Impact of climate variability and change on crime rates in Tangshan, China

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Abstract: Studies examining the relation between climate and human conflict often focus on the role of temperature and have diverging views on the significance of other climatic variables. Using a 6-year (from 2009 to 2014) dataset of crime statistics collected in a medium size city of Tangshan in China, we find strong, positive correlations between temperature and both violent and property crimes. In addition, relative humidity is also positively correlated with Rape and Minimal Violent Robbery (MVR). The seasonal cycle is a significant factor that induces good correlations between crime rates and climatic variables, which can be reasonably explained by the Routine Activity theory. We also show that the combined impacts of temperature and relative humidity on crime rates can be reasonably captured by traditional heat stress indices. Using an ensemble of CMIP5 global climate change simulations, we estimate that at the end of the 21st century the rates of Rape (violent crime) and MVR (property crime) in Tangshan will increase by 9.5 ± 5.3% and 2.6 ± 2.1%, respectively, under the highest emission scenario (Representative Concentration Pathway 8.5). The gross domestic product (GDP) is also shown to be significantly correlated with MVR rates and the regression results are strongly impacted by whether GDP is considered or not.

Keywords: climate, crime rate, temperature, relative humidity, heat stress, seasonality, GDP

1 Introduction

A growing number of research studies have demonstrated the impact of climate on human conflict, including large-scale conflict (Bernauer et al., 2012; Burke et al., 2009; Hsiang et al., 2013; Hsiang et al., 2011; O'Loughlin et al., 2012; Scheffran et al., 2012; Tol and Wagner, 2010; Zhang et al., 2011) (e.g., civil conflict, warfare, and human crisis) and crime (Barnett and Adger, 2007; Brunsdon et al., 2009; Horrocks and Menclova, 2011; Mares, 2013; Mehluma et al., 2006; Ranson, 2014; Shi et al., 2015; Skudder et al., 2016). A recent global synthesis work assembled and analyzed 60 previous quantitative studies and found out that 1σ (where σ denotes the standard deviation) change in the climate toward warmer temperature or more extreme rainfall increases the frequency of intergroup conflict by 14% and interpersonal violence by 4% (Hsiang et al., 2013). Another recent study pointed out that each degree Celsius increase in the annual mean temperature is associated with on average nearly 6% increase in homicides (Mares and Moffett, 2016).

Previous work investigating the influence of climate on crime rates often focused on the role of temperature. For example, a number of studies pointed out that temperature had a significant effect on crime (Barnett and Adger, 2007; Brunsdon et al., 2009; Horrocks and Menclova, 2011; Mares, 2013), and was often positively correlated with the number of crime incidents (Ranson, 2014). Rainfall and droughts have been also considered in the literature but their impacts are primarily on property crimes (Mehluma et al., 2006) and are often seen in low-income communities (Miguel, 2005). Prior criminological work on other climatic variables (humidity, wind speed, etc.) has largely been fruitless with contradicting results (Cohn and Rotton, 1997; James and Corcoran, 1990; Rotton and Cohn, 2001; Rotton and Cohn, 2004). For instance, a recent study examining the effect of relative humidity pointed out that relative humidity had a significant and positive correlation with crime rates (Mishra, 2014). Their results were nonetheless contradictory to another study (Gamble and Hess, 2012) showing that the correlation coefficient between relative humidity and crime rates was extremely small with a low significance level. As a result, whether climatic variables other than temperature such as relative humidity are also correlated with crime rates remains an open question.

Why do weather or climate variables affect crimes? The Routine Activity (RA) theory proposed by Cohen and Felson (1979) offers one perspective. In the RA theory, there are three necessary conditions for committing a crime: (1) a potential offender with the capacity to commit a crime; (2) a suitable target or victim; and finally (3) the absence of guardians capable of protecting targets and victims. The likely offender may be anyone with a motive to commit a crime and with the capacity to do so (Felson and Cohen, 1980). Cohen and Felson (1979) used the term "motivated offender" but in later work (Felson and Cohen, 1980) they avoided the term "motivated", as what they considered relevant was not the disposition or motivation to commit a crime but rather the physical factors that made it possible for a person to be involved in a crime. The suitable target is a person or property that may be threatened by an offender. The probability that a target is selected is influenced by the value, inertia (physical aspects of the person or good), visibility (exposure of targets), and access (Cohen and Felson, 1979; Felson and Clarke, 1998). The third and final element described in the RA theory is the absence of a capable guardian who can intervene to stop or impede a crime (Cohen & Felson, 1979). A guardian is defined as someone in whose presence the crime is not committed, and whose absence makes it more probable (Felson, 1995). In the framework of RA, higher but not extreme temperature is likely to increase mobility and social interaction (e.g., in summer), increasing the likelihood of a suitable target occurring and also present more opportunities for crimes to occur.

