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Original Contribution

Long-Term Ambient Temperature and Externalizing Behaviors in Adolescents

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The climate-violence relationship has been debated for decades, and yet most of the supportive evidence has come from ecological or cross-sectional analyses with very limited long-term exposure data. We conducted an individual-level, longitudinal study to investigate the association between ambient temperature and externalizing behaviors of urban-dwelling adolescents. Participants (n = 1,287) in the Risk Factors for Antisocial Behavior Study, in California, were examined during 2000–2012 (aged 9–18 years) with repeated assessments of their externalizing behaviors (e.g., aggression, delinquency). Ambient temperature data were obtained from the local meteorological information system. In adjusted multilevel models, aggressive behaviors significantly increased with rising average temperatures (per 1°C increment) in the preceding 1, 2, or 3 years (respectively, $\beta = 0.23$, 95% confidence interval (CI): 0.00, 0.46; $\beta = 0.35$, 95% CI: 0.06, 0.63; or $\beta = 0.41$, 95% CI: 0.08, 0.74), equivalent to 1.5–3.0 years of delay in age-related behavioral maturation. These associations were slightly stronger among girls and families of lower socioeconomic status but greatly diminished in neighborhoods with more green space. No significant associations were found with delinquency. Our study provides the first individual-level epidemiologic evidence supporting the adverse association of long-term ambient temperature and aggression. Similar approaches to studying meteorology and violent crime might further inform scientific debates on climate change and collective violence.

adolescence; aggression; ambient temperature; delinquency; environmental exposures; epidemiologic studies; longitudinal studies

Abbreviations: CBCL, Child Behavior Checklist; CI, confidence interval; nSES, neighborhood socioeconomic characteristics; SES, socioeconomic status.

The World Health Organization has declared violence to be a major global public health issue (1). For decades scientists have been studying why violence varies greatly across regions worldwide. Analyses of historical data showed associations between extreme temperature and episodes of social instability and interethnic violence in ancient China and Europe (2). Increased civil conflicts in regions near the equator prompted researchers to study their associations with climate change (especially ambient temperature) in the modern era (3, 4). A large meta-analysis (5) showed that 1-standard-deviation-higher temperature was associated with a 13.2% increase in intergroup conflicts. The hypothesized link between temperature and interpersonal conflict was also suggested by the positive spatial correlation between ambient temperature and crime rates (6), as well as an observed increase in violent crime during the summer relative to cooler months (7). However, with no individual-level longitudinal data, results of these ecological studies and cross-sectional analyses suffer from methodological limitations (e.g., lack of temporality and spatial confounding), making it difficult to draw causal inferences on the relationship between temperature and violence (2).

Violent acts are aggressive in nature. Several social-behavioral theories have been proposed to better understand the temperature-violence relationship. The negative affect escape model suggests that moderately high temperatures increase aggressive behavior, but in extremely high temperatures individuals will escape to minimize discomfort, which leads to reductions in aggression (8). The routine activity theory proposes that social interactions rise in warmer temperatures, which increases the probability of conflict (9). The general aggression model argues that heat increases one's state of hostility and physical arousal, leading to aggression (10).

More recently, the climate aggression and self-control in humans model posited that living in high-temperature environments makes individuals adopt a "fast life" strategy, focus less on the future, and practice less self-control, which are important determinants of aggression and violence (4). Limited data from earlier studies in experimental psychology, despite no consistent relationship between aggressive behavior and short-term temperature (8, 11, 12), were often used to support these previous theories. However, very little individual-level data are available to assess the validity of these theories and very little is known about the long-term exposure effects.

We conducted an individual-level, longitudinal study to investigate the association between long-term temperature and aggressive behaviors in an urban-dwelling population from Southern California. California's winter and spring seasons have been warming up since the mid-1970s (13), and annual average temperatures have risen about 1°F (approximately 0.6°C) over the last century (14). Our secondary aim was to investigate whether the putative adverse temperature-behavioral associations, if shown on aggression, extend to other forms of externalizing psychopathology, such as delinquency.

METHODS

Study design

Participants were drawn from the University of Southern California Risk Factors for Antisocial Behavior twin study. Families were recruited from Los Angeles County and surrounding areas, with the resulting sample reflecting the socioeconomic diversity of populations in the greater Los Angeles area (15). This ongoing cohort study includes over 780 monozygotic and dizygotic twin pairs (same sex and opposite sex) and triplets born in 1990–1995 and aged 9–10 years at study enrollment in 2000. Study protocols were approved by the University of Southern California Institutional Review Board.

The present study used data collected in 2001–2012, with up to 4 longitudinal assessments from childhood/preadolescence to late adolescence. Our analyses included 1,287 subjects (from 640 families), who had at least 2 assessments of aggressive/delinquent behaviors during the ages of 9–18 years, provided residential addresses during follow-up, and were part of complete twin or triplet sets (Figure 1).

