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LETTER

Global warming to increase violent crime in the United States

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Abstract

Recent studies have revealed large and robust correlations between seasonal climate and violent crime rates at regional scales within the continental United States, begging the question of how future climate change will influence violent crime rates. Here, we combine empirical models from previous studies with 42 state-of-the-art global climate models to make such projections, while accounting for key factors like regionality and seasonality, and appropriately combining multiple of sources of uncertainty. Our results indicate that the United States should expect an additional 3.2 [2.1–4.5] or 2.3 [1.5–3.2] million violent crimes between 2020 and 2099, depending on greenhouse gas emissions scenario. We also reveal critical dependencies of these violent crime projections on various global warming targets, such as those associated with the Paris Agreement (1.5 °C and 2 °C). These results emphasize the often-overlooked socially-mediated impacts of climate change on human health, with an estimated economic cost of $5 billion annually.

1. Introduction

1.1. Background

The link between weather and crime has drawn the attention of the fields of criminology and sociology since the mid-19th century (United States National Advisory Commission on Civil Disorders 1968, Block 1984, Cohn 1990, Field 1992, Gamble and Hess 2012, Mares 2013, Ranson 2014, Mares and Moffett 2016, Mares and Moffett 2019), with most previous studies identifying air temperature as the lead factor in the connection (Field 1992, Anderson *et al* 1997, Hipp *et al* 2004, Mares and Moffett 2016, Harp and Karnauskas 2018). Two mechanisms have emerged as likely drivers of this relationship: the temperature-aggression hypothesis—initially posed as the General Affective Aggression Model (Anderson *et al* 1996)—and the routine activities theory (Cohen and Felson 1979). The temperature-aggression hypothesis posits that individuals experiencing physiological heat stress are more likely to read personal interactions as aggressive than individuals not experiencing heat stress with subtle shifts toward more violent responses, accordingly. Given the necessary condition of high absolute temperature, the temperature-aggression hypothesis is limited to influencing behavior solely in relatively warm seasons and climates and would only impact violent crime—property crime, conversely, would be unaffected (Hipp *et al* 2004). The routine activities theory is a broader framework which postulates that any crime requires the convergence of a motivated offender, a potential victim, and the lack of a guardian capable of preventing or deterring a criminal occurrence (Cohen and Felson 1979). By altering patterns of individual behavior, periods of more pleasant (inclement) weather will increase (decrease) the rate of interpersonal interactions and affect the probability of these conditions being met and, consequently, of a crime occurring. In this context, for example, unseasonably mild weather during otherwise cold winter months would lead to higher crime rates, and not strictly those crimes that are violent in nature.

1.2. Motivation

Earlier work has attempted to quantify the relationship between crime and temperature with a handful of studies offering estimates of how crime rates are likely to respond to our changing climate. However, all previous estimates are either back-of-the-envelope or do not account for crucial regional (within a single nation) and seasonal dependencies recently discovered in the relationship between criminal activity and temperature (Hsiang *et al* 2013, Ranson, 2014, Hsiang *et al* 2017, Mares and Moffett, 2019). We established a methodology that allows for known regional (Mares and Moffett 2016, de Melo *et al* 2018, Linning *et al* 2017, Mares and Moffett 2019) and seasonal variations (Cohn and Rotton, 2000, McDowall *et al* 2012, Carbone-Lopez and Lauritsen 2013, McDowall and Curtis, 2015) to be detected and built into the statistical models developed (Harp and Karnauskas 2018). In particular, stronger relationships between temperature and both violent and property crime during wintertime months provided strong evidence for the routine activities theory as the main driver of the crime-temperature relationship. Moreover, we leveraged the fact that seasonal climate anomalies have a large spatial footprint, rendering linear correlations of approximately 0.8 between seasonal climate variability and regional violent crime rates (Harp and Karnauskas 2018). This novel methodology, along with the quantitative empirical models we derived, provide a framework for leveraging multiple future climate forcing scenarios as drivers for such models to quantify the projected response of violent crime at regional scales while accounting for the full suite of uncertainty from both global climate models (GCMs) and empirical models trained on historical data (Harp and Karnauskas 2018).

