The Effect of Weather on Crime in a Torrid Urban Zone

Juan C. Trujillo[a*] and Peter Howley[b]

Funding

This research was supported by the Newton Fund, the Colombian Administrative Department of Science, Technology and Innovation (COLCIENCIAS), and The Foundation for the Future of Colombia (COLFUTURO), under the Agreement 334 of 2015.

----

[a] Post-Graduate Researcher: Department of Environment and Geography, University of York, Wentworth Way, Heslington West Campus, York, North Yorkshire, YO10 5NG, United Kingdom.
*Corresponding author. E-mail: juan.trujillo@york.ac.uk, phone/fax number: +44 (0) 1904-324071 / +44 (0) 1904-322998.

[b] Associate Professor: Economics Division, Leeds University Business School, University of Leeds, Leeds, West Yorkshire, LS2 9JT, United Kingdom. E-mail: p.howley@leeds.ac.uk

The Effect of Weather on Crime in a Torrid Urban Zone

Abstract

This study investigates the relationship between weather and crime in Barranquilla, Colombia, a city in the Torrid Zone, which in contrast to more commonly studied temperate zones is hot and humid year-round. Our analysis is based on daily variations in four weather variables (temperature, relative humidity, precipitation, and wind speed), and two indicators of criminal activity, namely, homicides and interpersonal violence. To help identify statistical links, we add controls for temporal variables. Using count data models in the estimations, we do not find any statistically significant relationship between weather patterns and homicides. On the other hand, we find that weather can be an important predictor of interpersonal violence in this area. These findings draw attention to the importance of considering weather factors when designing a long-run urban security policy in one of the world's most vulnerable regions to climate change.

Key words: crime; violence; climate change; behaviour change; extreme environments

Introduction

Researchers across the social sciences have long been interested in the potential role that weather can play in influencing criminal activity. The last four decades in particular have witnessed a great deal of empirical work that supports the idea that weather can be a determinant of criminal activity, albeit mechanisms are still not fully understood (Cohn, 1990; Cotton, 1986; Feldman & Jarmon, 1979; Harries & Stadler, 1983; Harries et al., 1984; Horrocks & Menclova, 2011; Ranson, 2014). Presumably due to constraints on data availability, the empirical evidence in this area is, however, largely based on cities in the developed world, and mostly in temperate zones. In this study, we widen the existing geographical coverage of studies in this area by considering a city in a developing country situated in the Torrid Zone: Barranquilla, Colombia.[1] Barranquilla is Colombia's fourth most populous city, with 1,897,734 inhabitants (Departamento Administrativo Nacional de Estadística [DANE], 2005). It also acts as the Colombian Caribbean region's main economic and financial center. In contrast to temperate zones, the mean temperature in Barranquilla is very high and there is little variation throughout the year. Barranquilla features a tropical savanna climate and is characterized by heavy rainfall between April and November, coinciding with the easterly waves and the cyclone season.

Apart from different climatic conditions, one further difference relates to the socio-economic profile of residents in this urban zone, as compared to those in more often-studied cities in the developed world. In Barranquilla, poverty is at relatively high levels and its residents may have relatively less opportunity to escape the discomfort from extreme weather (e.g., air conditioning), as compared to individuals living in richer nations.[2] While Barranquilla has not always been regarded as a violent place, it was twice ranked in the world's 50 most violent cities.[3] Within Colombia's domestic context, during the period 2010-2016, Barranquilla reached the second highest homicide rate behind Cali, and the second highest rate of interpersonal violence behind Bogotá (Instituto Nacional de Medicina Legal y Ciencias Forenses [INMLCF], 2016). This violent background in combination with the hot and humid weather makes Barranquilla an interesting case study when it comes to studying the extent to which uncomfortable climatic conditions can be a source of stress that manifests in a higher prevalence of violent behaviors.

In order to estimate the relationship between weather and crime in this urban zone, we create a large time-series dataset consisting of weather variables such as temperature, relative humidity, precipitation, and wind speed. Using count data models, we examine the relationship between these weather variables and two indicators of criminal activity, namely, homicides and interpersonal violence. We also include a comprehensive set of temporal dummy variables capturing weekends, holidays, year, and rainy season as additional controls.

Background: Weather and Crime

The weather variable most commonly found to have a significant association with crime is temperature. While many studies have found a significant relationship, the nature of this relationship is, however, contested. The debate about the shape of the crime-temperature relationship (linear v. non-linear) emerged in the United States (US) in the mid-1970s and has remained a crucial topic among researchers in this area. In effect, some researchers posit that the link between temperature and crime is linear (Anderson & Anderson, 1984; Anderson et al., 2000; Bushman et al., 2005), whereas others argue that it is best captured by an inverted U-shaped relationship (Bell & Baron, 1976; Cohn & Rotton, 1997; Rotton & Cohn, 2000, 2001). Two theories provide conceptual underpinnings for the linear and U-shaped hypothesis. First, the general aggression model (GAM) postulates that an increase in temperature leads to increases in the likelihood that people will engage in hostile or aggressive acts, as hot temperatures have a physiological impact on humans by increasing feelings of hostility and aggression (Anderson, 2001; Anderson & Anderson, 1984; Anderson et al., 2000; Bushman et al., 2005; Butke & Sheridan, 2010). A wide variety of laboratory studies have provided evidence in support of this hypothesis, i.e., as heat increases so too does aggressiveness (Baron & Bell, 1975, 1976; Carlsmith & Anderson, 1979). By contrast, the negative affect escape model (NAE) postulates that the relationship between weather and crime is wavy or U-shaped in nature. This model asserts that a linear increase in crime and temperature can be observed up to a certain point because of increases in irritation and discomfort (Baron & Bell, 1976; Cohn & Rotton, 2005). After that point, further increases in temperature are actually associated with a reduction in crime, as people attempt to escape the discomfort caused by extremely high temperatures.

One final explanation for the temperature-crime link comes from what is known as the routine activity theory (RAT). This theory presents a more flexible approach between temperature and crime, which is not due to ‘heat stress’ *per se*. Rather, the explanation focuses on how behavioral patterns are altered as a result of seasonal change (see Carbone-Lopez & Lauritsen, 2013). In other words, the likelihood of criminal events is higher in situations in which there is a significant confluence of those who are relatively more likely to commit a crime and those who are prone to being their victims; for example, victims will leave their homes in greater numbers and come across criminals during more ‘pleasant’ weather (Cohen & Felson, 1979; Felson, 2000).