Behavioral assessment

Aggressive and delinquent behavior in the 6 months preceding each assessment was measured with the parent-reported version of the Child Behavior Checklist (CBCL) for ages 6–18 years. The high reliability and validity of the CBCL has been reported elsewhere (16). The Aggressive Behavior subscale consists of 20 items regarding both physical (e.g., fights, destroys things, physically attacks others, etc.) and verbal (e.g., argues, teases, screams, etc.) forms of aggression. The Delinquent (Rule-Breaking) Behavior subscale consists of 13 items, including lying, cheating, truancy, stealing, vandalism, arson, and substance use. Items were coded and scored on a 3-point scale (0: not true; 1: sometimes true; and 2: very true/often true) (17, 18), and continuous raw scores were created by summing across items. The CBCL was administered across all waves with a relatively high internal consistency for both aggressive (average Cronbach's α across waves, 0.87) and delinquent ($\alpha = 0.71$) behavior.

Estimation of ambient temperature exposure

Residential location data and geocoding. Residential addresses, prospectively collected through parent-reports at each visit, were sent to the University of Southern California Spatial Sciences Institute for geocoding, which followed standard procedures and returned high-quality geocodes, with successful matching by exact parcel locations or specific street segments for 98.6% of families. The remaining addresses were geocoded satisfactorily with Google Earth based on visual acceptance. The geographic distribution of the subjects' residential locations at baseline is presented in Web Figure 1 (available at https://academic.oup.com/aje).

Residential ambient temperature. Hourly meteorological data from 1990–2012 were obtained from the California Air Resources Board Air Quality and Meteorological Information System. Temperatures recorded at the closest site were assigned to each geocoded residence, with data drawn from a total of 67 meteorological sites. Data was preprocessed to remove abnormal and extreme values following standard practices recommended by the California Air Resources Board. Based on US historical temperature data, hourly values beyond the defined normal intervals (−45°C, 60°C) were removed as abnormal values. Further, based on the empirical distribution, inner fences (defined as the intervals: ($Q1 - 2 \times IQR$, $Q3 + 2 \times IQR$), where Q1 and Q3 are the first and third quartiles, respectively, and IQR is the interquartile range) were specified, and values outside these fences (−15°C, 45°C) were removed as potential outliers. A monthly time-series of average ambient temperature was constructed, and temperature was further aggregated for the periods 1, 2, and 3 years preceding each CBCL assessment. We did not aggregate the air temperature for shorter time periods because this could introduce issues of temporality, given that parents were asked to assess their child's behavior over the preceding 6 months. Additionally, exposures were not examined beyond 3 years because of the concern of overlap between adjacent exposure periods.

Relevant covariate data

A directed acyclic graph (19) was used to select potential covariates (Figure 2) known to predict externalizing behavior and likely influence where people lived (and thus their exposure to ambient temperature). These included age, sex, self-reported ethnicity (white, Hispanic, black, mixed, and other), household socioeconomic status (SES), neighborhood socioeconomic characteristics (nSES), and perceived neighborhood quality. Other covariates evaluated by the directed acyclic graph included neighborhood noise (e.g., traffic density, proximity to freeways and roads), other spatial covariates (e.g., neighborhood green space, relative humidity, and urbanicity), maternal risk factors (e.g., maternal smoking and exposure to secondhand smoke during pregnancy), and early-life risk factors (e.g., birth complications, premature birth, and low birth weight). See Web Appendix 1 for details on how these covariates were measured.

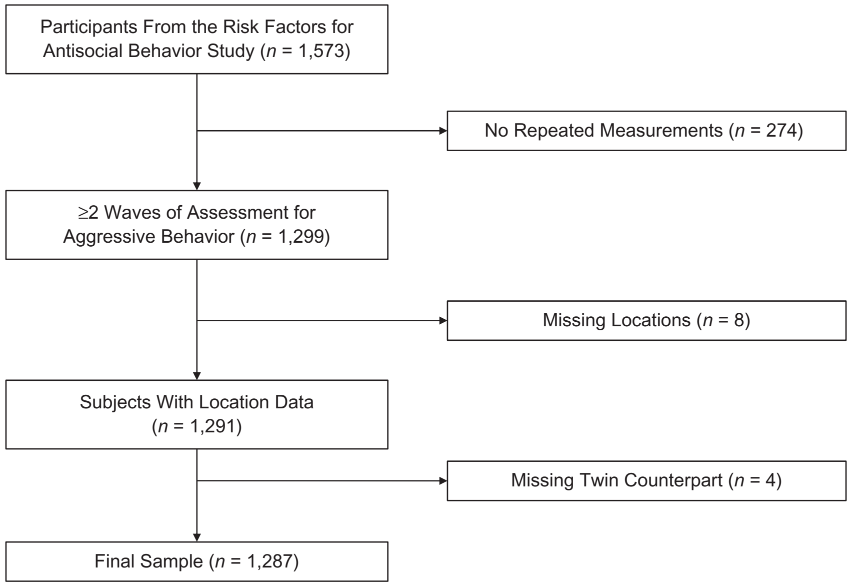

Figure 1. Selection of the study participants for the analysis of ambient temperature and aggressive behavior, Risk Factors for Antisocial Behavior Study, California, 2000–2012.