To calculate projections of changes in violent crime, we acquired surface air temperature projections from 47 global climate models (GCMs) associated with the fifth phase of the Coupled Model Intercomparison Project (CMIP5) and the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). CMIP5 is an ensemble of GCMs meant to encompass the range of scientific uncertainty by allowing individual models from various global institutions to evolve freely in response to the same, prescribed future greenhouse gas forcings (Taylor *et al* 2012). The IPCC requested that various scenarios—or Representative Concentration Pathways (RCPs)—be developed to 'be compatible with the full range of stabilization, mitigation, and baseline emissions scenarios available in the current scientific literature' (Moss *et al* 2008). Four RCPs were subsequently developed and named according to their change in radiative forcing in W m^{-2} at 2100—RCPs 2.6, 4.5, 6, and 8.5.

2. Methods

2.1. Building empirical models

The spatial variation of multi-model mean projections of surface air temperature is considerable, even across the continental US (figure 1(a) uses RCP8.5 forcing and the end-of-century period for an illustrative example). In addition, as noted previously, the quantitative sensitivity of violent crime to temperature also varies spatially (Harp and Karnauskas 2018, Mares and Moffett 2019). To enable the calculation of appropriate region-based projections, we adopted the optimal boundaries previously determined in our retrospective study, also identified in figure 1(a). Regions were determined through complementary processes of (1) a principal component analysis of seasonal temperature patterns over the continental US and (2) identifying regions with homogeneous relationships between temperature and crime that were distinguishable from all other regions; see Harp and Karnauskas (2018) for additional details.

The construction of the empirical models used in the present study is an extension of the methodology used in our retrospective study, but for linear regressions instead of correlations (Harp and Karnauskas 2018). Please refer to (Harp and Karnauskas 2018) for more details on the data sets used, delineation of region boundaries, and methods of data quality control.

2.2. Determining sensitivities of crime to temperature

After compiling crime and climate anomalies for 34 years (1981–2014) and for each region, a range of sensitivities of violent crime to temperature was created using a bootstrapping method. To do so, 34 data points (years) of data were randomly selected with replacement 10 000 times for each of the 60 region-months. The sensitivity of violent crime to temperature was then calculated by applying a linear regression onto each of these 10 000 samples, yielding a probability distribution function that fully describes the possible underlying relationship in terms of percent change of violent crime per degree Celsius (supplementary figure S1(a) is available online at stacks.iop.org/ERL/15/034039/mmedia).

2.3. Establishing global mean temperature thresholds

To apply this relationship onto future projections of climate, GCM output was obtained from a variety of CMIP5 models. We selected RCP4.5, a 'middle-of-the-road' scenario, and RCP8.5, the 'business-as-usual' scenario, for the basis of our future analysis. We selected these two scenarios as being both realistic given our present carbon budget trajectory, and disparate enough to produce a range of outcomes. However, we also cast our results in terms of global

