beings' sexual desire which is likely to induce sex offenses. There is evidence that high temperature could increase both man and women's sex drive by elevating their sex hormone level (Demir et al., 2016).

Routine activity theory emphasizes that warmer temperatures could alter people's routine activities or behaviors relating to crime (Rotton & Cohn, 2003). For example, during warm weather, people are more likely to go outsides, increasing the likelihood that motivated sex offenders encounter potential victims (Cohn, 1990; Rotton & Cohn, 2003). On the other hand, although may not applying to all countries, warmer weather may increase people's alcohol use (Knudsen & Skogen, 2015), while over 70 % of sexual assaults are alcohol-related (Monk & Jones, 2014).

4.3. The modification effects of humidity, precipitation, season, location, and offense type

The biological theory may explain why the effect of temperature rise on sexual crime could be enhanced by high relative humidity and increased precipitation, because high air moisture level could exaggerate people's uncomfortable hot feeling of high temperature by impeding sweat evaporation and heat dissipation (Alber-Wallerstrom & Holmer, 1985; Coffel, Horton, & de Sherbinin, 2018). This is in line with the observations that high relative humidity enhanced the impacts of high temperature on sleep quality (Okamoto-Mizuno et al., 1999) and emigration intentions (Zander & Garnett, 2020).

Both biological theory and routine activity theory can help to explain the stronger temperature-sex offense association in hot season compared to moderate season, because temperature rise in hot season is more likely to cause uncomfortableness (e.g., due to heat stress) and increase alcohol use than temperature rise in moderate season. However, the slightly stronger temperature-sex offense association in cold season compared to moderate season (P-value for difference = 0.066) is likely to be explained by routine activity theory. In cold season, temperature rise from cold levels to a more tolerable and pleasant level tends to increase people's outdoor activities significantly (Berman et al., 2020). By contrast, in moderate season when temperature is already in a relatively tolerable and comfortable level, temperature rise is not likely to alter people routine activities significantly.

This routine activity theory that temperature rise may increase outdoor activities can well explain why only sex offenses happened out of residence (open space, education, street) showed significant association with the temperature. It is possible that sex offenses occurring in residence are likely to be determined by many stable factors such as offenders' personal characteristics and the offender-victim relationship. Consequently, these offenses may be less likely to be crimes of opportunity compared with those occurring in open and public places, thus they can hardly be affected by triggering factors such as a temperature rise.

Different types of sex offenses showed different associations with temperature in our study. This phenomenon cannot be fully explained by both biological theory and routine activity theory alone. We proposed some speculations. Nonforcible sex offenses are a kind of sex offense that the victim was willing to participate the sexual intercourse, so it does not rely on the temperature-induced aggression, stressor, interpersonal-conflict or alcohol use, thus it showed non-significant association with temperature. Sexual assault with an object by definition relies on an "object or instrument" to commit the crime, thus it is more likely to be a planned rather than an impulsive crime. This may make it not likely to be associated with temperature rise which tends to affect impulsive behavior. However, the non-significant association for nonforcible sex offenses and sex offense with an object may also simply results from their relatively small sample size, thus further larger studies are warranted to confirm our findings. According to the FBI's investigation (Federal Bureau of Investigation, 2015), the most common age (i.e., the age appears most often) of victims of sodomy, fondling, and rape were 5 years, 14 years, and 15 years, respectively. The most common age of offenders of sodomy, fondling, and rape were 14 years, 14 years, and 18 years, respectively. Lower age of the victims means weaker self-defence ability, and lower age of the offenders means poorer self-control. This may explain why sodomy and fondling showed stronger associations with temperature than rape.