Besides temperature, there are a variety of other climatic variables that may have an impact on criminal behavior. Lab and Hirschel (1988), analyzing data on crime and climatic conditions in Charlotte, North Carolina, found that higher levels of relative humidity during summer months correlate with reduced personal violence. Similarly, Rotton and Frey (1985) and Rotton and Cohn (2000) in studies based in Dayton, Ohio, and Dallas, Texas, respectively, found a negative association between relative humidity and assaults.

Closely related to relative humidity, from a meteorological standpoint, is the amount of rainfall. Pakiam and Lim (1984), in a study based in Singapore, found an inverse relationship between rainfall and some types of theft. Similarly, Jacob et al. (2007) using weekly data from the US found that a one-inch increase in average weekly precipitation was associated with a 10% reduction in violent crime. Using daily data from 43 districts across New Zealand, Horrocks and Menclova (2011) observed a negative relationship between precipitation and the prevalence of violent crimes. However, Simister and Cooper (2005), in a study in Los Angeles, found no association between violent crime and precipitation. By way of monthly data from England and Wales, Field (1992) also did not find an association between precipitation and various categories of criminal activity.

These mixed findings relating to the impact of precipitation on crime may be as a result of aggregation bias. In effect, weekly and monthly data may not be suitable for identifying the effect of precipitation on crime as these data could be measuring an underlying seasonality pattern, as described by Mares (2013). Thus, shorter time periods (e.g., daily data) are more advantageous to analyze the effect of precipitation on crime as they can embody those anomalies in temperature that otherwise would be omitted.

Lastly, there are some studies which have found a negative association between windspeed and various types of criminal activity. Rotton and Frey (1985), for instance, found an inverse association between family disturbance complaints and daily wind speed. Cohn (1996), analyzing the association between temporal variables and weather, with requests for police presence in Minneapolis, Minnesota, determined that there were fewer police calls during windy periods. Investigating crime in Strathclyde, Scotland, Tompson and Bowers (2015) recorded that increased wind speed aligned with decreased numbers of street robberies, during summer months.

Data and Methodology

Data Sources

We obtained data on rates of homicides and interpersonal violence from the Colombian Institute of Legal Medicine and Forensic Studies (INMLCF). These data are based on daily information obtained by forensic experts following the guidelines established by the INMLCF. In particular, the INMLCF records the total number of homicides and cases of interpersonal violence that occur in Barranquilla on a daily basis (between the hours of 00:00 to 23:59). Homicides refer to the unlawful killing of one person by another.[4] On the other hand, interpersonal violence crimes comprised the following categories: quarrels (86.8%), retention, including kidnapping, hostage taking, etc. (7.3%), settling old scores (3%), drunkenness (1.2%), illicit activities (1.4%), bullying (0.2%), and stray bullet (0.1%).[5] Unfortunately, due to data constraints we are unable to disentangle interpersonal violence into each of these constituent categories and so in the analysis that follows we examine the relationship between weather and interpersonal violence which represents a combination of each of these different types of crime. One potential limitation with our analysis relates to measurement error when it comes to interpersonal violence. Given the fact it is likely that fewer violent acts will be reported than those that actually occurred, there may be under-reporting in the daily information of interpersonal violence cases (INMLCF, 2016).

We extracted our weather variables from the Colombian Institute of Hydrology, Meteorology and Environmental Studies (IDEAM). Each weather variable represents aggregated scores for

Barranquilla. Missing data found in weather variables represent only 1.76% of the total weather database.[6] This database contains average maximum daily temperature, average minimum daily temperature, total daily precipitation, and average daily wind speed. Due to the strong correlation with maximum daily temperature, minimum daily temperature was not included in the final estimations. Relative humidity is expressed through integer units corresponding to 0 (i.e., absolute dryness), and 100% (i.e., the total saturation of water vapor in the air). For our purposes, precipitation refers predominantly to rainfall but can also include hail. Lastly, temporal variables reflecting public holidays and weekends were acquired by browsing Colombia's calendar for every year of the study period. Weekends are defined as the time between Friday at 00:00 through Sunday to 23:59 hours.

Empirical Strategy

We model Crime (*C*), as it pertains to either interpersonal violence or homicides, as a function of weather variables (*W*) and temporal variables (*F*). Then, our model takes the following general form:

$$C_t = \alpha_0 + \beta_1 W_t + \beta_2 F_t + \varepsilon_t$$

$$t = 1, 2 \ldots, n$$

Weather variables (*W*) comprise maximum temperature (*Temperature*), relative humidity (*Humidity*), precipitation (*Precipitation*), and wind speed (*Windspeed*). The set of temporal variables (*F*) includes *Holidays* (1, if it is a public holiday; and 0, otherwise), *Weekends* (1, if it is either Friday, Saturday, or Sunday; and 0, otherwise), *RainySeason* (1, if a day falls into the rainy season; and 0, otherwise), as well as six dummy variables of year (from 2011 to 2016; 2010 is the year of reference).

Given the discrete nature of our response variables and their relatively low variability, the most suitable method for estimation is a count data model, as opposed to the more commonly employed ordinary least square estimations.[7] We used multivariate regression to elucidate the effects of the weather variables on each type of crime (homicides and interpersonal violence). Since the data were overdispersed, we used the negative binomial model for the estimations.[8] We analyzed the relationship between weather and crime using a generalized linear model (GLM) with a log-link function. We then resorted to time-series analysis in order to check the appropriateness of the data.[9] Using the Augmented Dickey-Fuller and the Phillips-Perron's unit-root tests, we tested the series for stationarity, and in all cases, we rejected the null hypothesis of a unit root process. We proceeded to test for first-order serial correlation of the residuals using the Durbin-Watson *d* statistic. An inspection of our models' residuals indicated a Durbin-Watson *d* value of 1.934 for homicides and 1.759 for interpersonal violence, which represents a first order autocorrelation of .03 ($p < .01$) and .08 ($p < .01$), respectively.[10] While this does not suggest that serial correlation is a serious bias, we adopted a cautious approach by using Newey-West standard errors to control for potential heteroscedasticity and serial correlation. Finally, we fitted regressions using Stata 15® and performed them separately for both homicides and interpersonal violence.[11]

Results

Descriptive statistics are shown in Table 1. The sample consists of 2,557 observations between 1 January 2010 and 31 December 2016. There was a total of 2,562 homicides reported during this period, representing 366 homicides on average per year.[12] The total cases of interpersonal violence recorded during the study period reached 25,479, representing a yearly average of 3,640 cases. Table 2 presents bivariate correlations. We observed a significant and positive correlation between *Temperature* and interpersonal violence. *Humidity* and *Precipitation*, contrastingly, were both significantly and negatively related with interpersonal violence. We observed no significant correlation between any of the weather variables and homicides, except *Windspeed* which was positively correlated with both homicides and interpersonal violence. In Figure 1 and 2 we provide a visual illustration of the monthly patterns in both homicides and interpersonal violence alongside our key weather variables, namely, *Temperature* and *Humidity*.