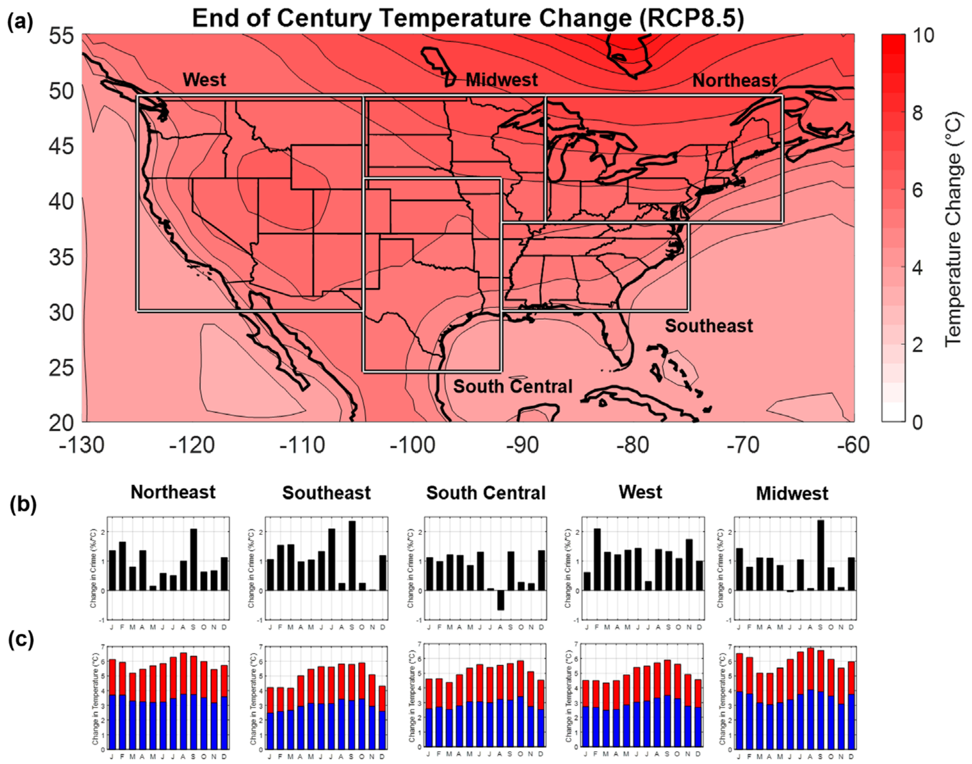

Figure 1. Regions, climate-crime relationships, and temperature projections. (a) Multi-model ensemble mean prediction of annual mean surface air temperature change in 2081–2100 under RCP8.5 over the continental US (°C, relative to preindustrial). (b) Empirical sensitivity of violent crime to seasonal temperature anomalies for each region and calendar month (% per °C). (c) Projected changes in surface air temperature (°C, relative to preindustrial) for each region and calendar month for RCP4.5 (blue) and RCP8.5 (red). Marked borders on a identify regions used for individual crime projections, as motivated by our retrospective study (Harp and Karnauskas 2018).

warming targets. Since each CMIP5 model may have a different climate sensitivity (the change in global mean surface temperature per unit change in greenhouse gas forcing), different models will reach, for instance, 2 °C of global mean warming in different future years. This allows us to quantify explicitly the dependence of our results on global warming targets associated with the Paris Agreement. For a baseline, we used all 47 historical model runs (1850–2005), which are driven by estimated historical radiative forcings, 30 model runs from the middle-of-the-road scenario (RCP4.5), and 42 models from the business-as-usual scenario (RCP8.5), where projections from the latter two span from 2006 through 2100.

Our analysis focused on the traditional end-of-century benchmarks for both RCP4.5 and RCP8.5, where end-of-century was considered 2080–2099. In addition, we also focused analysis around specific temperature thresholds, which may be more useful for decision-makers and policymakers. To this end, we considered the global mean temperature warming thresholds of 1.5 °C, 2 °C, 3 °C, and 4 °C (the latter was not applicable for the majority of RCP4.5 models). Utilizing this methodology allowed for a direct comparison of various levels of global mean warming, a useful metric when focusing on the costs and benefits of working to limit the effects of climate change to a targeted outcome. This form of analysis also provides a control for varying equilibrium climate sensitivities across the different models.

To determine the model years used for each temperature threshold, the global mean temperature was calculated for each model and compared against pre-industrial historical output for the respective model, where pre-industrial is defined as 1850–1900 by the Intergovernmental Panel for Climate Change (Intergovernmental Panel on Climate Change 2018). When a ten-year running mean of the global mean temperature exceeded the specified threshold, the month of exceedance was noted and the ten years of temperature projections on either side of the exceedance month were used for further analysis. It should be noted that RCP8.5 simulations were used for the temperature threshold calculations given that temperature thresholds are by definition independent of forcing scenario and the RCP8.5 set includes an additional 12 GCMs.