Statistical analysis

We constructed 3-level mixed-effects models (20) with the restricted maximum likelihood and an unstructured covariance structure, regressing repeated measures of aggressive/delinquent behavior scores on temperature, while accounting for within-family (random intercept and slope (age))/within-individual (random intercept) correlations and potential confounding by multiple covariates (see Web Appendix 2). Additionally, we explored whether the putative associations were driven by temporal versus

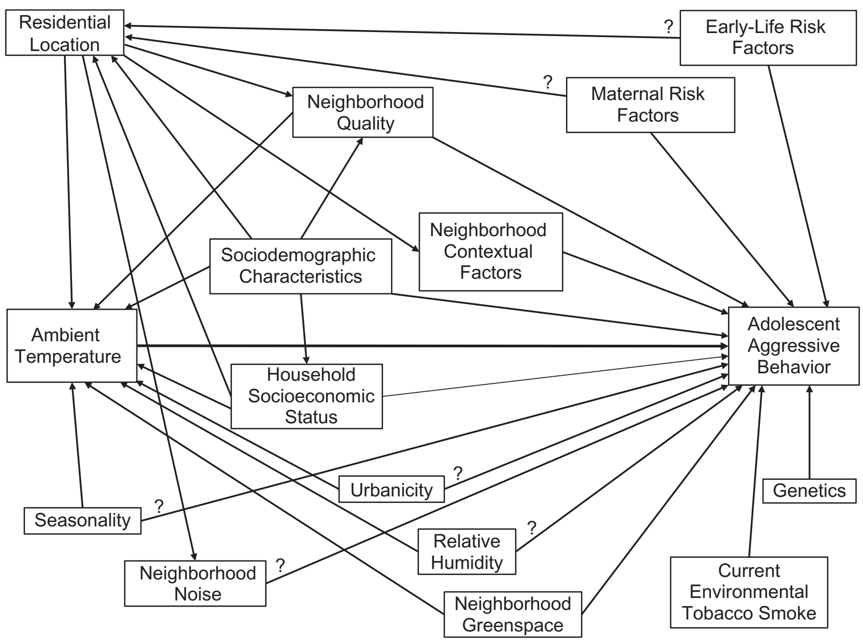

Figure 2. Directed acyclic graph of the relationship between ambient temperature and aggressive behavior, Risk Factors for Antisocial Behavior Study, California, 2000–2012. Pathways designated with a question mark represent structural relationships between the covariate and exposure/outcome that do not have sufficient prior causal knowledge. These covariates were included in sensitivity analyses to see whether effect estimates changed substantially under the assumed structural relationship. Sociodemographic characteristics: age, sex, and race/ethnicity; neighborhood contextual factors: socioeconomic characteristics; maternal risk factors: maternal smoking and exposure to secondhand smoke during pregnancy; early-life risk factors: birth complications, premature birth, and low birth weight.

spatial variation in temperature (see Web Appendix 3). Time-varying covariates included age and georeferenced characteristics of residential locations.

Based on our directed acyclic graph, the following were considered to be confounders and included in fully adjusting models: age, sex, ethnicity, household SES, school nSES, self-perceived neighborhood quality, and neighborhood green space in a 1,000-m buffer surrounding residences. Sensitivity analyses were conducted to evaluate possible confounding by other covariates, such as other spatial covariates, traffic noise, maternal risk factors, and early-life risk factors that were not included in our main models. Therefore, we carried out additional analyses further adjusting for seasonality, urbanicity, relative humidity, traffic density, and proximity to freeways and roads (proxies for traffic noise); maternal smoking and exposure to secondhand smoke during pregnancy (proxies for maternal risk factors); and birth complications, premature birth, and low birth weight (proxies for early-life risk factors). Last, we conducted analyses to explore whether the observed associations could be modified by sex, household SES, and neighborhood green space. For better precision of the resulting stratum-specific estimates, continuous measures of potential modifiers were dichotomized at the median (high vs. low). All analyses were performed using SAS, version 9.4 (SAS Institute, Inc., Cary, North Carolina).

RESULTS

Distributions of temperature and behavior scores

Individuals who were older at baseline (i.e., the first valid CBCL assessment), white or Hispanic, from lower-SES families, from residential and school neighborhoods with lower socioeconomic characteristics, or born to mothers who smoked or were exposed to secondhand smoke during pregnancy were more likely to reside in locations with higher levels of ambient temperature (e.g., in the third and fourth exposure quartiles), compared with their counterparts (Tables 1 and 2). Locations with higher temperature were more likely to be urban areas with lower relative humidity, higher levels of green space, and higher traffic density, and were closer to freeways but further from major roads. Temperature estimates (range of means = 17.48°C–17.53°C; range of standard deviations, 0.76–0.88) were highly correlated with each other (range of Spearman's R, 0.87–0.96) (Web Table 1). According to the intraclass correlation coefficient, 56%–66% of the total variance of long-term ambient temperature occurred between families, suggesting that both geographic and temporal variations contributed to the difference in long-term temperature estimates for our study participants.