The RA theory has been widely used in crime research to explain the seasonality, the spatial and temporal distributions of crime. For instance, Landau and Fridman (1993) used RA to explain the seasonality of homicide and robbery in Israel, considering crime as a function of three main elements: motivated offenders, suitable targets, and the absence of guardians; Andresen and Malleson (2013) investigated the existence of seasonality in crime and used the RA theory to explain the spatial variations of certain crimes; Drawve et al. (2014) extended the RA theory to understanding variations in the likelihood of an offender being arrested; Pereira et al. (2016) investigated the temporal variations (seasons, months, days of week, and periods of day) of homicide in Recife, Brazil, a city with a tropical climate, and employed the RA theory as one of the theoretical arguments.

In addition to RA, other theories also exist and offer different perspectives. For example, the General Affect (GA) model proposes that higher temperatures facilitate effective aggression (Cohn and Rotton, 2000). The Negative Affect Escape (NAE) model suggests that human aggression increases with temperature because of increases in discomfort, but only up to a certain point beyond which the relationship will become negative (Bell, 1992). Based on the GA model and the NAE model, heat stress may be a key to explaining the relation between the climate and crime rates. As the heat stress increases, the level of discomfort increases, which leads to more crimes. Even in the framework of RA, whether a crime occurs or not is strongly tied to the offender's individual-level motivation and incentive, which may be affected by heat stress. Numerous psychological studies showed that relative humidity could strongly affect human comfort. In fact, many heat stress indices include relative humidity (ACSM, 1984; Buzan et al., 2015; Dunne et al., 2013; Fischer et al., 2012; Ingram, 1965; Kovats and Hajat, 2008; Masterson and Richardson, 1979; Oleson et al., 2015; Pal and Eltahir, 2015; Sherwood and Huber, 2010; Steadman, 1984; Thom, 1959). It is thus not unreasonable to expect that relative humidity also affects crime but it is still unclear whether traditional heat stress indices could capture their impacts on crime.

To examine the relation between climate variables and crime rates, monthly records of six different types of crimes (i.e., Homicide, Assault, Rape, Robbery, Burglary, and Minima Violent Robbery) and two climatic variables (i.e., temperature, and relative humidity) collected in Tangshan, China during 2009 to 2014 are used. Annual GDP data provided by Tangshan government are also used. Tangshan, with a population of 7.6 million and area of 13,472 km^2, is an industrial city in northeastern China, which is approximately 150 kilometers southeast of Beijing and the center of city is located at 39.62 N, 118.18 E. The city is challenged with a rising number of crimes in recent years with more than 170, 000 crime incidents between 2009 and 2014 but is a less studied area in the literature. Tangshan has a monsoon-influenced, humid continental climate with cold and dry winters and hot and rainy summers. The annual mean temperature of Tangshan is 11.5 °C, with monthly average temperatures of −5.1 °C and 25.7 °C in January and July, respectively. About 60% of its annual precipitation (about 610 mm) falls in July and August.

In this paper, we first investigate the separate impacts of temperature and relative humidity on six types of crimes by time series analysis and simple regression. Then the combined impacts of temperature and relative humidity on crime rates are studied using five traditional heat stress indices. Finally, using an ensemble global climate change simulations from Coupled Model Intercomparison Project Phase 5 (CMIP5), we investigate climate-induced changes in crime rates in Tangshan in the late 21st century under three different emission scenarios (Representative Concentration Pathways).

2 Methods

2.1 Data and regression analysis

The analysis for this paper is based on a 6-year (from 2009 to 2014) dataset of monthly crime numbers provided by the Municipal Public Safety Bureau of Tangshan, China from the crime statistics database. This dataset includes 3 categories, namely, “Cases reported”, “Cases confirmed”, and “Cases solved”. Cases reported is collected from the 110 calls data (like 911 calls data in the US), but this is a voluntary report and the crime types cannot always be confirmed. Thus, the data used in this paper are Cases confirmed, which can provide more accurate crime counts. All data used in this paper are raw data without any modification. The data used in this study have some limitations. For example, aggravated and simple assaults are not separated. Simple assaults are often considered sensitive to any reporting biases. For instance, simple assaults get reported at higher rates during pleasant months because more people are out, witnessing crimes and calling police. This is also true in China. What is unique about Chinese cities is that the population density is often very large. As a result, there is enough number of people witnessing any assault (which is always considered as an unusual incident) and calling to police even in winter. Another limitation is that raw crime counts for some types of crime (e.g. Homicide) are very low, and it may lead to some problems such as over dispersion in our statistical analysis. To avoid over dispersion, crime rates (crime incidents/10^6 people) are used rather than the raw crime counts. An example of the data format is shown in Table A1.