Instead of considering the mean or median warming of the suite of models, each model output was considered to be one of many equally probable realizations of the future climate state (supplementary figure S1(b)). Accordingly, to fully encompass the possible outcomes of change in violent crime, the entire sample of 10 000 bootstrapped sensitivities of violent crime to temperature was multiplied against every model projection, as demonstrated in supplementary figure S1(c). This process was repeated for each scenario at the region-month scale, producing 420 000 (300 000) equally likely future realizations of violent crime change for a region-month under RCP8.5 (RCP4.5).

2.4. Applying derived crime sensitivities to future climate states

Monthly projections were subsequently converted from percentage change in violent crime to a violent crime count by multiplying the percentage change projections by a baseline violent crime rate for each region: a four-year running mean centered upon 2014, the most recent year given data availability. While this method of conversion using a baseline allows us to appropriately contextualize the expected change in crime, it also assumes a static crime level, a clearly inaccurate projection. However, given the impossibilities of predicting future levels of crime, not to mention decoupling them from the inherent increased crime attributable from climate, using a 2014 baseline serves as a useful benchmark for producing reasonable projections. To ensure the highest precision and fully incorporate the annual cycle in violent crime, the potential realizations of monthly change in violent crime were not simply multiplied by the annual 2014 total of violent crime for each region but also by the mean seasonal cycle of violent crime. This seasonal cycle varies from 14% to 18% above and below the annual rate in summer and winter, respectively. This final step properly weights the projected monthly change in violent crime. Translating projections into crime counts creates a common denominator to allow for regional projections to be combined into a single US-wide total.

2.5. Producing annual and cumulative end-of-century projections

For each of the scenarios considered—1.5 °C, 2 °C, 3 °C, and 4 °C of global mean warming, as well as end-of-century RCP4.5 and RCP8.5—we calculated annual and cumulative end-of-century projections using the following steps. An annual projection of additional violent crime over a non-warmed world was aggregated by randomly combining one of each of the GCM-specific 10 000 equally probable realizations for January with one of the 10 000 equally probable realizations for February from the same model, and so on and so forth. This was completed at the region level, the results of which were then summed to produce a nationwide total. Repeated for each GCM, this process results in 420 000 (300 000) possible annual realizations of additional violent crime for the RCP8.5 (RCP4.5) forcing experiment, as depicted in figure 3(a). We considered the mean of these realizations to be the actual projection while the 95% confidence interval is determined by taking the 2.5th and 97.5th percentiles of the final distribution of annual projections. These annual projections are the projections described earlier and shown in the right half of figure 5.

To create the cumulative projections of additional violent crime compared to a non-warmed counterfactual, the distributions of annual realizations were combined in a similar fashion. One of the 10 000 bootstrapped crime-temperature sensitivities were randomly selected without replacement for each region-month to produce 10 000 sets of yearly region-specific sensitivities. These 10 000 sets were then multiplied by the 2020–2099 time series of monthly temperature anomaly projections for each GCM to again produce 420 000 (300 000) equally likely realizations of cumulative additional violent crime incurred by the end of the century for the RCP8.5 (RCP4.5) forcing experiments (figure 3(b)). It should be noted that three parallel uncertainty-handling processes produced the three cumulative time series from 2020–2099 shown in supplementary figure S3. Figure S3(c) was created using the methodology described above, while the methodology underlying figures S3(b) allowed for the sets of crime-temperature sensitivities to be applied to monthly temperature anomalies pulled from multiple GCMs within a given time series. In addition, the process beneath figure S3(a) also allowed for year-to-year variation within crime-temperature sensitivities (e.g. the sensitivity for January 2021 may be different from 2020). The three parallel processes ultimately produced similar cumulative totals, though associated uncertainty varied dramatically.

3. Results and discussion

3.1. Violent crime projections and context

We project that, for example, the Northeastern US will experience an increase in violent crime of 4.8% and 8.0% during January at the end of the century under RCP4.5 and RCP8.5 radiative forcing, respectively (figure 2(a)). The mean monthly percentage change for all five regions for both the RCP4.5 and RCP8.5 forcing scenarios at the end-of-century is shown in supplementary figure S2. For the same region-month, we expect an increase in violent crime of 1.8%, 3%, 5%, and 7% for a 1.5 °C, 2 °C, 3 °C, or 4 °C warmer world with greater warming also leading to greater projection uncertainty. Not only are the resultant distributions non-normal with a positive skew, but the distributions themselves widen—indicative of increased uncertainty of the projections—at higher temperatures as a result of wider model spread associated with more extreme radiative forcing. Although we now move toward nationwide projections, the underlying distributions were calculated for each region-month combination using all climate model experiments.