4.4. The lag impacts of ambient temperature on sex offense

Our findings about the lag impacts of ambient temperature on daily sex offense is new to previous studies. Although two recent studies have found similar lag pattern for the impacts of ambient temperature on violent crime, they did not report any data for sex offense (Berman et al., 2020; Xu et al., 2020). The positive association between current day temperature (lag0) and sex offenses on lag 1–2 days suggests that some temperature induced sex offenses takes time to happen. In this scenario, the negative factors (e.g., aggression, interpersonal conflicts, offenders encountering victims, alcohol use) induced by temperature rise is only the start point, the sex offender make take days for deviant fantasy, planning, cognitive distortion before committing offense (Hudson, Ward, & McCormack, 1999; Pithers, 1990). The negative association between current day temperature (lag0) and sex offenses on lag 4–6 days suggests a "temporal displacement". In other words, some sex offenses on lag 3–8 days were displaced to earlier days (lag 0–2 days) due to temperature rise on the current day (lag 0), making the associations in later lags become null or negative. Without capturing this temporal displacement as previous studies did (Cohn, 1993; Gamble & Hess, 2012; McLean, 2007), the true effect of temperature on sex offenses would have been overestimated. The plausible underlying cause of the temporal displacement is that some sex offenses may have been determined by many pre-disposing factors, such as offenders' belief in rape myths, aggressive tendencies, empathic deficits, and childhood abuse experience (DeGue, DiLillo, & Scalora, 2010; McMackin, Leisen, Cusack, LaFratta, & Litwin, 2002). Without effective intervention, some of this sex offenses would like to happen soon or later, while temperature rise tends to be a triggering factor that makes them happens earlier, e.g., by increasing aggression level, alcohol use or the likelihood that offenders encounter victims.

4.5. Implications of our findings

Our study could have important social implications by documenting an important social impact of climate change. A significant proportion of sex offenses were attributable to temperatures higher than city-specific median temperatures in our estimation, suggesting temperature an important environmental factor that might affect sexual crimes. The inactive mitigation response is anticipated to result in a 2.6–4.8 °C rise

in global average surface temperature by the end of this century compared to baseline period (1986–2005) (Watts et al., 2018). In our study, the OR was estimated to be 1.045 for sex offense with a 5 °C increase in daily mean temperature. Thus 2.6–4.8 °C increases correspond to ORs ranged from 1.023 to 1.043, or 2.3 % to 4.3 % increases in sex offense, assuming all other risk factors unchanged under climate change (Xu et al., 2019). Therefore, without effective interventions or major progress in crime prevention, the future world is likely to see more sexual crimes, and effective climate mitigation would help to reduce this risk.

Our study also provides some useful information for targeted prevention of temperature-induced sex offenses. The linear and positive association between temperature and sex offense can inform more effective allocation of policing and community resources of preventing sexual crime according to outdoor temperature (Berman et al., 2020). For example, during hot days, police departments could reinforce their workforce and activities e.g. security patrols, camera surveillance, that could deter potential sex offenders (Cohn, 1990); potential victims of sexual crime especially women may need to raise their safety awareness, and avoid going outside alone and drinking too much alcohol. The increasing risk of sexual crime could be integrated as a part of the early alerts in cities' heat warning system in order to let the public realize this risk (Toloo, Fitzgerald, Aitken, Verrall, & Tong, 2013). Many heat-protection advice (e.g., stay in cool or air-conditioned environment, keep hydrated, avoid drinking alcohol and going outside during hot weather) for mitigating heat-related health risks (Hajat, O'Connor, & Kosatsky, 2010; World Health Organization, 2019) might also be helpful to reduce the risk of heat-related sexual crime, although more evidence are needed.

4.6. Strengths and limitations

Our study adds to previous literature with several new features. First, this is the first study that evaluated the proportion of sex offenses attributable to temperature. This approach could provide more important information for the public than just evaluating the association. Second, the time-stratified case-crossover design based on daily sexual crime data allows us to control for regional and temporal confounders, and to account for variations within several days. This helps us to evaluate the association between temperature and sex offenses in a more accurate manner compared to using monthly or yearly crime data. Third, our study is the first that has accounted for the lagged effects of temperature on sexual crime. Fourth, our stratified analyses by offense type, season, location were novel and could provide new implications for mechanisms and targeted preventions of temperature related sex offenses. Finally, with data from multiple cities over 10 years, our study has the largest sample size and geographical variation compared to previous studies based on daily crime data (Cohn, 1993; Gamble & Hess, 2012; McLean, 2007). This ensures sufficient statistical power and leads to better generalizability.