In total, six different crime types are included, namely, Homicide, Assault, Rape, Robbery, Burglary and Minimal Violent Robbery (MVR), all of which are common crime types in China. Here Assault includes both aggravated assault and simple assault. Robbery is considered as a violent crime. Minimal Violent Robbery is a unique type of property crime in China, which is similar to Robbery but with minimal even no violence. That is, Robbery is to obtain properties by means of violence; while MVR is to obtain properties of a person who is unaware. As an example, if someone steals a necklace from a lady when the lady is unaware throughout the whole incident, it is reported as stealing; if someone takes the necklace away from the lady’s neck when she is unaware, but at the instant the lady realizes that someone is taking her necklace away but could not stop it, this is reported as Minimal Violent Robbery; if someone obtains the necklace from the lady by violence, it is reported as (violent) Robbery.

In order to examine whether there are linear relationships between crime rates and climate variables, simple regression analysis is conducted using the following equation,

$$A = \alpha_0 + \alpha_1 B + \varepsilon \tag{1}$$

where A represent the crime rates (crime incidents/10^6 people), B represents the value of climate variables, α_0 and α_1 are parameters, and ε is an error term. In this paper, climate variables include temperature and relative humidity or indices formulated by combining them. Here α_0 represents the socio-economical influence on crime. It has been long recognized that crime rates are strongly affected by socio-economic factors. For instance, increases in gross domestic product (GDP) may be accompanied by increases in crime rates. In the same time, increases in the number of police officers and security measures may reduce crime incidents. In this paper, we recognize the importance of socio-economic factors and assume that α_0 is either a constant or a linear function of GDP ($\alpha_0 = \lambda$ GDP).

To examine the relationship between human comfort and crime rates, five heat stress indices are conducted as shown in Table 1. All heat stress indices considered in our study combine the effects of temperature and relative humidity. Only the results with the Simplified Wet Bulb Globe Temperature (sWBGT) are discussed here since results with other heat stress indices are very similar.

Table 1 Heat stress indices

Indices	**Descriptions**
Simplified Wet Bulb Globe Temperature **(sWBGT)** (ACSM, 1984)	$\mathrm{sWBGT} = 0.56T + 0.393e + 3.94$
Humidity Index **(HUMIDEX)** (Masterson and Richardson, 1979)	$\mathrm{HUMIDEX} = T + 0.56(e - 10)$
Temperature Humidity Index for Comfort **(THIC)** (Ingram, 1965)	$\mathrm{THIC} = 0.72T_{\mathrm{w}} + 0.72T + 40.6^{*}$
Temperature Humidity Index for Physiology **(THIP)** (Ingram, 1965)	$\mathrm{THIP} = 0.63T_{\mathrm{w}} + 1.17T + 32$
Discomfort Index **(DI)** (Thom, 1959)	$\mathrm{DI} = 0.5T_{\mathrm{w}} + 0.5T$

* T_{w} is the wet bulb temperature ($^{\mathrm{o}}$C) (Ingram, 1965) and e is the water vapor pressure that can be calculated from T and RH at a given pressure (Buzan et al., 2015).

2.2 Future projections

To estimate future changes in crime rates in Tangshan at the end of the century (2094−2099) due to changes in climatic variables, monthly data from 13 different CMIP5 models (listed in Table 2) are used in this paper. The use of CMIP5 model data in our study is justified by the fact that the size of Tangshan is comparable to the spatial resolution of these global climate models (~ 100 × 100 km^2). For each model, three representative concentration pathways (RCP2.6, RCP4.5 and RCP8.5), which represent different emission scenarios and thus socio-economic changes, are considered.

First, we calculate changes in climate variables between the beginning of the century (2009 − 2014) and the end of the century (2094 − 2099) by

$$\Delta B_i = B_i^{2094-2099} - B_i^{2009-2014} \tag{2}$$

where ΔB_i represents changes in the climate variable or the heat stress index B in the i^{th} month. By doing so, we also remove the mean bias in the climate simulations. Second, we compute the change in crime rates for every type of crime based on

$$\Delta A_{ji} = \alpha_{1j} \Delta B_i \tag{3}$$

where ΔA_{ji} represents the change in crime rate for the j^{th} type of crime in the i^{th} month. α_{1j} is the parameter obtained from regression analysis. Third, we take the mean of 12 months to obtain the change of crime numbers ΔA for every crime and every model:

$$\Delta A_j = \frac{\sum_{i=1}^{n} \Delta A_{ji}}{n} \tag{4}$$

where ΔA_j represent the mean change of the j^{th} type of crime and n is the number of months in the period. It is stressed that ΔA refers to changes in crime rates due to changes in climatic variables and changes in crime rates due to socio-economic changes are not considered here. Finally, we calculate the ensemble mean of the j^{th} type of crime and also the standard deviation across 13 models.

Table 2 CMIP5 models.