To calculate projections of US annual total additional violent crimes to be expected in a warmer world, all 60 region-month projections for a given year were

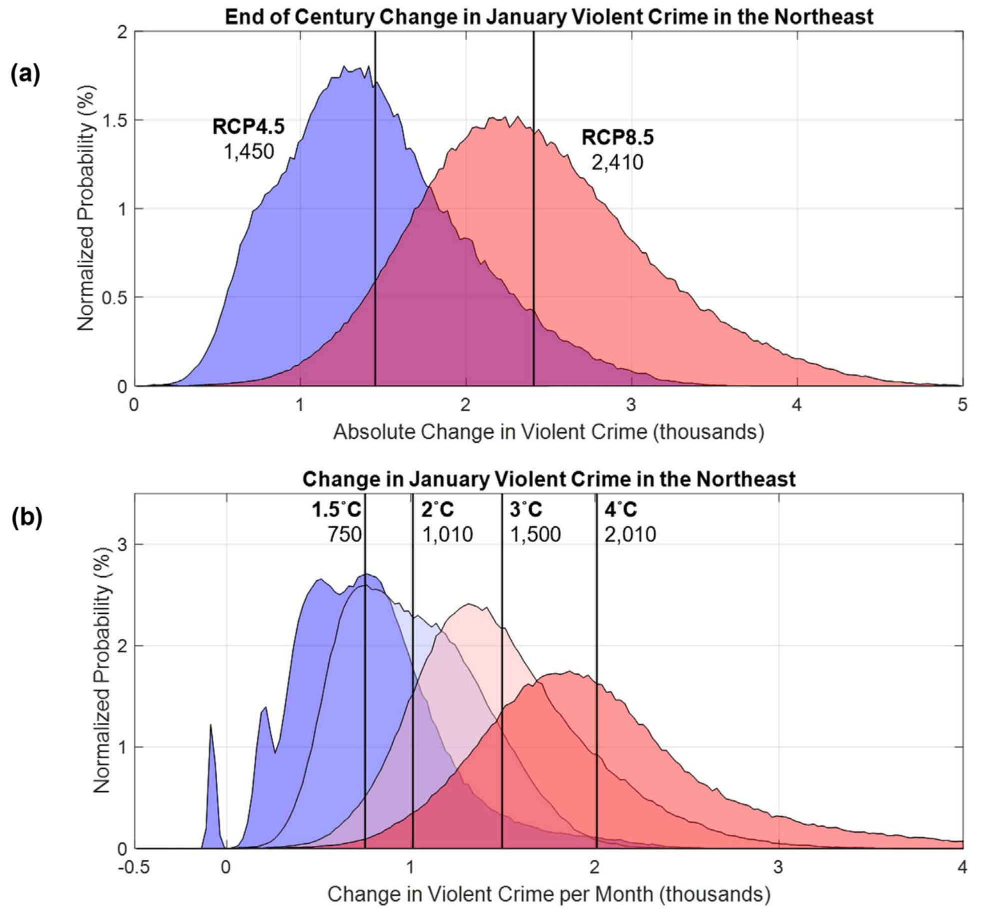

Figure 2. Change in Regional Violent Crime Under Different Warming Scenarios. (a) Normalized probability distributions of the expected change in violent crime for January in the Northeast at the end of the century under the RCP4.5 and RCP8.5 forcing experiments. (b) Same as (a) but where probability distribution functions are based off of changes in global mean temperature instead of RCPs. Vertical lines and their labels represent means of the respective distributions.