However, several limitations of this study should be acknowledged. Firstly, the cities included in the present study are all in the US, which may not apply to other countries. Countries with different social contexts, cultural backgrounds, laws against sex offenders, women's social status, and climatic characteristics might see different associations. Secondly, a significant proportion of sex offenses were unreported to the police and thus were missed by our study (Weiss, 2010; Welch & Mason, 2007; Zijlstra et al., 2017).This may cause an underestimation of the temperature-sex offenses association. Thirdly, using the city average daily temperature to represent individuals' ambient temperature could cause a random error of exposure assessment. This random error is likely to attenuate the real association and make the confidence interval wider, particularly in a city with large area size. This may explain why the temperature-sex offense association in Los Angeles (the city with the largest area size among the seven cities) only reached borderline significance ($P = 0.079$), despite its larger sample size than other cities. Fourth, due to confidentiality of relevant data, our study and all existing studies to our best knowledge did not t evaluate whether the temperature-sex offenses association can be modified by the age, sex, race, social-economic status of the victims and offenders, and the victim-offender relationships. Future studies with more detailed information may provide more insights. Finally, our study cannot evaluate the pathways through which temperature affects sex offense, due to the unavailability of data on potential mediators (e.g., aggression level, sleep deprivation, outdoor activities, alcohol use), which warrants further investigations.

5. Conclusions

Daily ambient temperature was positively associated with sex offenses in seven large US cities, but only for certain types (sodomy, fondling and rape) and in certain locations (open space, education, street but not residence). The association could be modified by season, relative humidity and precipitation. This study highlights the potential adverse effects of climate change on future sexual crime and provides some information for targeted preventions.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A

Data quality check

When constructing this multi-city crime dataset, Matthew Ashby has performed some initial quality checks on the crime data for each city, such as excluding cases with location out of city boundary, and excluding years with incomplete daily records (see https://osf.io/jbswz/ for details). However, Dr. Ashby did not check data for all specific offenses (more than 60 offense types). We further checked city-specific data on sex offenses by describing the daily number of sex offenses (Figs. A1–A2). The extreme low number of sex offenses in New York is not likely to be true, as New York is the most populated city in the US. We checked the original data source (see https://osf.io/zyaqn/wiki/1.%20Data%20sources/) for New York and found the most plausible reason is that information on most sex offenses in New York were not opened, in order to protect the victims' privacy. The sharp increase in number of sex offenses since 2016 in Detroit is likely to reflect a technical change in the data included and opened by the city government, rather than a true trend in sexual crime, because crime data in Detroit before and after December 2016 were derived from two separated files. Therefore, sex offense data from New York and Detroit tends to be unreliable thus should be excluded from our analyse.