Model abbreviation	Institution
CESM1-CAM	National Center for Atmospheric Research, USA
FGOALS-G2.0	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences
GFDL-CM3	NOAA Geophysical Fluid Dynamics Laboratory, USA
GFDL-ESM2G	As in GFDL-CM3
GFDL-ESM2M	As in GFDL-CM3
HadGEM2-AO	National Institute of Meteorological Research/Korea Meteorological Administration, Korea
HadGEM2-ES	Met Office Hadley Centre, UK
IPSL-CM5A-MR	Institute Pierre Simon Laplace, France
MIROC5	Model for Interdisciplinary Research on Climate, Japan
MIROC-ESM	As in MIROC5
MIROC-ESM-CHEM	As in MIROC5
MPI-ESM-LR	Max Planck Institute for Meteorology, Germany
MPI-ESM-MR	As in MPI-ESM-LR

3 Results and discussions

3.1 Simple regression analysis

First, the temporal variations of climatic variables and crime rates during 2009 to 2014 are shown in Fig.1. From this figure, we can see that temperature (T) shows clear seasonal cycles during the study period; relative humidity (RH) also shows seasonal cycles but with some irregularities. No clear long-term trend is detected for T but a slightly increasing trend is observed for RH. Most crime types (except Homicide) have generally increasing trends. Moreover, for Rape and Minimal Violent Robbery (MVR), clear seasonal cycles are also seen, similar to those of T and RH.

Next, simple regression analysis is conducted to examine the relation between monthly crime rates and monthly mean temperature (T) and relative humidity (RH) (see Methods). Lagged impacts on crime rates are not considered in this paper since they have been shown to be insignificant by a previous study (Ranson, 2014). The six crime types are broadly separated into two major categories:

property crimes (i.e., Burglary, and MVR) and violent crimes (i.e., Murder, Assault, Rape and Robbery). Table 3 shows a strong relationship between temperature and MVR (property crime, R^2 = 0.51), which can be also seen from Fig. 1. This result suggests that increases in certain property crimes are associated with increases in the temperature.

The effect of temperature on property crimes such as MVR may be interpreted by the RA theory. Higher but not extreme temperature is more likely to increase mobility and social interaction, increasing the likelihood of a suitable target occurring and also present more opportunities for property crimes to occur. However, it is pointed out that police presence may also be associated with temperature or other weather conditions (Horrocks and Menclova, 2011), e.g. in warmer days, the increasing social interaction may also increase the police presence, which may result in fewer crimes as criminals may realize the increased probability of being caught.

On the other hand, as shown in Table 3, the R^2 value between Burglary and temperature is only 0.09, suggesting that Burglary is not strongly associated with temperature. The RA theory also explains why Burglary, which happens indoors, is not well correlated with temperature. Burglary offenders are more likely to commit crimes when people are outside and where the security level is low. Thus, most of the Burglary crimes in China occur at 7~9 am when people just go out to work in weekdays or at 0~2 am when people are in deep sleep (Chen et al., 2009), and are not strongly associated with the weather conditions. The fact that temperature is not associated with Burglary is consistent with previous studies (Chen et al., 2011; Ranson, 2014).

For violent crimes, the R^2 values between Rape and temperature is larger than 0.4, suggesting that higher Rape rates are significantly associated with higher temperatures. This is consistent with Fig.1 as well as many previous studies (Barnett and Adger, 2007; Horrocks and Menclova, 2011; Ranson, 2014). The effect of temperature on Rape may also be interpreted by RA. For instance, Rape shows a distinct seasonal cycle that correlates with the seasonal cycle of temperature since in summers people are more likely to be outside, come into contact with one another, and go back home late, thereby presenting more opportunity for Rape to occur. In the meantime, one can argue that heat stress may also contribute to, at least part of, the relation between Rape and temperature. According to the GA model, higher temperatures increase human discomfort and may therefore lead to crime occurrence.

However, the relations between temperature and violent crimes cannot be always explained by these theories. For example, Table 3 suggests a less significant relationship between temperature and violent Robbery (R^2 is 0.10). This is consistent with our recent study examining the difference between Robbery and MVR in Beijing, China (Hu et al., 2017). Based on the GA and NAE models, when human discomfort is beyond the threshold where the criminal's motivation to escape uncomfortable situations outweighs the motivation to be aggressive, violent Robbery will no longer increase or even decrease with increasing heat stress (Hu et al., 2017). So affected by opportunities, targets, guardians, and human comfort, the relation between violent Robbery and temperature is more complex and less significant than the relation between MVR and temperature (Hu et al., 2017).

In summary, the correlations between several types of property and violent crimes and temperature are good due to the seasonality in both crime and temperature data, which can be reasonably explained by the RA theory. This does not necessarily mean that heat stress does not play a role. Even in the framework of RA, whether a crime occurs or not is strongly tied to the offender's motivation and incentive. In some cases the individual-level motivation and incentive may have little to do with temperature (and other climate variables), but in other cases they may be affected by temperature (and other climate variables) due to for example human discomfort. Nonetheless, even if heat stress plays a role, it is extremely difficult to separate the role of temperature in terms of inducing human discomfort and thus crime from the role of temperature in terms of increasing the probability of suitable targets occurrence in the RA framework.