Table 1: Summary of Daily Statistics

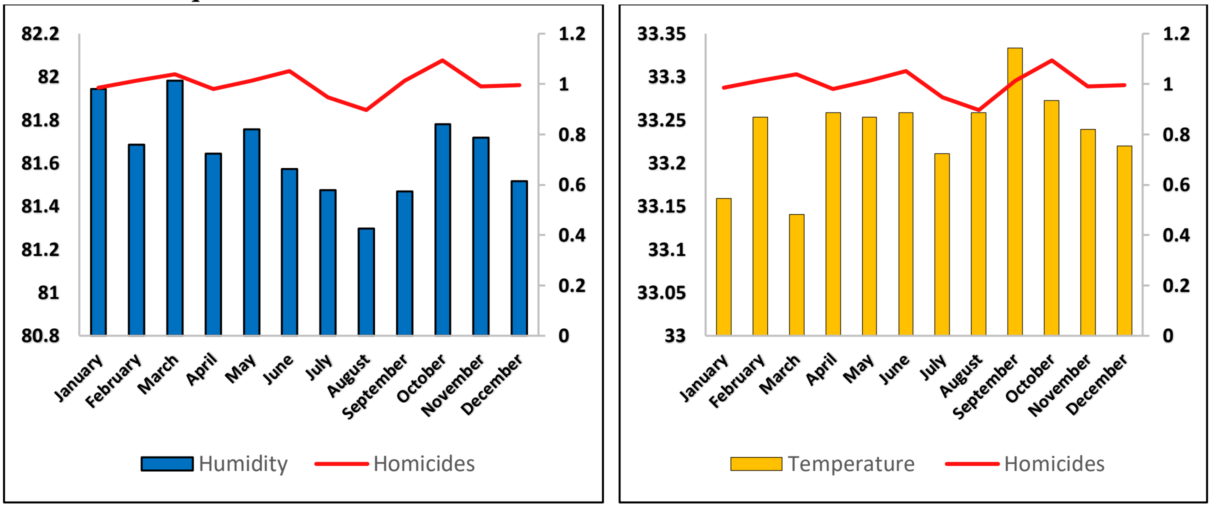
Variables	Description	Mean	St. Dev.	Min.	Max.
Homicides	Number of daily cases of homicides	1.001955	1.115229	0	7
Interpersviolence	Number of daily cases of interpersonal violence	9.964411	5.745508	0	52
Temperature	Daily average of maximum temperature in degrees Celsius	33.25147	1.669634	28	39
Humidity	Daily average of relative humidity in percentages	81.65311	4.803221	64	97
Precipitation	Daily average of precipitations in millimeters	2.936336	11.0638	0	126
Windspeed	Daily average of wind speed in kilometers per hour	12.9741	4.83554	1.3	81
Holidays	National and local holidays	0.065702	0.2478089	0	1
Weekends	Weekend days	0.285882	0.451922	0	1
RainySeason	Annual period between April and November	0.667970	0.471034	0	1

Table 2: Correlation Matrix

	Homicides	*Interpersviolence*	*Temperature*	*Humidity*	*Precipitation*	*Windspeed*
Homicides	1					
Interpersviolence	0.235***	1				
Temperature	-0.0000541	0.0444**	1			
Humidity	-0.036	-0.0805***	-0.0744***	1		
Precipitation	-0.0254	-0.0723***	-0.106***	0.285***	1	
Windspeed	0.0459**	0.0703***	-0.139***	-0.605***	-0.219***	1

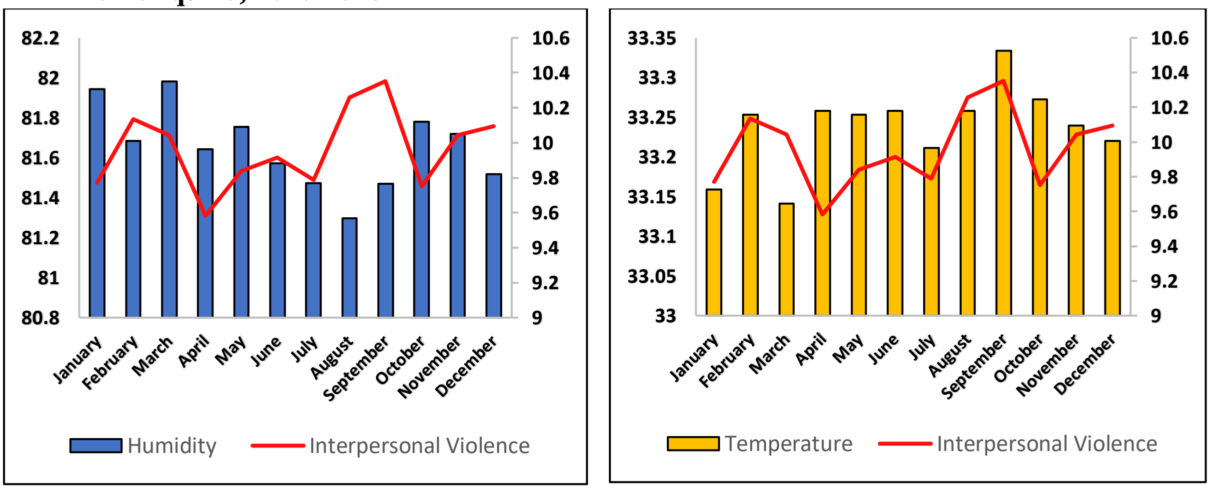
* $p < .1$ ** $p < .05$ *** $p < .01$

Fig. 1: Monthly Average Evolution of Homicides and Weather Variables. Barranquilla, 2010-2016



Source: Authors' elaboration

Fig. 2: Monthly Average Evolution of Interpersonal Violence and Weather Variables. Barranquilla, 2010-2016



Source: Authors' elaboration

Multivariate Analysis: Homicides

Table 3 reports the estimates relating to our analysis of the relationship between weather patterns and homicides. We display our estimates in the form of an incidence rate ratio (*IRR*) for a 1 unit change in the covariates.[13] We observed no significant relationship at either the 1 or 5% level between *Temperature* and homicides in Barranquilla, albeit *Humidity* and *Windspeed* turned out to be statistically significant at the 10% significance level. These results are in line with previous literature which suggests that, due to their premeditated nature, homicides are less likely to be responsive to changes in temperature than non-lethal crimes such as quarrels or assaults, wherein social interaction, coupled with aggression plays an important role (Ceccato, 2005; Cohn, 1990; Maes et al., 1993; Michael & Zumpe, 1983; Michel et al., 2016). However, the sample size may underestimate this result. As compared to interpersonal violence, homicides occur relatively infrequently, which makes it much harder to reliably identify any effects if they exist. We also observed no seasonal differences (rainy v. non-rainy season) in homicide rates. Lastly, we found that homicides were 64% higher on weekends than weekdays (*IRR* = 1.641, $p < .01$).