Individuals with higher aggressive behavior scores (e.g., in the highest quartile) were younger and more likely, compared with their counterparts, to be boys, to be from households of lower SES, in which parents perceived poorer neighborhood quality, to be born to mothers who smoked or were exposed to secondhand smoke during pregnancy, and to have lower birth weights (Tables 3 and 4). Increased delinquent behaviors (e.g., more delinquencies; Web Table 2) were more common in boys, in Hispanic and black families, in lower-SES households and neighborhoods, in poorer-quality neighborhoods, near limited green-space, and with maternal smoking or exposure to secondhand smoke during pregnancy, compared with their counterparts. According to the intraclass correlation coefficient, 42% of the variability in aggressive and delinquent behavior scores was attributable to between-family differences, with the remaining 58% contributed by within-family differences including changes over time. A statistically significant association between age and externalizing behaviors was consistently found, with decreasing aggression scores by 0.15–0.19 (for 1-, 2-, and 3-years-prior models, respectively, 95% confidence intervals (CIs): −0.22, −0.12; −0.23, −0.13; and −0.21, −0.10;) per year and increasing delinquency scores by 0.04–0.06 (for 1-, 2-, and 3-years-prior models, respectively, 95% CIs: 0.04, 0.08; 0.03, 0.08; and 0.03, 0.08) per year (data not shown).

Associations between estimated temperature and externalizing behavior

In the base model of age-dependent trajectory accounting for within-family/individual correlations, temperature was associated with higher aggressive behavior (1 year: $\beta = 0.26$, 95% CI): 0.03, 0.48; 2 year: $\beta = 0.36$, 95% CI: 0.08, 0.65; 3 year: $\beta = 0.37$, 95% CI: 0.04, 0.69; Table 5). Adjustment for sex, race/ethnicity, household SES, school nSES, perceived neighborhood quality, and green space only modestly decreased the effect estimates, which remained statistically significant (Table 5: adjusted model I), except for 1-year-prior temperature (95% CI: −0.00, 0.46). The slight differences in effect estimates were caused primarily by race, school nSES, and residential green space. The overall results of our adjusted analyses suggest a consistent pattern of higher aggression associated with elevated ambient temperature, with the estimates of the adverse associations (per 1°C increase) equivalent to 1.5–3.0 years of delay in age-related behavioral maturation. In our exploratory analyses examining the association of temperature with temporal versus spatial variation, although we found that baseline temperature increased aggressive behavior, the association was not statistically significant, whereas the association attributable to temporal variation of temperature remained (1 year prior: $\beta = 0.25$, 95% CI: 0.01, 0.49; 2 years prior: $\beta = 0.36$, 95% CI: 0.06, 0.67; 3 years prior: $\beta = 0.47$, 95% CI: 0.11, 0.82; Web Table 3). These results suggest that the observed association may be driven primarily by changes in temperature across time and, to a lesser extent, by between-area differences.

Sensitivity analyses (Table 5) showed no substantial changes to the observed adverse temperature associations after further accounting for proxies of neighborhood noise and other spatial covariates, as well as maternal/early-life risk factors, although a small number of less-precise estimates became marginally significant. Furthermore, adjusting for seasonality resulted in modest changes to the point estimates of 1-, 2-, and 3-years-prior exposures, with the associations with 2- and 3-years-prior average temperature remaining statistically significant (Web Table 4).

In contrast, there were no significant associations between temperature and delinquent behavior across any models (Web Table 5).

Modification of the association between temperature and aggressive behavior

The association of higher aggressive behavior scores with temperature was slightly stronger among girls and families of low (vs. high) SES but was substantially reduced in individuals residing in

Table 1. Distributions of Population Characteristics at Baseline in Relation to Temperature Averaged Over the 1-Year Period Prior to Baseline (n = 1,217)[a], Risk Factors for Antisocial Behavior Study, California, 2000–2012