The relations between RH and crime rates are quite different and interesting. Rape and MVR are significantly correlated with RH (R^2 > 0.1 and p < 0.05). Robbery and Burglary are also significantly associated with RH but the R^2 values are small. From the results, we can infer that RH is associated with both violent (such as Rape) and property (such as MVR) crimes, which is again largely due to the seasonality of RH and that of crime rates. It is pointed out that the seasonal cycle of RH is not as distinct as that of T, which may be the reason that all of R^2 values between RH and crime rates are much lower than those between T and crime rates, and most of relations between crimes (i.e. Homicide, Assault, Robbery and Burglary) and RH are not significant. One can argue that the good correlations between RH and Rape/MVR, which largely come from the seasonality in both crime and RH data, can be also explained by the RA theory. In summer, the likelihood of suitable targets increases thereby presenting more opportunities for crimes and in the meantime, the RH is also high. On the other hand, one can also argue that higher RH leads to reduced human comfort and may motivate more crimes (similar to the GA model).

Based on time series analysis and regression results and using R^2 = 0.16 (which corresponds to a correlation coefficient of 0.4) as a threshold, we conclude that Rape and MVR are significantly associated with both temperature and relative humidity. The correlations between climate variables and other types of crimes are less robust.

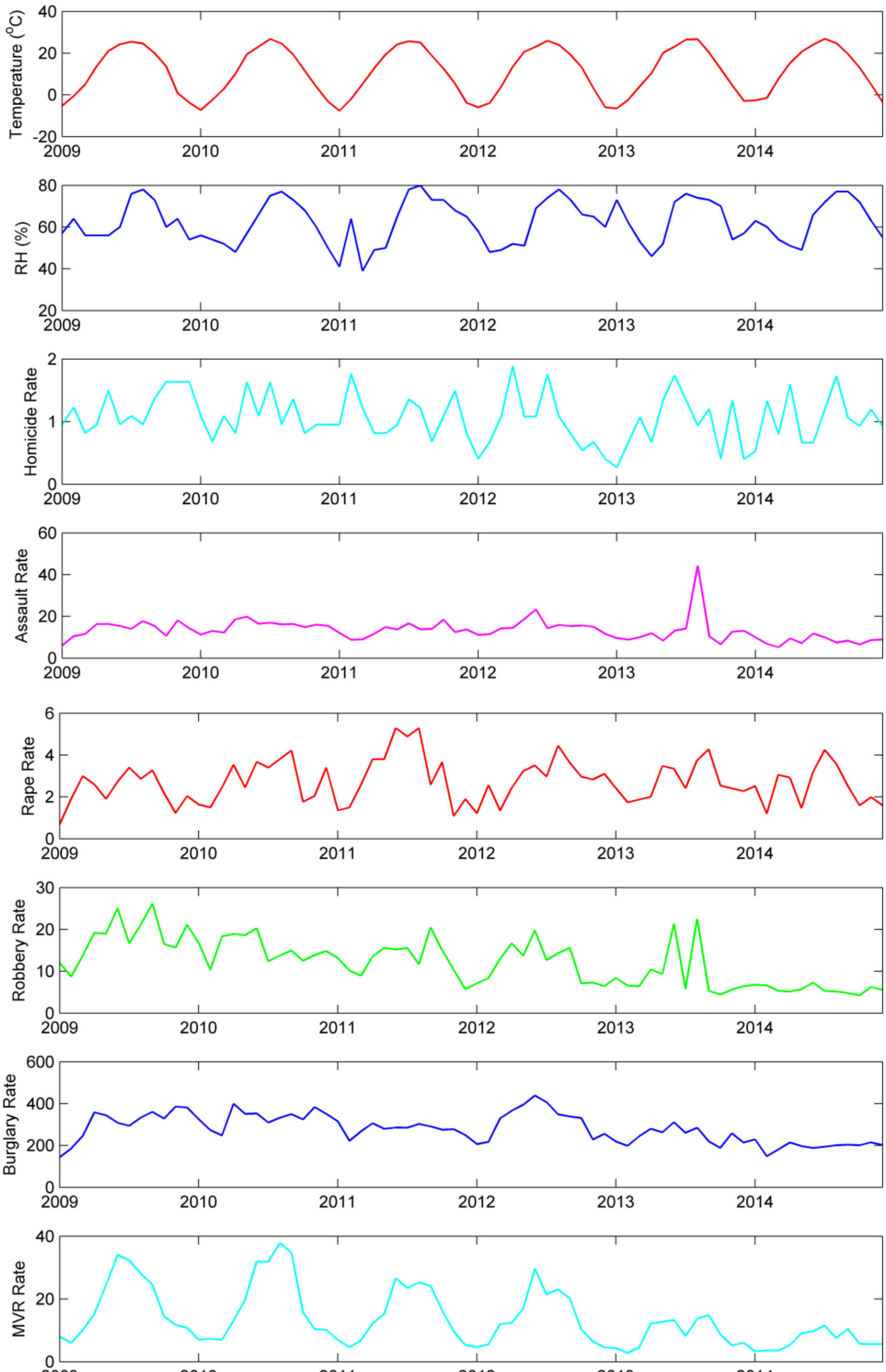

Fig.1 Temporal distributions of climatic variables and crime rates during 2009 to 2014.