Table 3: Daily Influence of Weather on Homicides

	IRR	Newey-West SE
Temperature	0.981	0.0220
Humidity	0.990	0.0056*
Precipitation	0.999	0.0015
Windspeed	1.004	0.0023*
Weekends	1.641	0.0390***
Holidays	1.153	0.1207
RainySeason	1.071	0.0683
N	2557	

IRR is Incidence Rate Ratio.

SE is Standard Error.

Fixed-effect time coefficients of year are omitted.

*$p < .1$ **$p < .05$ ***$p < .01$

Interpersonal Violence

In contrast to homicides, weather appears to play a substantive and statistically significant role in predicting rates of interpersonal violence (see Table 4). First, our findings suggest that there is a linear and positive relationship between daily maximum temperature and interpersonal violence in consonance with the GAM. The coefficient on the squared term, which tested for non-linearities, was not statistically significant and so we dropped it from the analysis.[14] Looking at effect sizes, a one-degree Celsius (^oC) rise in maximum temperature is associated with a 0.8% increase in interpersonal violence (*IRR* = 1.008, $p < .05$). The maximum temperature in this city ranges from a low of 28^oC to a high of 39^oC. Based on this analysis, we would expect that, all things being equal, a maximum potential 9% swing in the rates of interpersonal violence, depending on temperature levels.

Table 4: Daily Influence of Weather on Interpersonal Violence

	IRR	Newey-West SE
Temperature	1.008	0.0037**
Humidity	0.993	0.0010***
Precipitation	0.998	0.0002***
Windspeed	1.002	0.0020
Weekends	1.578	0.0285***
Holidays	1.504	0.0449***
RainySeason	1.037	0.0259
N	2557	

IRR is Incidence Rate Ratio.
SE is Standard Error.
Fixed-effect time coefficients of year are omitted.
$^*p < .1$ $^{**}p < .05$ $^{***}p < .01$

Second, relative humidity is negatively associated with interpersonal violence (*IRR* = 0.993, $p < .01$). A one-percent rise in *Humidity* correlates with a 0.7% decrease in interpersonal violence. *Humidity* in Barranquilla ranges from a low of 64% to a high of 97%. Therefore, our estimates suggest that we should expect rates of interpersonal violence to be, all things being equal, approximately 23% higher on days with relative humidity levels of 64%, as compared to 97%. Lastly, like *Humidity*, *Precipitation* is negatively associated with interpersonal violence (*IRR* = 0.998, $p < .01$). A 10-millimeter increase in precipitation is associated with a 2% decrease in the incidence of interpersonal violence cases. Taken together, these results suggest that the climatic environment can play a significant role in predicting rates of interpersonal violence in this urban zone. Put differently, our analysis suggests that rates of interpersonal violence are likely to be significantly higher on relatively hot and dry (or less humid) days, than on relatively hot and humid days.[15] Temporal variables also appear to be important with rates of interpersonal violence being 50.4 and 57.8 percent higher on *Holidays* (*IRR* = 1.504, $p < .01$) and *Weekends* (*IRR* = 1.578, $p < .01$).[16]

Robustness Checks

As a robustness check, instead of using temperature and humidity in our regression analysis, we used a combined 'Heat Index'. The Heat Index accounts for both temperature and humidity in its calculation and provides a measure of overall discomfort likely felt by an individual due to the combination of both temperature and relative humidity on any given day.[17] Recent examples of work which have used a combined 'Heat Index' include Schinasi and Hamra (2017) and Sommer and Bind (2018). These studies found a linear and positive association between Heat Index and rates of violence in Philadelphia and Boston, respectively. The results relating to our estimates of the relationship between Heat Index and crime can be seen in Appendix A. Our Heat Index measure attracts a positive and statistically significant coefficient (*IRR* = 1.012, $p < .01$) when it comes to interpersonal violence, which further supports the suggestion that weather variation can play an important role in influencing non-lethal criminal behavior. Conversely, Heat Index was not statistically significant in the case of homicides which again is similar to our earlier estimates relating to the relationship between weather and homicides.

As a sensitivity check, we replicated our analysis in Table 3 and 4, but this time the estimations include robust or bootstrapped standard errors instead of Newey-West (Appendix B). This does affect the precision of our estimates to some degree as standard errors are somewhat larger but not greatly so.[18] For instance, our findings regarding significance thresholds remain unaffected when it comes to our analysis of homicides. When it comes to interpersonal violence, both humidity and precipitation are statistically significant at conventional significance levels, but temperature no longer attracts a statistically significant coefficient due to a larger standard error (increases from 0.0037 to 0.0072).

Discussion

There has been a growing body of work to support the suggestion that weather can be an important factor in explaining variation in criminal behavior. Previous findings relating to a weather-crime link may not apply, however, to conurbations like Barranquilla located in the Torrid Zone (a geographical area of the globe where average temperatures are high throughout the year). This stands in contrast to the more typical cold and hot seasons of temperate zones.

The results of our study suggest that weather is significantly related with criminal activity in Barranquilla, but it depends on the type of crime. Specifically, our analysis suggests that weather patterns can substantially affect the risk of observing interpersonal violence[19], though here they are unrelated to homicides. We suggest these differences are due to the different motivations involved and the behaviors required for violent acts. Interpersonal violence is most often a spontaneous aggressive act in response to a minor dispute. It is therefore relatively more susceptible to changes in comfort brought about by extreme weather.[20] Unlike interpersonal violence, homicides, particularly in this region, are generally pre-planned acts and thus less likely to be affected by spontaneous acts of aggression brought on by extreme weather (Maes et al., 1993; Michael & Zumpe, 1983; Rotton & Cohn, 2003). Of course, homicides also occur much less frequently than interpersonal violence and so an alternative explanation is simply that it is much more difficult to identify the effect of weather on homicides. One implication of these findings is that climate change, which is projected to lead to increases in temperature in this tropical region, may lead to a rise in the current rates of interpersonal violence.[21]

Our findings align with many other studies in different climatic zones which have likewise found a significant relationship between temperature and various types of criminal activity. The nature of this relationship is still, however, contested. Some research points to a linear relationship wherein an increase in temperature will increase the likelihood of aggressive acts. This has been referred to as the GAM model. Other research points to an inverted U-shaped or wavy relationship, with a linear increase in crime observable up to a certain temperature, after which people attempt to escape the heat discomfort leading to a reduction in crime. This has been referred to as the NAE model.