Characteristic	Quartile of Temperature, °C[b]								*P* Value[c]
	15.50–17.03 (*n* = 303)		17.04–17.43 (*n* = 304)		17.44–17.84 (*n* = 306)		17.85–19.07 (*n* = 304)		
	No.	%	No.	%	No.	%	No.	%	
Sex									0.07
Male	140	23.6	162	27.3	135	22.7	157	26.4	
Female	163	26.2	142	22.8	171	27.5	147	23.6	
Ethnicity									<0.01
White	113	30.5	76	20.5	82	22.1	100	27.0	
Hispanic	68	15.5	119	27.1	131	29.8	122	27.7	
Black	54	36.7	42	28.6	30	20.4	21	14.3	
Mixed	50	24.6	53	26.1	50	24.6	50	24.6	
Other or missing	18	32.1	14	25.0	13	23.2	11	19.6	
Maternal smoking during pregnancy									<0.01
No	263	24.0	267	24.3	283	25.8	284	25.9	
Yes	30	45.5	22	33.3	6	9.1	8	12.1	
Maternal SHS during pregnancy									<0.01
Never	171	23.5	161	22.1	180	24.7	216	29.7	
Hardly ever	62	30.5	42	20.7	53	26.1	46	22.7	
Occasionally or more	60	25.9	86	37.1	56	24.1	30	12.9	
Birth complications									0.22
No	173	24.0	184	25.5	193	26.8	171	23.7	
Yes	113	26.8	102	24.2	93	22.1	113	26.8	
Premature									0.98
No	102	25.1	100	24.6	101	24.9	103	25.4	
Yes	185	24.6	189	25.2	192	25.6	185	24.6	
Low birth weight									0.07
No	162	23.0	169	23.9	194	27.5	181	25.6	
Yes	121	29.1	105	25.2	95	22.8	95	22.8	
Urbanicity									<0.01
Nonurban areas	2	11.8	11	64.7	2	11.8	2	11.8	
Urban areas	301	25.1	293	24.4	304	25.3	302	25.2	

Abbreviation: SHS, secondhand smoke.
[a] Total number of subjects decreases slightly due to missing values.
[b] Quartile 1 median, 16.8; quartile 2 median, 17.3; quartile 3 median, 17.6; quartile 4 median, 18.2.
[c] *P* value for Pearson χ^2 test comparing the distribution of temperature across population characteristics.

neighborhoods with high (vs. low) levels of green space (Web Figure 2). The adverse association of long-term temperature was 2–3 times greater in girls and 1.5–4 times greater in families with low SES levels; however, these differences were not statistically significant (*P* for interaction >0.05). Interestingly, the temperature-aggression associations were largely diminished among individuals residing in high-green-space neighborhoods, whereas the adverse association of long-term ambient temperature was much greater among individuals residing in low-green-space areas, with the observed differences reaching statistical significance (*P* for interaction <0.05).

DISCUSSION

In this large, and to our knowledge likely the first, individual-level longitudinal study on urban-dwelling children and adolescents (aged 9–18 years), we found strong evidence for higher aggressive behavior associated with increasing long-term exposure to ambient temperature at residential locations. The adverse effect estimates were equivalent to the difference in aggression scores between adolescents who are 1.5–3 years apart in age. These associations could not be explained by individual or household sociodemographic factors, nSES characteristics, or perceived

Table 2. Mean Values of Population Characteristics at Baseline in Relation to Temperature Averaged Over the 1-Year Period Prior to Baseline (n = 1,217), Risk Factors for Antisocial Behavior Study, California, 2000–2012

Characteristic	Quartile of Temperature, °C[a]				*P* Value[b]
	15.50–17.03 (n = 303) Mean (SD)	17.04–17.43 (n = 304) Mean (SD)	17.44–17.84 (n = 306) Mean (SD)	17.85–19.07 (n = 304) Mean (SD)	
Age, years	10.4 (1.8)	10.1 (1.6)	10.4 (2.0)	11.3 (2.4)	<0.01
Household SES	44.3 (11.4)	43.4 (10.8)	40.1 (11.7)	42.1 (12.4)	<0.01
Residential nSES	0.1 (1.0)	0.0 (1.1)	−0.2 (0.8)	0.0 (1.0)	<0.01
School nSES	0.2 (1.2)	−0.1 (1.0)	−0.2 (0.7)	−0.1 (0.9)	<0.01
Neighborhood quality[c]	26.9 (8.6)	26.7 (9.8)	28.0 (11.2)	27.3 (9.7)	0.31
Neighborhood green space ($\times 10^{-2}$)	31.9 (8.0)	32.2 (7.6)	31.5 (7.7)	33.3 (8.0)	0.03
Proximity to freeways, m	1.1 (0.9)	1.2 (0.9)	0.8 (0.7)	0.9 (0.7)	<0.01
Proximity to roads, m	0.9 (0.8)	0.9 (0.7)	1.0 (0.7)	1.2 (0.8)	<0.01
Traffic density ($\times 10^{-2}$)	96.5 (167.5)	79.5 (109.5)	132.6 (219.6)	115.8 (208.5)	<0.01
Relative humidity, %	64.0 (9.3)	64.1 (7.2)	63.1 (6.8)	59.6 (5.8)	<0.01

Abbreviations: nSES, neighborhood socioeconomic characteristics; SD, standard deviation; SES, socioeconomic status.

[a] Quartile 1 median, 16.8; quartile 2 median, 17.3; quartile 3 median, 17.6; quartile 4 median, 18.2.

[b] *P* value for analysis of variance test comparing means of population characteristics across quartile of temperature.

[c] Neighborhood quality was measured using a parent-reported questionnaire regarding criminal and gang related activities, unemployment, vandalism, substance use, etc., with higher scores indicating a more negative perception of neighborhood quality.

neighborhood quality, and remained robust with adjustment for local spatial characteristics, maternal risk factors, and early-life risk factors. The observed adverse association with aggressive behavior was slightly stronger among girls and individuals from low-SES households, and it was substantially diminished in those in high-green-space neighborhoods.