To evaluate whether changes in temperature and relative humidity will lead to significant changes in the crime rates, an empirical estimate is used here following the global synthesis study (Hsiang et al., 2013) mentioned earlier. That is, if a 1σ (where σ denotes the standard deviation) increase in a climate variable leads to a change in the crime rate greater than 10% (relative to its mean), then it is considered significant. As shown in Fig. 2, we can see that for each 1σ increase in T, increases in the number of Rape and MVR are larger than 20%, especially MVR which experiences an increase of over 45%. For each 1σ increase in relative humidity, the increase in MVR is larger than 20%. These results are broadly consistent with the simple regression results in Table 3.

Table 3 Simple regression analysis results (R^2) between crime rates and temperature (T, °C) and relative humidity (RH, %).

	Homicide	Assault	Rape	Robbery	Burglary	MVR
T	**0.10***	**0.13***	**0.44***	**0.10***	0.09*	**0.51***
RH	0.02	0.05	**0.17***	0.00	0.00	**0.21***

* denotes a significance level lower than 0.05

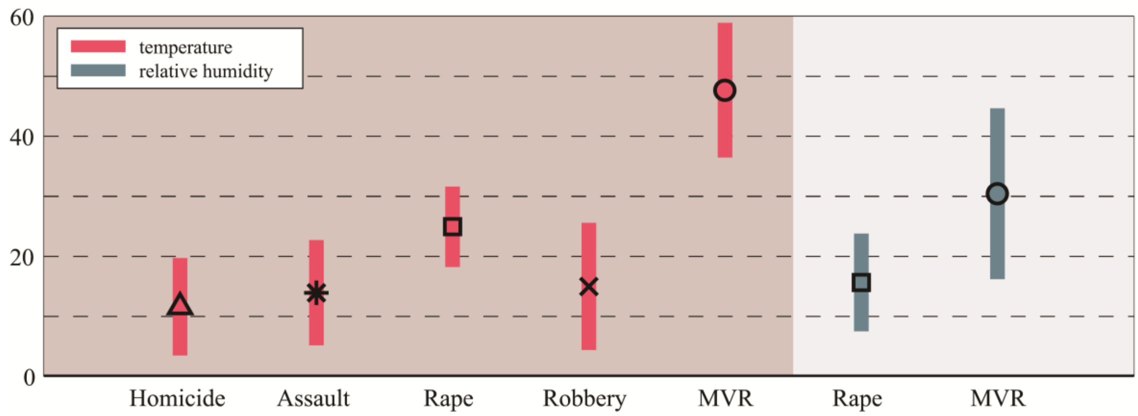

Fig.2 Impacts of temperature (T, °C) and relative humidity (RH, %) on crime rates. Each marker represents the estimated impact of a 1σ increase in a climate variable, expressed as a percentage change in the outcome variable relative to its mean. Whiskers represent the 95% CI (confidence interval) for this estimate. The results are mainly determined by the parameter α_1 in Eq. 1 and its 95% confidence interval.

3.2 Heat stress indices

We further test whether traditional heat stress indices (see Table 1), including Simplified Wet Bulb Globe Temperature (sWBGT), Humidity Index (HUMIDEX), Temperature Humidity Index for Comfort (THIC), Temperature Humidity Index for Physiology (THIP) and Discomfort Index (DI), can capture the climate influence on crime. Results indicate that the R^2 values for heat stress indices in simple regression analysis are extremely similar to those for temperature due to the dominant role of temperature in these heat stress indices (see Table 4). This is because heat stress indices are all very sensitive to temperature but less sensitive to RH, as shown in Fig. A1.

We further conduct a step-wise regression analysis in order to produce an index that has a similar form as sWBGT but yields the best correlation with crime rates. While the resulting index does have slightly different coefficients or weights for T and RH compared to sWBGT, the R^2 values no longer increase for the six crime types considered here. Based on this, we conclude that the combined impacts of temperature and relative humidity on Rape and MVR rates can be reasonably captured by traditional heat stress indices.

Table 4 Simple regression analysis results (R^2) between crime rates and different heat stress indices.