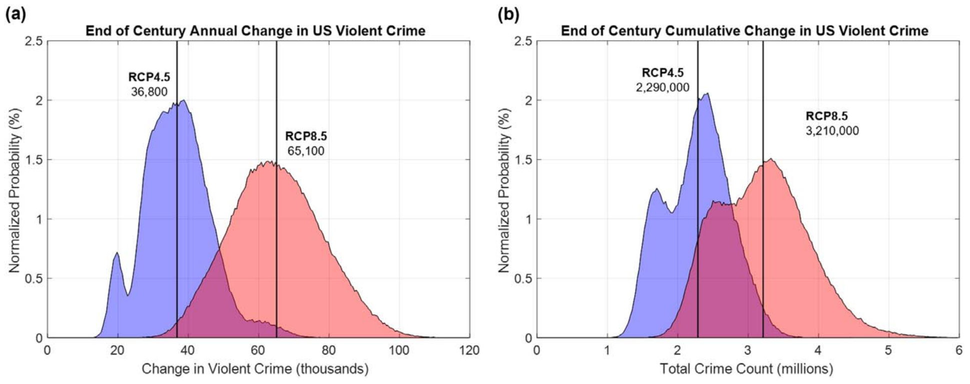

Figure 3. Change in US Violent Crime by the End of the Century. (a) Normalized probability distribution of expected annual additional violent crimes for the US at the end-of-century under RCP4.5 and RCP8.5 forcing experiments. (b) Same as (a) but for cumulative totals for the US from 2020 to 2099. Vertical lines and their labels represent means of the respective distributions.

simply summed. The projection under RCP4.5 forcing is an additional 36 800 violent crimes per year by the end of the century compared to an additional 65 100 violent crimes per year for the RCP8.5 scenario (figure 3(a)). Though there is overlap in the uncertainty between the two experiments, both are significantly different from zero at the 95% confidence level. As noted earlier, RCPs with stronger greenhouse gas forcing—and therefore larger responses of surface air temperature—lead to greater uncertainty of the projections. The US-wide, annual totals from 2020–2099 (shown in figure 5, right) can be integrated over time to project *cumulative* changes in violent crimes (figure 3(b) and supplementary figure S3). For the US, we project an additional 3.2 million (2.3 million) violent crimes under RCP8.5 (RCP4.5) forcing by the end of the century

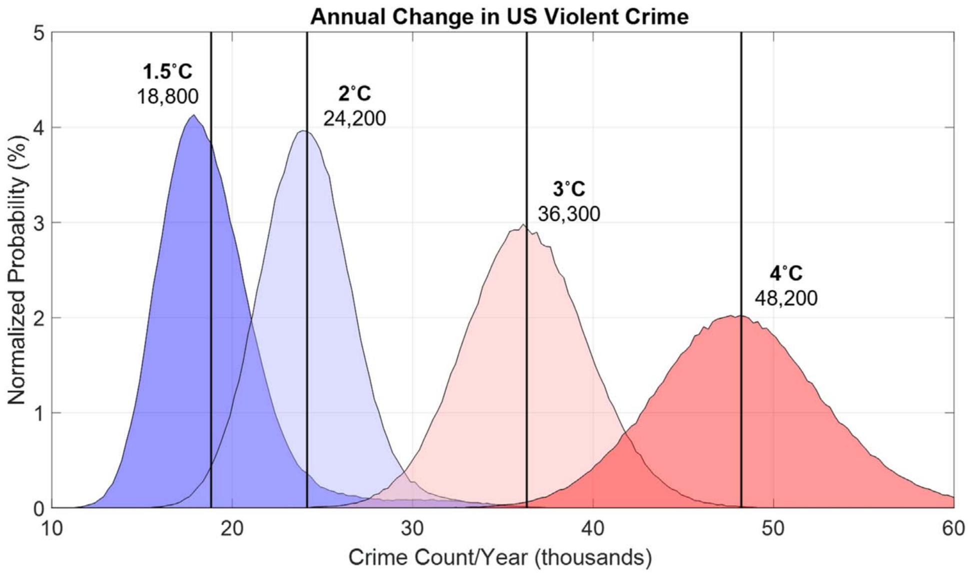

Figure 4. Expected Annual Change in US Violent Crime for Various Global Mean Warming Thresholds. Normalized probability distributions of US annual additional violent crimes expected for 1.5 °C, 2 °C, 3 °C, and 4 °C of global mean warming. Vertical lines and their labels represent means of the respective distributions.

compared to baseline (*i.e.* a non-warmed world). These projections are both statistically and societally significant; for context, these cumulative totals are roughly the equivalent of 2.5 (2) times the total number of violent crimes in the US in 2014 (United States Department of Justice 2015).