Our study findings, if replicated by others, will have important public health implications. In our study, an increment of 1°C in ambient temperature across multiple time scales was associated with a 0.23–0.41-point increase in aggression scores. These small individual-level differences can translate to a significant population impact (21). According to Achenbach and Rescorla (18), a CBCL raw score that is 2 standard deviations above the mean represents a clinically significant level of aggressive behavior. In our sample, mean raw scores were 4.86 (standard deviation, 5.03), similar to previous reports (22). Assuming this mean score for California adolescents (n = 3.5 million) at present (23), we estimated that 78,947 would present aggressive behavior scores above the clinical range. However, a 0.32-points-higher aggression score (midpoint between 0.23 and 0.41) due to elevated long-term ambient temperature would shift the population mean to 5.18, resulting in an additional 4,787 clinical cases (a 6.1% increase) in California adolescents alone. With its annual average temperature projected to increase by another 4°F (approximately 2.2°C) this century (14), California may become both warmer and more socially disordered in the next few decades if the rise of ambient temperature continues without effective interventions.

The observed lack of association with delinquency suggested the relationship between temperature and externalizing psychopathology may be more specific to the aggressive phenotype. Considerable heterogeneity in externalizing behaviors is well-documented (24), and previous studies with factor analyses have consistently indicated that there are 2 distinct behavioral phenotypes: an aggressive/oppositional factor and a nonaggressive/delinquent factor (25). Aggressive behavior incorporates physical aggression (e.g., hitting, bullying, fighting), as well as aspects of an aggressive personality (e.g., arguing, hot-tempered, boasting), while delinquency refers to behaviors that break societal rules (e.g., truancy, stealing, vandalism, drug use) and tend to be committed with other peers (24). Although aggressive and delinquent behaviors are correlated and co-occur at high rates, evidence suggests possible genetic and environmental etiological distinctions between them (26). For instance, studies on personality traits have found that affective dysregulation/negative affectivity is primarily specific to aggressive behavior (27, 28). Neuroimaging studies have shown that abnormalities in the brain regions (e.g., prefrontal cortex, amygdala, and anterior cingulate cortex) and networks involved in emotion regulation may result in an increased propensity for aggression and violence (29). Put together, these social-neurosciences data, along with our novel findings, point to the need for future studies to investigate vulnerable brain regions and neural networks in response to increased ambient temperature.

In our study, we found that the observed adverse association between temperature and aggressive behavior in the main analyses (Table 5) were greatly reduced in participants living in neighborhoods with high levels of green space (Web Figure 2). The mechanisms underlying the strong moderation by green space are unclear, but a few plausible explanations could be proposed. First, green space may directly decrease ambient temperatures by providing shade and preventing the air from warming, by decreasing resistance to air flow, and by promoting cooling by convection and by evapotranspiration (30). Second, green space may cut the air-pollution exposure effect if the adverse-temperature effect, in part, might result from poor air quality with increased ozone and fine particles known to be sensitive to overall climate change (31). However, epidemiologic evidence linking air-pollution exposure with aggressive behaviors remains elusive, and the outdoor levels

Table 3. Distributions of Population Characteristics at Baseline in Relation to Baseline Aggressive Behavior (n = 1,217)[a], Risk Factors for Antisocial Behavior Study, California, 2000–2012

Characteristic	Quartile of Aggressive Behavior[b]								P Value[c]
	0.0–1.0 (n = 293)		2.0–4.0 (n = 365)		4.2–7.4 (n = 242)		8.0–39.0 (n = 307)		
	No.	%	No.	%	No.	%	No.	%	
Sex									<0.01
Male	121	20.4	171	28.8	133	22.4	169	28.5	
Female	172	27.6	194	31.1	119	19.1	138	22.2	
Ethnicity									0.45
White	96	25.9	106	28.6	74	20.0	95	25.6	
Hispanic	100	22.7	134	30.5	91	20.7	115	26.1	
Black	26	17.7	48	32.7	35	23.8	38	25.9	
Mixed	56	27.6	62	30.5	35	17.2	50	24.6	
Other or missing	15	26.8	15	26.8	17	30.4	9	16.1	
Maternal smoking during pregnancy									<0.01
No	266	24.3	338	30.8	230	21.0	263	24.0	
Yes	6	9.1	11	16.7	16	24.2	33	50.0	
Maternal SHS during pregnancy									<0.01
Never	194	26.7	235	32.3	130	17.9	169	23.2	
Hardly ever	38	18.7	65	32.0	62	30.5	38	18.7	
Occasionally or more	43	18.5	49	21.1	51	22.0	89	38.4	
Birth complications									0.06
No	181	25.1	222	30.8	154	21.4	164	22.8	
Yes	89	21.1	122	29.0	85	20.2	125	29.7	
Premature									0.40
No	93	22.9	126	31.0	93	22.9	94	23.2	
Yes	181	24.1	220	29.3	149	19.8	201	26.8	
Low birth weight									0.04
No	174	24.7	224	31.7	148	21.0	160	22.7	
Yes	94	22.6	110	26.4	87	20.9	125	30.1	
Urbanicity									0.89
Nonurban areas	5	29.4	4	23.5	3	17.7	5	29.4	
Urban areas	288	24.0	361	30.1	249	20.8	302	25.2	