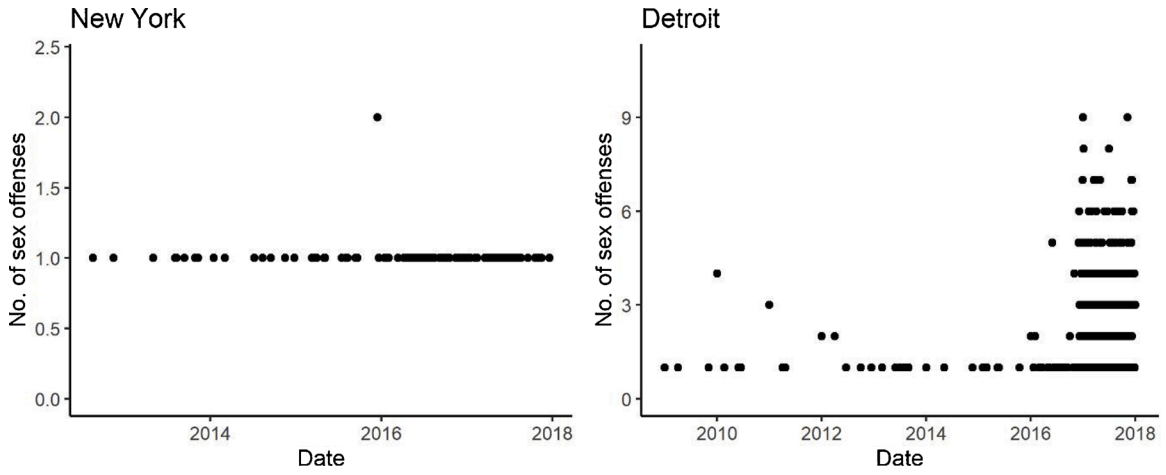

Fig. A1. The daily counts of sex offenses in New York and Detroit.
Note: To make the figure more readable, we did not show daily observations with zero sex offense.