Cumulative totals for the various temperature threshold scenarios are not possible since the number of months into the future that model projections cross temperature thresholds (e.g. 1.5 °C increase in global mean temperature) can vary dramatically depending on the equilibrium climate sensitivity of the particular climate model. For instance, comparing cumulative change in violent crime for a model that reaches 1.5 °C of warming in 2040 will produce much different results than for a different model which crosses the same threshold in 2080. We can, however, compare differences in the additional US violent crimes expected annually (figure 4).

As expected given the linear empirical relationship between crime and temperature found in our retrospective study (Harp and Karnauskas 2018) and others mentioned previously, the greater the temperature increase, the greater the number of additional violent crimes expected at that global warming threshold. However, since the actual warming in a given region may lag behind or accelerate beyond the global mean warming due to regional climate dynamics (e.g. land warms faster than ocean, high-latitude warming is amplified), the regional temperature, and therefore violent crime projections, for a given warming threshold will not be a perfect reflection of the global temperature increase (e.g. see background map in figure 1(a)). Upon taking these factors into account, we project that global mean temperature increases of 1.5 °C, 2 °C, 3 °C, and 4 °C would contribute an additional 18 800, 24 200, 36 300, and 48 000 violent crimes per year, respectively (figure 4). The resulting mean monthly percentage change for all five regions for both the RCP4.5 and RCP8.5 scenarios at the end-of-century is shown in supplementary figure S2.

Finally, we further convey the magnitude of our projections of US-wide annual additional violent crimes in the context of observed interannual variability. In other words, how do these projections compare to normal fluctuations from year to year that society experiences in the present physical and societal climate? The recorded interannual variability of US-wide annual crime totals fluctuates in the range of tens of thousands of crimes per year (figure 5). The projected annual increase in US violent crimes for RCP8.5 meets the extreme of that baseline variability by near the end of the century, while the RCP4.5 projections reach the range of normal fluctuations by mid-century and level off. The projections for RCP8.5 by the end of the century are greater than the annual anomaly in violent crime in all but two years in the observed crime data and exceed even years when considered as a proportion of the baseline. Even if the increased violent crime contributed by future temperature increases is relatively small compared to the annual total of US violent crime, it is sizable when placed against observed interannual variability—an equally important benchmark.

3.2. Potential limitations

There are two caveats to the present methodology. First, it is important to note that our results should not be interpreted as a prediction of absolute numbers of violent crimes, but rather the *expected difference in*