Our findings are in keeping with the GAM, as opposed to NAE model, as we observe no threshold effects when it comes to the relationship between temperature and interpersonal violence. Arguably, the temperature range observed in Barranquilla may explain the lack of a U-shaped or wavy relationship. More specifically, in contrast to many other study regions such as those in the US, the temperature range is relatively narrow in Barranquilla and therefore difficult to identify any non-linearity. A further possible explanation is that individuals in different study contexts will have different opportunities to escape the discomfort caused by high temperature. For example, residents in tropical cities like Barranquilla with extreme poverty will be relatively less able to use air-conditioning devices as a means to avoid the discomfort from high heat, as compared to residents in many cities within temperate zones. While we point to some possible explanations here, we suggest that a useful avenue for future research would be to explore in more detail what mechanisms can explain observed structural differences (GAM v. NAE) in the relationship between temperature and crime across study regions.

In line with much prior work, we also find that, regardless of weather, rates of interpersonal violence and homicides are substantially higher on weekends (Ceccato, 2005; Rotton & Cohn, 2003). We also found that rates of interpersonal violence were higher on public holidays. These findings are consistent with RAT, which suggests that violent behavior is more likely to occur during people's 'free' time.

In contrast to temperature, we observed a negative relationship between relative humidity and interpersonal violence. One potential explanation is that high relative humidity might act as a signal of incoming precipitation for residents, thus encouraging them to stay indoors. A further possibility is that high levels of relative humidity can reduce concentration and induce sleepiness (Howarth & Hoffman, 1984). Our study also finds that precipitation is negatively related with interpersonal violence. One possible explanation is that heavy rainfall can greatly hinder pedestrian mobility throughout Barranquilla due to flash floods.

Overall, our results show the potential importance of weather when it comes to predicting crime even in cities such as Barranquilla, where temperature variation is much less than in more often-studied temperate zones. For instance, it would seem that weekends and/or public holidays, when it is relatively hot and dry, may be at risk for a spike in cases of interpersonal violence. Apart from police resources, public safety measures may include preparing hospitals, first responders, and other healthcare providers to expect some increases in admissions in the presence of these weather conditions.

Declaration of Conflicting Interests: None

References

Anderson, C. A. (2001). Heat and violence. *Current Directions in Psychological Science*, *10*, 33-38. doi : 10.1111/1467-8721.00109

Anderson, C. A., & Anderson, D. C. (1984). Ambient temperature and violent crime: Tests of the linear and curvilinear hypotheses. *Journal of Personality and Social Psychology, 46*, 91-97. doi: 10.1037/0022-3514.46.1.91

Anderson, C. A., Anderson, K. B., Dorr, N., DeNeve, K. M., & Flanagan, M. (2000). Temperature and aggression. *Advances in Experimental Social Psychology, 32*, 63-133. doi: 10.1016/S0065-2601(00)80004-0

Bailey, H. P. (1960). A method of determining the warmth and temperateness of climate. *Geografiska Annaler*, *42*, 1-16. doi: 10.2307/520173

Baron, R. A., & Bell, P. A. (1975). Aggression and heat: Mediating effects of prior provocation and exposure to an aggressive model. *Journal of Personality and Social Psychology*, *31*, 825-832. doi:10.1037/h0076647

Baron, R. A., & Bell, P. A. (1976). Aggression and heat: The influence of ambient temperature, negative affect, and a cooling drink on physical aggression. *Journal of Personality and Social Psychology*, *33*, 245-255. doi:10.1037/0022-3514.33.3.245

Bell, P. A., & Baron, R. A. (1976). Aggression and heat: The mediating role of negative affect[1]. *Journal of Applied Social Psychology, 6*, 18-30. doi:10.1111/j.1559-1816.1976.tb01308.x

Bushman, B. J., Wang, M. C., & Anderson, C. A. (2005). Is the curve relating temperature to aggression linear or curvilinear? Assaults and temperature in Minneapolis reexamined. *Journal of Personality and Social Psychology*, *89*, 62-66. doi:10.1037/0022-3514.89.1.74

Butke, P., & Sheridan, S. C. (2010). An analysis of the relationship between weather and aggressive crime in Cleveland, Ohio. *Weather, Climate, and Society*, *2*, 127-139. doi:10.1175/2010WCAS1043.1

Carbone-Lopez, K., & Lauritsen, J. (2013). Seasonal variation in violent victimization: Opportunity and the annual rhythm of the school calendar. *Journal of Quantitative Criminology*, *29*, 399-422. doi:10.1007/s10940-012-9184-8

Carlsmith, J. M., & Anderson, C. A. (1979). Ambient temperature and the occurrence of collective violence: A new analysis. *Journal of Personality and Social Psychology*, *37*, 337-344. doi:10.1037/0022-3514.37.3.337

Ceccato, V. (2005). Homicide in São Paulo, Brazil: Assessing spatial-temporal and weather variations. *Journal of Environmental Psychology*, *25*, 307-321. doi:10.1016/j.jenvp.2005.07.002

Cepeda, L. (2011). Los sures de Barranquilla: La distribución espacial de la pobreza. *Documentos de Trabajo Sobre Economía Regional y Urbana*, No. 142. Retrieved from http://repositorio.banrep.gov.co/bitstream/handle/20.500.12134/3045/Los%20sures%20de%20Barranquilla.%20La%20distribuci%C3%B3n%20espacial%20de%20la%20pobreza.pdf?sequence=1

Cohen, L. E., & Felson, M. (1979). Social change and crime rate trends: A routine activity approach. *American Sociological Review*, *44*, 588-608. doi:10.2307/2094589

Cohn, E. G. (1990). Weather and crime. *British Journal of Criminology*, *30*, 51-64. doi:10.1093/oxfordjournals.bjc.a047980

Cohn, E. G. (1996). The effect of weather and temporal variations on calls for police service. *American Journal of Police*, *15*, 23-43. doi:10.1108/07358549610116545