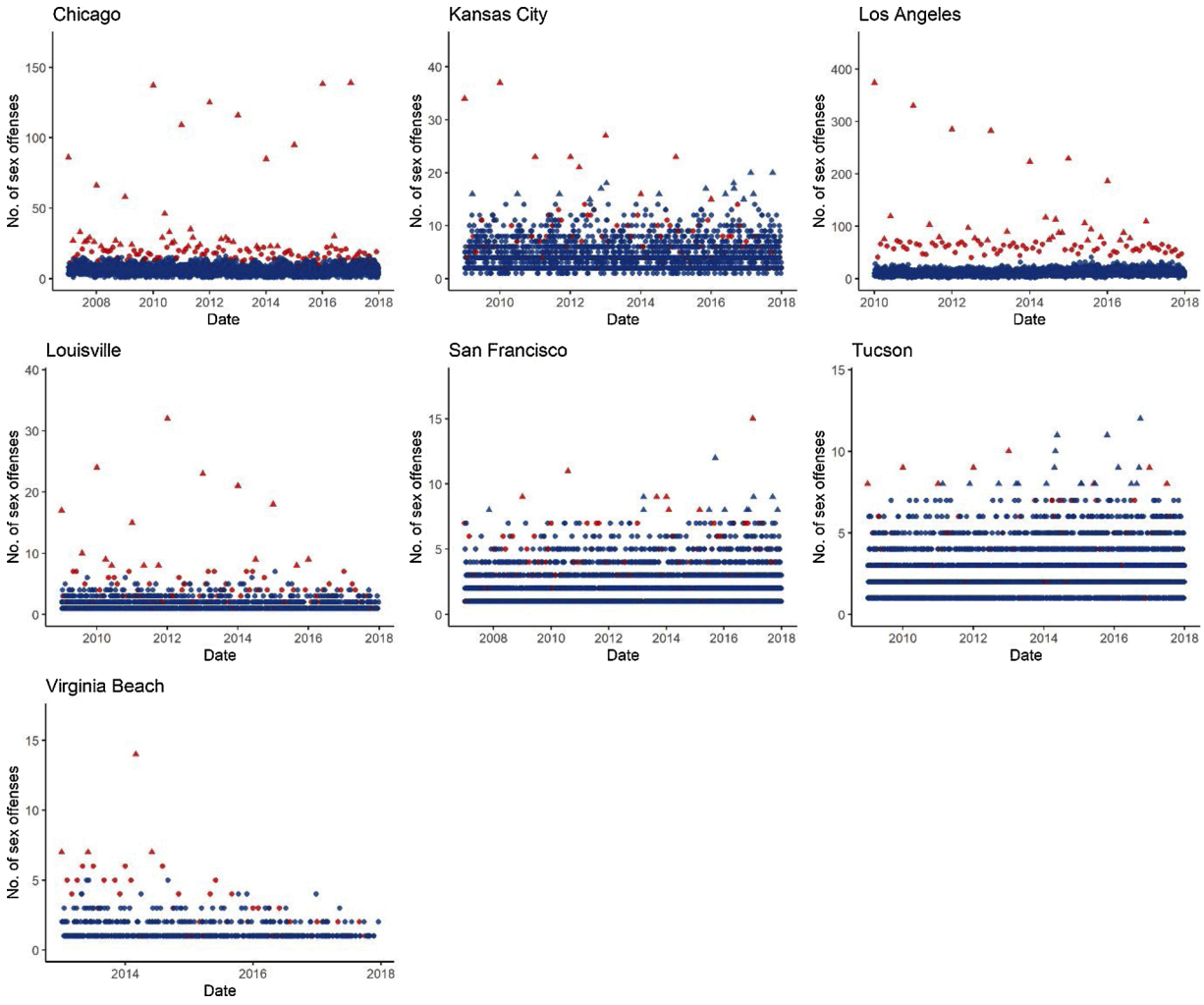

Fig. A2. The daily counts of sex offenses in Chicago, Kansas City, Los Angles, Louisville, San Francisco, Tucson, and Virginia Beach.
Notes: To make the figure more readable, we did not show daily observations with zero sex offense. Those triangle dots (regardless of color) represent extreme daily observations (daily counts $\geq$ city-specific 99th percentile of non-zero daily counts), and round dots (regardless of color) represent non-extreme daily observations. Those red dots (regardless of shape) represent daily observations at the first day of month (e.g, Jan 1, June 1, Dec 1), and blue dots (regardless of shape) represent daily observations at other days of month.

Table A1
The definition and number of cases of different types of sex offenses in this study.

Type of sex offense	Definition by Federal Bureau of Investigation (FBI)	No. of cases (%)
rape*	The carnal knowledge of a person, without the consent of the victim, including instances where the victim is incapable of giving consent because of his/her age or because of his/her temporary or permanent mental or physical incapacity.	40498 (41.7 %)
sodomy	Oral or anal sexual intercourse with another person, without the consent of the victim, including instances where the victim is incapable of giving consent because of his/her age or because of his/her temporary or permanent mental or physical incapacity.	8696 (9.0 %)
sexual assault with an object	To use an object or instrument to unlawfully penetrate, however slightly, the genital or anal opening of the body of another person, without the consent of the victim, including instances where the victim is incapable of giving consent because of his/her age or because of his/her temporary or permanent mental or physical incapacity.	3952 (4.1 %)
fondling	The touching of the private body parts of another person for the purpose of sexual gratification, without the consent of the victim, including instances where the victim is incapable of giving consent because of his/her age or because of his/her temporary or permanent mental or physical incapacity.	36112 (37.2 %)
nonforcible sex offenses	The term nonforcible means the victim was willing to participate in sexual intercourse. Nonforcible sex offense includes incest and statutory rape.	5592 (5.8 %)
incest	Nonforcible sexual intercourse between persons who are related to each other within the degrees wherein marriage is prohibited by law.	81 (0.1 %)
statutory rape	Nonforcible sexual intercourse with a person who is under the statutory age of consent.	5511 (5.7 %)
other sex offenses	Sex offenses that was not classified as any of the types described above, include but not restricted to child sexual abuse, sexual imposition, bestiality, female genital mutilation.	2250 (2.3)

Note:* in this study, cases classified as rape did not include statutory rape. We combined incest and statutory rape as nonforcible sex offenses in the subgroup analyses (see Fig. 3).

Table A2
Results of sensitivity analyses by changing maximum lag of daily mean temperature and df of lag days, and by removing precipitation and relative humidity from the model.

Model	Odds ratio (95 % CI)	*P*-values* for difference
Primary model (lag0–8d, df = 3)	1.045 (1.028, 1.063)	Ref
Lag0-6d, df = 3	1.044 (1.028, 1.060)	0.999
Lag0-7d, df = 3	1.042 (1.026, 1.059)	0.885
Lag0-9d, df = 3	1.045 (1.028, 1.063)	0.904
Lag0-10d, df = 3	1.047 (1.029, 1.066)	0.903
Lag0–8d, df=4	1.045 (1.028, 1.063)	0.989
Lag0–8d, df=5	1.047 (1.030, 1.065)	0.806
Not adjusted for precipitation	1.044 (1.026, 1.061)	0.880
Not adjusted for relative humidity	1.041 (1.024, 1.057)	0.692
Not adjusted for precipitation and relative humidity	1.041 (1.024, 1.057)	0.704

Note: df is the degree of freedom of the lag days. Odds ratio represents the overall association between every 5 °C increase in daily mean temperature and sex offenses in lag days. P-values for difference tested the difference between different models, and they were estimated by meta-regression. CI = confidence interval.