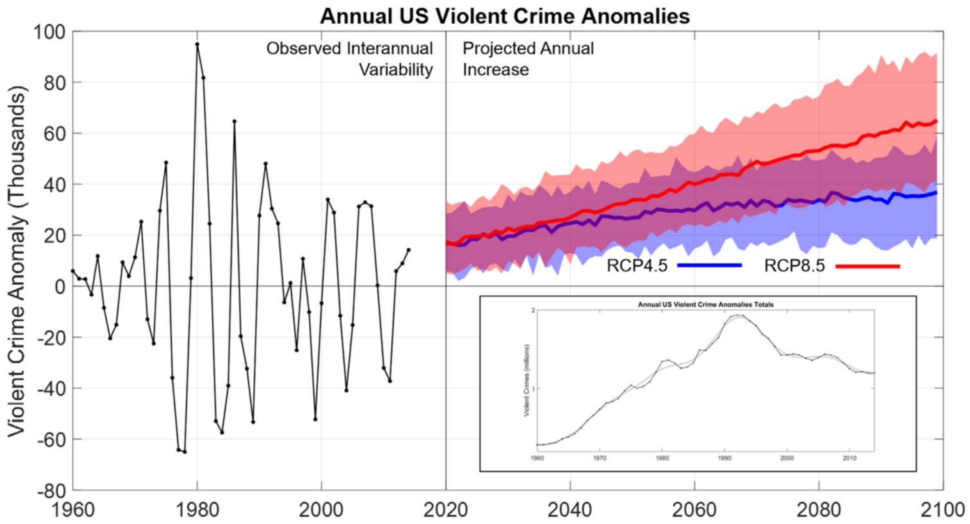

Figure 5. US Violent Crime Anomalies. Left Annual anomaly of US violent crime from the ten-year running mean. Right Projected annual increase of violent crimes for RCP4.5 (blue) and RCP8.5 (red) forcing scenarios. Inset Actual annual US violent crimes total (Federal Bureau of Investigation 2017) are plotted (black) alongside a ten-year running mean (thick gray).

crime levels compared to a non-warmed global climate. That is, we project the additional violent crimes *contributed by warming*. Criminology and the factors governing variability in crime rates are complex and dependent upon a number of non-environmental factors including, but not limited to, police force strength, broad socioeconomic trends, and demographics. While our methodology is able to leverage the variability about the low frequency variability dominated by multidecadal trends, it does not attempt to forecast changes to the nation-wide crime rate moving forward and uses a baseline of 2014 crime rates for the above future projections. Second, we assume that the sensitivity of violent crime to seasonal climate is stationary—i.e. it will remain stable moving forward with no personal or societal adaptations to warming on this time scale. We compared the observed sensitivities (empirical model parameters) across the first and second halves of observational record (spanning 1981–2014) and did not detect any significant differences. However, this rudimentary analysis focuses on a small subset of data and may not accurately reflect the capacity of human behavior to adapt to warmer temperatures and modify the natural response implied by the routine activities theory accordingly, as suggested by some recent social experimental studies (Moore *et al* 2019).

4. Conclusion

Our methodology directly integrates regional and seasonal differences that have been overlooked in previous attempts to understand the implications of future climate change for violent crime, in addition to incorporating variations in spatial patterns inherent to projected changes in air temperature in GCMs. Through use of the full complement of GCMs, and by performing analysis at temperature thresholds in addition to more typical time endpoints, this process has allowed for a more comprehensive future projection than has been previously performed. Natural extensions of this work include utilizing finer units of spatial and temporal aggregation with data from the Federal Bureau of Investigation's National Incident Based Reporting System, though this approach may be limited by data availability. Future research should also focus on determining the stationarity of the sensitivity of crime to temperature—does this *sensitivity itself* vary depending on temperature?

Ultimately, by producing an estimate of future additional crime linked to rising global temperatures, this work illuminates another hidden cost of climate change—both human and economic—to be considered in decision-making. For context, the projections of additional violent crimes per year (figure 5, right) are comparable to the 2013 total of *all* vector-borne diseases in the US—51 258—a more conventional and widely discussed climate and health connection (Beard *et al* 2016). Further, using cost-of-crime estimates (Chalfin 2015) allows for a back-of-the-envelope approximations of the additional cost of crime through the end of the century: 496 (341) billion US dollars for RCP8.5 (RCP4.5), roughly equivalent to the 2019 GDP of Thailand (Denmark) (World Bank 2019). It is likely that this cost will not be actually realized as additional resources may be devoted to law enforcement, though increasing police force size has its own economic cost (Ranson 2014). Regardless of the framing, it is clear that the impact of climate change on violent crime is significant and merits broader consideration by the scientific community and decision-makers alike.

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Data availability statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study. All data analyzed were acquired from data portals that are free and open. We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups for producing and allowing their model output to be publicly available (http://esgf-node.llnl.gov/). We extend gratitude to the US Department of Energy's Program for Climate Model Diagnosis and Intercomparison for providing coordinating support and leading the development of software infrastructure for CMIP in partnership with the Global Organization for Earth System Science Portals. We extend our gratitude to the Criminal Justice Information Services branch of the FBI for maintaining and providing the UCR data set (https://ucrdatatool.gov/).

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