Cohn, E. G., & Rotton, J. (1997). Assault as a function of time and temperature: A moderator-variable time-series analysis. *Journal of Personality and Social Psychology*, *72*, 1322-1334. doi:10.1037/0022-3514.72.6.1322

Cohn, E. G., & Rotton, J. (2005). The curve is still out there: A reply to Bushman, Wang, & Anderson's (2005). "Is the curve relating temperature to aggression linear or curvilinear?". *Journal of Personality and Social Psychology*, *89*, 67-70. doi:10.1037/0022-3514.89.1.67

Consejo Ciudadano para la Seguridad Pública y Justicia Penal de México. (2016). *Seguridad, Justicia y Paz*. Retrieved from https://www.seguridadjusticiaypaz.org.mx/biblioteca/download/6-prensa/239-las-50-ciudades-mas-violentas-del-mundo-2016-metodologia

Cotton, J. L. (1986). Ambient temperature and violent crime. *Journal of Applied Social Psychology*, *16*, 786-801. doi:10.1111/j.1559-1816.1986.tb01168.x

Departamento Administrativo Nacional de Estadística. (2005). *Censo General 2005*. Perfil Barranquilla-Atlántico. DANE: Bogotá, Colombia. Retrieved from http://www.dane.gov.co/index.php/estadisticas-por-tema/demografia-y-poblacion/censo-general-2005-1/censo-general-2005

Departamento Administrativo Nacional de Estadística. (2017). *Monetary and multidimensional poverty in Colombia 2016*. DANE: Bogotá, Colombia. Retrieved from https://www.dane.gov.co/index.php/estadisticas-por-tema/pobreza-y-condiciones-de-vida/pobreza-y-desigualdad/pobreza-monetaria-y-multidimensional-en-colombia-2017

Dhaene, G., & Hoorelbeke, D. (2004). The information matrix test with bootstrap-based covariance matrix estimation. *Economics Letters*, *82*, 341-347. doi.org/10.1016/j.econlet.2003.09.002

Efron, B., & Tibshirani, R. (1986). Bootstrap methods for standard errors, confidence intervals, and other measures of statistical accuracy. *Statistical Science*, 54-75. doi:10.1214/ss/1177013815

Feldman, H. S., & Jarmon, R. G. (1979). Factors influencing criminal behavior in Newark: A local study in forensic psychiatry. *Journal of Forensic Science*, *24*, 234-239. doi:10.1520/JFS10814J

Felson, M. (2000). The routine activity approach as a general crime theory. *Criminological Perspectives: Essential Readings*, *2*, 160-167. doi:10.4135/9781452232232.n11

Field, S. (1992). The effect of temperature on crime. *British Journal of Criminology, 32,* 340-351. doi:10.1093/oxfordjournals.bjc.a048222

Freedman, D. A. (2006). On the so-called “Huber sandwich estimator” and “robust standard errors”. *The American Statistician, 60,* 299-302. doi:10.1198/000313006X152207

Harries, K. D., & Stadler, S. J. (1983). Determinism revisited assault and heat stress in Dallas, 1980. *Environment and Behavior*, *15*, 235-256. doi:10.1177/0013916583152006

Harries, K. D., Stadler, S. J., & Zdorkowski, R. T. (1984). Seasonality and assault: Explorations in inter-neighborhood variation, Dallas 1980. *Annals of the Association of American Geographers*, *74*, 590-604. doi:10.1111/j.1467-8306.1984.tb01476.x

Hilbe, J. M. (2014). *Modeling count data* (1st ed.). Cambridge, UK: Cambridge University Press.

Horrocks, J., & Menclova, A. K. (2011). The effects of weather on crime. *New Zealand Economic Papers*, *45*, 231-254. doi:10.1080/00779954.2011.572544

Howarth, E., & Hoffman, M.S. (1984). A multidimensional approach to the relationship between mood and weather. *British Journal of Psychology, 75,* 15-23. doi:10.1111/j.2044-8295.1984.tb02785.x

Instituto de Hidrología, Meteorología y Estudios Ambientales. (2018). *Documento Metodológico Estadísticas Variables Meteorológicas*. Instituto de Hidrología, Meteorología y Estudios Ambientales, Bogotá, D.C., Colombia. Retrieved from http://www.ideam.gov.co/documents/11769/72085840/Documento+metodologico+variables+meteorologicas.pdf/8a71a9b4-7dd7-4af4-b98e-9b1eda3b8744

Instituto Nacional de Medicina Legal y Ciencias Forenses (2016). *Forensis 2016. Datos para la Vida*. Bogotá, D.C., Colombia. Retrieved from http://www.medicinalegal.gov.co/documents/20143/49526/Forensis+2016.+Datos+para+la+vida.pdf

Jacob, B., Lefgren, L., & Moretti, E. (2007). The dynamics of criminal behavior: Evidence from weather shocks. *Journal of Human Resources*, *42*, 489-527. doi:10.3368/jhr.XLII.3.489

King, G., & Roberts, M. E. (2015). How robust standard errors expose methodological problems they do not fix, and what to do about it. *Political Analysis, 23,* 159-179. doi:10.1093/pan/mpu015

Lab, S. P., & Hirschel, J. D. (1988). Climatological conditions and crime: The forecast is…? *Justice Quarterly*, *5,* 281-299. doi:10.1080/07418828800089731

Maes, M., Meltzer, H. Y., Suy, E., & De Meyer, F. (1993). Seasonality in severity of depression: Relationships to suicide and homicide occurrence. *Acta Psychiatric Scandinavian*, *88*, 156-161. doi:10.1111/j.1600-0447.1993.tb03431.x

Mares, D. (2013). Climate change and crime: Monthly temperature and precipitation anomalies and crime rates in St. Louis, MO 1990-2009. *Crime, Law and Social Change*, *59,* 185-208. doi:10.1007/s10611-013-9411-8

Mares, D. M., & Moffett, K. W. (2016). Climate change and interpersonal violence: A "global" estimate and regional inequities. *Climatic Change*, *135,* 297-310. doi:10.1007/s10584-015-1566-0

Michael, R. P., & Zumpe, D. (1983). Sexual violence in the United States and the role of season. *American Journal of Psychiatry*, *140*, 880-886. doi:10.1176/ajp.140.7.883

Michel, S. J., Wang, H., Selvarajah, S., Canner, J. K., Murrill, M., Chi, A., Efron, D.T., & Schneider, E. B. (2016). Investigating the relationship between weather and violence in Baltimore, Maryland, USA. *Injury*, *47*, 272-276. doi:10.1016/j.injury.2015.07.006

Montgomery, D.C., Jennings, C.L., & Kulahci, M. (2015). *Introduction to time series analysis and forecasting* (2nd ed.). Hoboken, New Jersey: John Wiley & Sons, Inc.