Abbreviation: SHS, secondhand smoke.
[a] Total number of subjects decreases slightly due to missing values.
[b] Quartile 1 median, 0; quartile 2 median, 3; quartile 3 median, 6; quartile 4 median, 11.
[c] P value for Pearson χ^2 test comparing the distribution of aggressive behavior across population characteristics.

of fine particles had been declining in Southern California (32) despite rising ambient temperatures since 2000. Third, exposure to ambient temperature and neighborhood green space may act on common pathways jointly influencing the human brain. The natural environment (including green space) can beneficially activate the prefrontal cortex (33) and can decrease negative affect and increase positive affect (34), which may counteract the influence of temperature. Last, green space in urban environments may help preserve the microbial biodiversity needed to optimize brain health and development (35); therefore, adolescent brains may be more resilient to high temperatures if they reside in areas with higher levels of green space. Future studies are needed to examine these possible mechanisms, and the resulting new knowledge may contribute to developing neurobiologically based adaptation and intervention strategies to mitigate the influence of temperature on growing urban-dwelling populations (30).

Epidemiologic studies with individual-level data collected from community-based samples may provide a useful population context to reassess previous theories on the temperature-violence relationship, as illustrated below. First, the negative affect escape model was developed to explain an assumed curvilinear relationship between short-term temperature and aggression (8), which

Table 4. Mean Values of Population Characteristics at Baseline in Relation to Baseline Aggressive Behavior ($n = 1{,}217$), Risk Factors for Antisocial Behavior Study, California, 2000–2012

Characteristic	Quartile of Aggressive Behavior[a]				P Value[b]
	0.0–1.0 (*n* = 293) Mean (SD)	2.0–4.0 (*n* = 365) Mean (SD)	4.2–7.4 (*n* = 242) Mean (SD)	8.0–39.0 (*n* = 307) Mean (SD)	
Age, years	11.0 (2.3)	10.5 (2.0)	10.5 (2.0)	10.3 (1.8)	<0.01
Household SES	43.9 (11.5)	42.9 (11.8)	41.5 (12.0)	41.5 (11.4)	0.04
Residential nSES	0.1 (0.9)	−0.1 (0.9)	0.0 (1.1)	−0.1 (1.1)	0.15
School nSES	0.0 (0.9)	−0.0 (1.0)	−0.0 (1.0)	−0.1 (1.0)	0.41
Neighborhood quality[c]	25.4 (8.7)	27.3 (10.2)	28.2 (10.3)	28.1 (9.9)	<0.01
Neighborhood green space ($\times 10^{-2}$)	32.8 (7.7)	32.0 (7.7)	32.2 (8.4)	32.0 (7.6)	0.59
Proximity to freeways, m	1.0 (0.9)	0.9 (0.8)	1.0 (0.8)	1.0 (0.8)	0.56
Proximity to roads, m	1.0 (0.8)	1.0 (0.7)	1.0 (0.8)	1.0 (0.7)	0.85
Traffic density ($\times 10^{-2}$)	97.5 (152.0)	106.6 (191.9)	99.3 (173.3)	119.4 (203.7)	0.45
Relative humidity, %	62.2 (7.6)	62.7 (7.2)	63.3 (7.8)	62.8 (8.0)	0.47

Abbreviations: nSES, neighborhood socioeconomic characteristics; SD, standard deviation; SES, socioeconomic status.

[a] Quartile 1 median, 0; quartile 2 median, 3; quartile 3 median, 6; quartile 4 median, 11.

[b] *P* value for analysis of variance test comparing means of population characteristics across quartile of aggressive behavior.

[c] Neighborhood quality was measured using a parent-reported questionnaire regarding criminal and gang related activities, unemployment, vandalism, substance use, etc., with higher scores indicating a more negative perception of neighborhood quality.

Table 5. Associations Between Temperature[a] During Previous Years and Aggressive Behavior, Risk Factors for Antisocial Behavior Study, 2000–2012