	Homicide	**Assault**	**Rape**	**Robbery**	**Burglary**	**MVR**
sWBGT	0.10*	0.14*	**<u>0.46*</u>**	0.10*	0.08*	**<u>0.52*</u>**
HUMIDEX	0.10*	0.13*	**<u>0.46*</u>**	0.10*	0.08*	**<u>0.52*</u>**
THIC	0.10*	0.13*	**<u>0.45*</u>**	0.10*	0.09*	**<u>0.51*</u>**
THIP	0.10*	0.13*	**<u>0.45*</u>**	0.10*	0.09*	**<u>0.51*</u>**
DI	0.10*	0.13*	**<u>0.45*</u>**	0.10*	0.09*	**<u>0.51*</u>**

* denotes a significance level lower than 0.05

To examine the combined impacts of socio-economic factors and heat stress on Rape and MVR, two methods are used. First, the impact of socio-economic factors on Rape and MVR is assumed to be time invariant. Second, the impact of socio-economic factors on Rape and MVR is assumed to be a linear function of GDP. That is, in the following equation,

$$\text{Crime\_Rate} = \lambda GDP + \alpha_1 sWBGT + \varepsilon \tag{5}$$

λ is zero in the first method and is non-zero in the second method. Due to the significant differences in the magnitude of these variables (GDP, sWBGT and crime rates), data are first normalized following

$$X = \frac{x - MinValue}{MaxValue - MinValue}. \tag{6}$$

Table 5 The values of α_1, λ, and R^2 in two different methods

Crimes	**Rape**	**Rape (with GDP)**	**MVR**	**MVR (with GDP)**
α_1	0.462	0.461	0.577	0.583
λ	-	0.041 (not significant)	-	-0.315
R^2	**0.45**	**0.45**	**0.52**	**0.72**

The results show that whether including GDP in Eq. 5 does not matter much for Rape as the R^2 value is the same (0.45) and λ = 0.04 in the second method is not significant. On the other hand, after considering the impact of GDP on MVR, the R^2 value becomes 0.72, which is much larger than that with only sWBGT (R^2 = 0.52), indicating that MVR is indeed significantly correlated with GDP. Interestingly, it is shown that λ for MVR is -0.315 in the second method, implying that GDP is negatively correlated to MVR rate. This result indicates that although higher GDP may be accompanied by increases in the exposure of valuable targets and the number of offenders, higher GDP is also often associated with a larger population (hence the rate is reduced) and tends to lead to increased security level in China.

3.3 Future changes in crime rates

Based on the relation between crime rates and sWBGT (see Table 5), monthly outputs from 13 CMIP5 models (see Table 2) are used to estimate future changes in crime rates due to changes in climate variables in Tangshan towards the end of the 21st century (2094−2099). Changes in GDP are not considered here given our focus on the role of climate. As such, we also use the α_1 values obtained by the first method (see Table 5) in Eq. 3 for projection. Note that the two methods yield almost identical α_1 values. Three representative concentration pathways (RCP) are analyzed: RCP2.6, RCP4.5 and RCP8.5. We first examine whether the projected changes in the climatic variables are within the envelope of conditions found today or represent an extrapolation outside the range of current conditions (not shown). As expected, although some model results are outside the range of observations, the ensemble mean is well within the observed range in the current climate.

As shown in Table 6, Rape and MVR experience increases towards the end of 21st century but the increases are highly dependent on the RCPs. The changes are relatively small (lower than 5%) under RCP2.6 and RCP4.5. However, relatively strong increases (about 10%) are observed for Rape under RCP8.5 scenarios. The uncertainties in the projection reflect the model spread.

Table 6 Percentage changes in crime rates towards the end of the 21st century (2094 − 2099).

Crimes	Rape	MVR
RCP2.6	0.9% (3.2%)	0.2% (1.1%)
RCP4.5	3.5% (2.1%)	0.9% (0.8%)
RCP8.5	9.5% (5.3%)	2.6% (2.1%)

*Numbers out of parentheses indicate the mean of 13 global climate model results and numbers in parentheses represent uncertainties due to the spread of climate simulations.

4 Conclusions and discussions

This study demonstrates a strong influence of climate variables including temperature and relative humidity on crime rates using crime statistics and observed climate records collected in Tangshan, China. It is found that temperature is not the only climatic variable that has significant correlations with crime rates; relative humidity is also associated with certain crime types. Seasonality plays an important role, which can be reasonably explained by the Routine Activity theory. Traditional heat stress indices reasonably capture the combined impact of these climate variables on crime rates. Using global climate model simulations, one violent crime (Rape) is estimated to increase by 3.5 ± 2.1% under the RCP4.5 scenario and by 9.5 ± 5.3% under the RCP8.5 scenario; while one property crime (MVR) is estimated to increase by 2.6 ± 2.1% under RCP8.5 at the end of the 21st century due to climate change.