National Weather Service. (2018). *Meteorological Conversions and Calculations: Heat Index Calculator*. Retrieved from http://www.wpc.ncep.noaa.gov/html/heatindex.shtml

Newey, W.K., & West, K.D. (1987). A simple, positive semi-definite, heteroscedasticity and autocorrelation consistent covariance matrix. *Econometrica*, *55*, 703-708. doi:10.2307/1913610

Pakiam, J. E., & Lim, J. (1984). Crime and weather in Singapore. *International Journal of Comparative and Applied Criminal Justice*, *8*, 210-220. doi:10.1080/01924036.1984.9688799

Pérez, G. J., & Salazar, I. (2007). La pobreza en Cartagena: Un análisis por barrios. *Documentos de Trabajo Sobre Economía Regional y Urbana*, No. 94. Retrieved from http://repositorio.banrep.gov.co/bitstream/handle/20.500.12134/3003/La%20pobreza%20en%20Cartagena.%20Un%20an%C3%A1lisis%20por%20barrios.pdf?sequence=1

Ranson, M. (2014). Crime, weather, and climate change. *Journal of Environmental Economics and Management*, *67*, 274-302. doi:10.1016/j.jeem.2013.11.008

Rotton, J., & Cohn, E. G. (2000). Violence is a curvilinear function of temperature in Dallas: A replication. *Journal of Personality and Social Psychology*, *78*, 1074-1081. doi:10.1037/0022-3514.78.6.1074

Rotton, J., & Cohn, E. G. (2001). Temperature, routine activities, and domestic violence: A reanalysis. *Violence and Victims*, *16*, 203-215. doi:10.1891/0886-6708.16.2.203

Rotton, J., & Cohn, E.G. (2003). Global warming and US crime rates: An application of routine activity theory. *Environment and Behavior*, *35*, 802-25. doi:10.1177/0013916503255565

Rotton, J., & Frey, J. (1985). Air pollution, weather, and violent crimes: Concomitant time-series analysis of archival data. *Journal of Personality and Social Psychology*, *49*, 1207-1220. doi:10.1037/0022-3514.49.5.1207

Schinasi, L. H., & Hamra, G. B. (2017). A time series analysis of associations between daily temperature and crime events in Philadelphia, Pennsylvania. *Journal of Urban Health*, *94*, 892-900. doi:10.1007/s11524-017-0181-y

Simister, J., & Cooper, C. (2005). Thermal stress in the USA: Effects on violence and on employee behaviour. *Stress and Health*, *21*, 3-15. doi:10.1002/smi.1029

Smith, J., & McAleer, M. (1994). Newey–West covariance matrix estimates for models with generated regressors. *Applied Economics*, *26*, 635-640. doi:10.1080/00036849400000034

Sommer, A., & Bind, M.A. (2018). Short term effects of daily weather characteristics on violent crimes in the Boston area. Retrieved from http://oem.bmj.com/content/75/Suppl_1/A24.2

Tompson, L. A., & Bowers, K. J. (2015). Testing time-sensitive influences of weather on street robbery. *Crime Science*, *4*, 1-11. doi:10.1186/s40163-015-0022-9

Winkelmann, R. (2008). *Econometric analysis of count data* (5th ed.). Berlin Heidelberg: Springer-Verlag.

Endnotes

[1] The temperature within the Torrid Zone is usually humid, warm and moist all year round. As Bailey describes it "*...the torrid climate lacks not only a cool season, but cool weather.*" (Bailey, 1960, p. 7).

[2] Official data show that approximately 21.7% of Barranquilla's population live in poverty and 2.8% in extreme poverty (DANE, 2017). However, Cepeda (2011) estimated that 40.7% of Barranquilla's population lives under the poverty line, placing it as the third Colombian city with the highest percentage of people living in poverty. An earlier study by Perez and Salazar (2007) ranked Barranquilla as having the highest poverty rates in Colombia.

[3] In 2011 and 2012 Barranquilla ranked 42nd and 50th respectively among the 50 world's most violent cities according to the Mexico's Citizens' Council for Public Security's annual ranking. The 2016 annual ranking shows that more than 80% of the 50 world's most violent cities were in Latin America (Brazil, Colombia, Mexico, and Venezuela), sharing the rest with cities from South Africa (Cape Town, Nelson Mandela Bay, Durban, and Johannesburg) and the United States (Saint Louis, Baltimore, Detroit, and New Orleans). See Consejo Ciudadano para la Seguridad Pública y la Justicia Penal [CCSPJP], (2016).

[4] The National Institute of Legal Medicine and Forensic Sciences, the state-supported entity that leads the forensic services to the justice administration in Colombia, has certain inclusion criteria regarding official homicide data. One of these criteria stipulates that the date of the violent act must have occurred between January 1st and December 31st of the current year, and that it has also been presented as a death case that has been known by the medical-forensic system. Those cases in which a necropsy determines that they happened on dates other than those reported are excluded from official homicide data (INMLCF, 2016).

[5] According to the National Institute of Legal Medicine and Forensic Sciences, non-lethal violence cases and their corresponding average participation in Colombia during the period 2010-2016 were recorded

as follows: interpersonal violence (54.1%), socio-political violence (14.2%), economic violence (7.3%), and violence against marginalized groups (24.5%).

[6] Altogether, there were 45 days with missing data. These missing values are related to data collected that did not attain the tolerance limits applied to each of the climate variables (Instituto de Hidrología, Meteorología y Estudios Ambientales, 2018). Since it is convenient to have the entire data series for a time series analysis, we decided to fill these gaps through multiple imputation using the expectation maximization algorithm. All these imputations were performed in SPSS 24®. As for missing data on *Precipitation*, we manually imputed its empty cells with zero since those dates either corresponded to the non-rainy season or its adjacent figures were zero.

[7] Count data refer to the number of occurrences of an event in a predetermined period (e.g., hour, day, month, year). The number of crimes in a city per day is an example of count data. Count data comprise only non-negative integers. When count data are a function of a set of explanatory variables, they become a count data model. In this study, we analyze two count data models, that is, two categories of daily crime (count data) as a function of weather (explanatory variables). The categories of daily crime relate to homicides and interpersonal violence. For a more detailed explanation of count data models, we refer the interested reader to Hilbe (2014).