For other seven cities, the main problem of the crime data is the existence of extreme daily counts of sex offenses (Fig. A2). Those extreme daily counts significantly deviated from the city-specific main distribution of daily counts. We did not find an official explanation for these extreme observations. However, we found that most of extreme daily counts (triangle dots regardless of color in Fig. A2) were at the first day of a month (e.g., Jan 1, June 1. Red dots regardless of shape in Fig. A2). Therefore, a plausible explanation is that some sex offenses without exact date record (e.g. the victim did not remember the exact date) were simply recorded as the first day of the month or even the first day of the year, when the only information of month and year was available. We exclude sex offenses on days with extreme daily counts to ensure our analysis is not affected by unreliable date records.

Table A3
Results of sensitivity analyses by using daily minimum and daily maximum temperature.

Model	Odds ratio (95 % CI)	*P*-values* for difference
Primary model (Daily mean temperature)	1.045 (1.028, 1.063)	Ref
Daily minimum temperature	1.047 (1.029, 1.066)	0.645
Daily maximum temperature	1.040 (1.024, 1.056)	0.885

Note: Odds ratio represents the overall association between every 5 °C increase in temperature and sex offenses in lag0–8 days. P-values for difference tested the difference between different models, and they were estimated by meta-regression. CI = confidence interval.

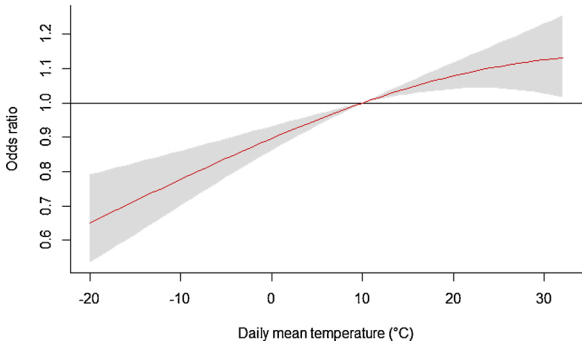

Fig. A3. The linearity of the relationship between daily mean temperature and sex offenses during lag 0–8 days, modelled by a distributed lag non-linear model with quadratic B-spline for temperature.

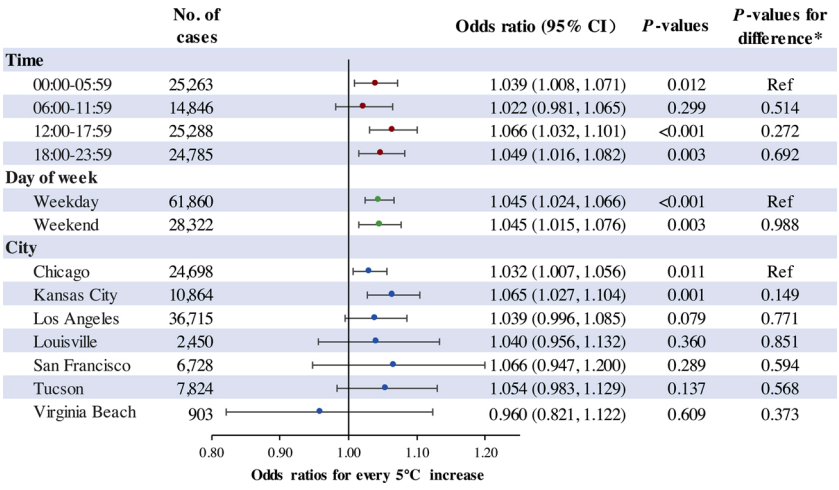

Fig. A4. The association between ambient temperature and sex offenses during lag 0–8 days, stratified by time range, day of week and city.
Note: *P-values for testing the difference between subgroups, estimated by meta-regression. CI = confidence interval.

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