There are a few important implications that need to be pointed out. First and foremost, the influence of socio-economic factors on crime rates is complicated. Here we assume that the influence of socio-economic factors is a linear function of GDP. Using simple regression, we find that GDP significantly correlates with MVR rates and including GDP does make a difference in the regression results. When GDP is considered, the R^2 value increases from 0.52 to 0.72. The influence of GDP on Rape rate is relatively small, and when we include GDP, the results do not change much. Second, we do not differentiate "climate variability" from "climate change" as both are included in monthly variations of climate variables in observational data and climate model results. It is clear from Fig. 1 that the seasonal cycle is a significant factor that induces good correlations between certain crime rates and climatic variables. As a result, future changes in Rape and MVR can be induced by changes in the seasonal cycle and/or the long-term change in the mean climate state. Third, although the focus of our study is on climate variability and change, we acknowledge that fluctuations in temperature, relative humidity, and wind speed at daily scales (i.e., weather variability) are probably more related to fluctuations in crime rates if heat stress were to play an important role. This may be also why the R^2 values in our study are only in the medium level (around 0.2 to 0.5). However, we stress that our analyses of observational data and model simulations are performed at the same time scale (i.e., monthly), and hence the estimations are consistent with the assumptions and the scale selected in our study. Finally, it is important to point out that our study is focused on only one city in China. Consequently, although our results are expected to have policy implications for the city of Tangshan and potentially the greater Hua-bei area of China, whether these results are broadly transferable is a question that needs to be explored in future investigations.

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Appendix

Sensitivity analysis of heat stress indices to changes in temperature and relative humidity

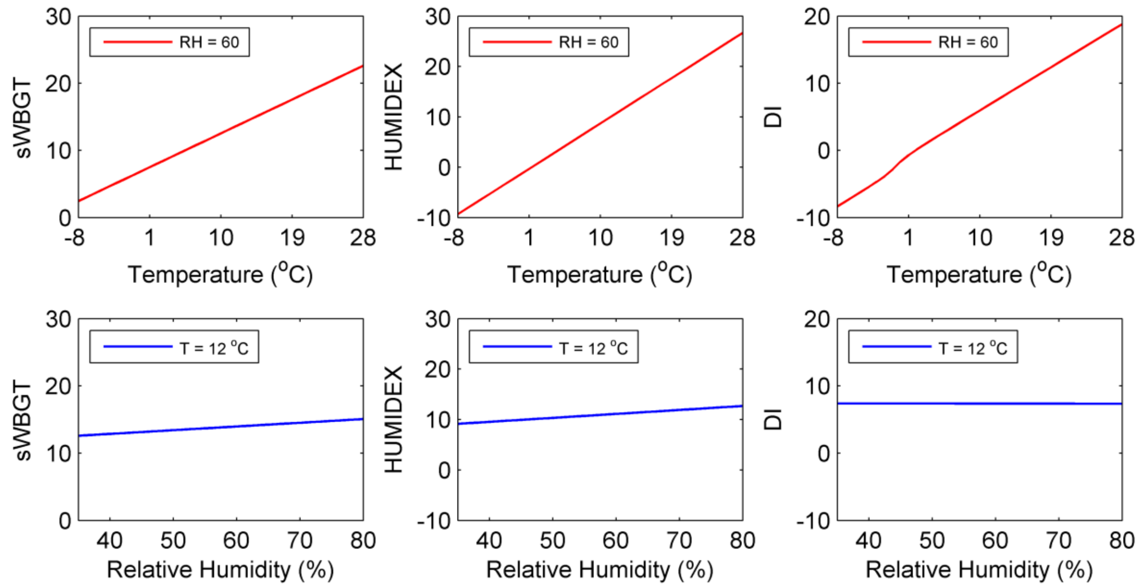

Fig. A1 Sensitivity analysis of heat stress three indices: sWBGT, HUMIDEX and DI.

It can be seen that sWBGT is very sensitive to temperature but less sensitive to RH, which is why the R^2 values for sWBGT are quite similar to those for temperature. Other indices analyzed here including HUMIDEX and DI are also very sensitive to temperature but less sensitive to RH.

Explanation of crime data used in this study

The crime data in China are collected in different ways. The 110 calls data (like 911 calls data in the US) provide one way of estimating the crime incidents. However, this is a voluntary reporting system and the crime types cannot always be confirmed at the moment when people dial 110 for help. Another source of crime data is from the crime statistics database in which the crime type is confirmed. The data used in this paper is from the crime statistics database provided by the Municipal Public Safety Bureau of Tangshan City. All data used in this paper are raw data without any modification. An example of the data format is shown as Table A1. The data used in this study is from the middle column named "Cases confirmed".

Table A1 An example of the crime data record in Tangshan, China

Crimes	March 2014		
	Cases reported	Cases confirmed	Cases solved
…	**…**	**…**	**…**
Homicide	8	8	7
Assault	60	56	45
Rape	23	23	16
Robbery	41	40	10
Burglary	1499	1389	382
MVR	28	27	1
…	**…**	…	**…**
In total	-	--	-