[8] Overdispersion denotes a large individual variability of the data in comparison with the mean (Winkelmann, 2008). In our case, overdispersion implies that crimes can occur many times on some days, but relatively infrequently on others.

[9] For an introductory approach to time-series analysis, see Montgomery et al. (2015).

[10] To facilitate the Durbin-Watson (D-W) test, we performed an OLS regression using both homicides and interpersonal violence respectively as our dependent variables. According to the D-W tables, for a significance level of 1%, k = 7, and $n \geq$ 200, the lower limit is d_L = 1.697 and the upper limit is d_U = 1.841. Statistically, the D-W test means there is no positive serial correlation in the model of homicides (d = 1.934); however, the test is inconclusive for the model of interpersonal violence (d = 1.759).

[11] The dataset and the code are available upon request.

[12] In 2016, 398 homicides were officially registered in Barranquilla, which represented 34.7 homicides per 100,000 inhabitants. Some urban zones with a tropical climate similar to that of Barranquilla are classified as being among the world's most violent cities. These include Barquisimeto (Venezuela), Valencia (Venezuela), and São Luís (Brazil), which reached 72.3, 54.9, and 53 homicides per 100,000 inhabitants, respectively. By way of comparison, U.S. cities like Baltimore, New Orleans, and Saint Louis registered homicide rates of 54.9, 41.4, and 59.2, respectively (See CCSPJP, 2016).

[13] The IRR shows the incidence rate incidence rate in a group of people exposed to crimes (i.e., homicide or interpersonal violence) divided by the incidence rate in an unexposed group of people, which acts as a comparison group. Formally,

$$IRR = \frac{IR_e}{IR_u}$$

where IR = incidence rate, e = exposed, and u = unexposed. That is, an IRR of 1.0 shows same rates in the two sections; an IRR larger than 1.0 demonstrates an expanded risk for the exposed group of people, while an IRR under 1.0 demonstrates a diminished risk for the exposed group.

[14] We also grouped *Temperature* into bins and interacted each of them with the same variable in levels to check for non-linearities. We observed no statistical significance in any of the estimates.

[15] As we mentioned above, Barranquilla has a tropical savanna climate, according to the Köppen-Geiger Climate Classification. The annual climate of Barranquilla is characterized by two marked seasons: the "rainy" and the "dry". The rainy season begins in April and lasts until late November. Days in the rainy season are generally warmer than in the dry season because it is humid. Conversely, during the dry season, which corresponds to the Winter in the Northern Hemisphere, there are cooler temperatures,

clear skies, high gusts of wind, and lower humidity; therefore, days are typically sunnier and cooler throughout the season.

[16] As a sensitivity check, we also excluded Fridays from *Weekends* in the estimations and the results were robust to this change: for the model of homicides (IRR = 1.366, $p < .01$), and for interpersonal violence (IRR = 1.335, $p < .01$).

[17] The Heat Index (HI) is an indicator of heat discomfort created by the U.S. National Oceanographic and Atmospheric Administration (NOAA). The HI is calculated using relative humidity levels and temperature in degrees Fahrenheit. For details about its calculation, see National Weather Service (2018).

[18] Each type of standard errors has its advantages and limitations depending upon the model and the residuals' distribution (King & Roberts, 2015). Robust standard errors (White) compensate for heteroskedasticity in the model, but if the series have serial correlation the estimates obtained are likely to be biased (Freedman, 2006). It is also possible that the residuals' distribution is skewed. Bootstrapped standard errors provide a bias correction that is asymptotically good, but only when it has been proven that the residuals' distribution shows some degree of skewness (Dhaene & Hoorelbeeke, 2004; Efron & Tibshirani, 1986). Lastly, if there is autocorrelation bias in the residuals, using heteroskedasticity-autocorrelation consistent standard errors is the most feasible alternative for large samples (Newey & West, 1987; Smith & McAleer, 1994).

[19] Another pathway for future work to explore would be to examine the relationship between weather and other categories within non-lethal crimes such as assaults and property crimes.

[20] The description made by Anderson (2001, p.34) is compelling here: "Heat-induced discomfort makes people cranky […] A minor provocation can quickly escalate, especially if both participants are affectively and cognitively primed for hostility by their heightened level of discomfort. A mild insult is

more likely to provoke a severe insult in response when people are hot than when they are more comfortable. This may lead to further increases in the aggressiveness of responses and counter-responses."

[21] Mares and Moffett (2016) show evidence of the increasing influence of climate change on interpersonal violence in thirteen Latin American countries.

Appendix A

Heat Index

	Homicides	Interpersonal Violence
HeatIndex	0.999	1.012
	[0.0131]	[0.0014]***
Precipitation	0.998	0.998
	[0.0019]	[0.0002]***
Windspeed	1.009	1.006
	[0.0016]***	[0.0024]**
Weekends	1.642	1.580
	[0.0387]***	[0.0295]***
Holidays	1.154	1.504
	[0.1200]	[0.0431]***
RainySeason	1.031	1.005
	[0.0556]	[0.0299]
N	2557	

Estimates are incidence rate ratios (IRR).
Newey-West standard errors in brackets.
Fixed-effect time coefficients of year are omitted.
*$p < .1$ **$p < .05$ ***$p < .01$

Appendix B

Robust and Bootstrapped Standard Errors

	Robust SE		Bootstrapped SE	
	Homicides	Interpersonal Violence	Homicides	Interpersonal Violence
Temperature	0.981 [0.0151]	1.008 [0.0072]	0.981 [0.0149]	1.008 [0.0072]
Humidity	0.990 [0.0061]*	0.993 [0.0027]***	0.990 [0.0056]*	0.993 [0.0027]***
Precipitation	0.999 [0.0022]	0.998 [0.0009]**	0.999 [0.0020]	0.998 [0.0009]**
Windspeed	1.004 [0.0059]	1.002 [0.0025]	1.004 [0.0064]	1.002 [0.0022]
Weekends	1.641 [0.0721]***	1.578 [0.0340]***	1.641 [0.0699]***	1.578 [0.0388]***
Holidays	1.153 [0.1072]	1.504 [0.0777]***	1.153 [0.1129]	1.504 [0.0697]***
RainySeason	1.071 [0.0629]	1.037 [0.0281]	1.071 [0.0573]	1.037 [0.0289]
N	2557	2557	2557	2557

Estimates are Incidence Rate Ratios (IRR).
Fixed-effect time coefficients of year are omitted.
Standard errors (SE) appear in brackets.
*p < .1 **p < .05 ***p < .01