Model	1 Year Prior *n* = 1,217		2 Years Prior *n* = 1,208		3 Years Prior *n* = 1,204	
	β	95% CI	β	95% CI	β	95% CI
Base[b]	0.26[c]	−0.03, 0.48	0.36[c]	0.08, 0.65	0.37[c]	0.04, 0.69
Adjusted I[d]	0.23	−0.00, 0.46	0.35[c]	0.06, 0.63	0.41[c]	0.08, 0.74
Sensitivity analyses[e]						
With proximity to freeways	0.24[c]	−0.01, 0.46	0.37[c]	0.08, 0.65	0.41[c]	0.08, 0.74
With proximity to roads	0.24[c]	−0.01, 0.47	0.37[c]	0.08, 0.65	0.43[c]	0.10, 0.77
With traffic density in 300-m area	0.23	−0.00, 0.45	0.35[c]	0.06, 0.63	0.41[c]	0.08, 0.74
With relative humidity	0.23	−0.01, 0.46	0.34[c]	0.05, 0.63	0.40[c]	0.07, 0.73
With urbanicity	0.23	−0.00, 0.46	0.35[c]	0.07, 0.64	0.42[c]	0.09, 0.75
With maternal smoking during pregnancy	0.24[c]	−0.00, 0.47	0.36[c]	0.07, 0.64	0.41[c]	0.08, 0.75
With maternal SHS exposure during pregnancy[f]	0.26[c]	−0.02, 0.50	0.41[c]	0.12, 0.70	0.41[c]	0.07, 0.75
With birth complications	0.25[c]	−0.02, 0.49	0.35[c]	0.06, 0.64	0.41[c]	0.07, 0.75
With premature birth	0.27[c]	−0.04, 0.51	0.39[c]	0.10, 0.68	0.45[c]	0.11, 0.79
With low birth weight	0.22	−0.02, 0.46	0.34[c]	0.05, 0.63	0.39[c]	0.05, 0.73

Abbreviations: CI, confidence interval; SHS, secondhand smoke.

[a] Results of the multilevel mixed-effects models, with regression coefficient (β) and 95% confidence interval expressed as the difference in aggression scores per 1°C increase in average long-term temperature.

[b] Accounting for within-family (random intercept and slope (age))/within-individual (random intercept) correlations in the model of age-dependent trajectory.

[c] $P < 0.05$ (Wald test).

[d] Model adjusted for age, sex, ethnicity, household socioeconomic status, perceived residential neighborhood quality, school neighborhood socioeconomic characteristics, and neighborhood green space in 1,000-m buffer surrounding residences.

[e] Adjusted I with the additional adjustment of the listed covariate. Total number of subjects decreases slightly due to missing values.

[f] Excluding subjects whose mothers smoked during pregnancy.

was not compatible with our study on long-term exposures. Second, our study showed that the association of higher aggressive behavior scores with temperature was greatly decreased in neighborhoods with high levels of green space, which may promote social cohesion and interaction (36). This observation, therefore, did not provide strong support for the routine activity theory (9), which would have predicted that the temperature-aggression association would become stronger in areas with increased green space. Third, the climate aggression and self-control in humans model, which emphasizes the critical role of increased impulsivity and less self-control in human behavior responding to climate with hot temperatures (4), was not consistent with our observation of a more specific association between temperature and aggression. In previous studies on predictors of externalizing behaviors, diminished behavioral control was related primarily to nonaggressive/delinquent behavior (27), which was not associated with increased temperature in our study. Here, we offer a neurotoxicological framework as an alternative to the prevailing social-behavioral theories to explain the temperature-aggression/violence associations (37). Long-term exposure to increased temperature is conceptualized as part of the environmental stressors that may target specific human brain networks, inducing stress responses (38) that compromise the neural circuitry of emotion regulation and predispose the affected individuals to aggressive behaviors. This neurotoxicological framework extends the generalized aggression model, which argues that extreme heat represents one situational factor that may put individuals in a more physically aroused state, leading to aggressive behavior (39). However, our new conceptual framework could support the modulation by neurotrophic environments (e.g., neighborhood green space) and also account for population heterogeneity (e.g., increased vulnerability in girls; interacting with social adversities resulting from low SES) in environmental stress responses testable in both human studies and experimental models.

A few study limitations should be recognized. First, we used the parent-reported CBCL to assess externalizing behavior, and parents may not be aware of their children's behaviors outside of the home. Although the Youth Self-Report of the CBCL was available, it is not validated for ages ≤10 years and was only administered after ages 14–15 years, making it unsuitable for our longitudinal analyses over ages 9–18 years. Additionally, this instrument may not perform as well in children with certain mental health conditions (e.g., autism spectrum disorder). Second, our study examined long-term (1- to 3-year) average temperatures, which only captured the meteorological variation reflecting both the microclimate difference in ambient temperature and its temporal change over 12 years. Such local-scale difference in temperature could be influenced by humidity, but the adverse association remained robust after controlling for humidity (Table 5). Future studies with individual-level data are needed to examine the associations of ambient temperature and aggression across multiple geographic regions. However, our study findings have strong internal validity, because the revealed associations were less subject to confounding by local and political context, an important concern raised in previous critiques (40). Third, our exposure assessment relied on estimates of ambient temperature, and we did not measure indoor temperature or monitor the time-activities across various indoor-outdoor microenvironments. Therefore, the estimated exposure levels may not reflect the true air temperatures experienced by each individual. However, it is important to note that high levels of correlation (approximate Pearson's $r = 0.90$) have been found between average indoor temperature and outdoor temperature recorded at the local airport in previous studies (41) with an extended period (approximately 1 year) of monitoring data collected in cities with latitudes similar to Los Angeles (34.05°N). If the expected nondifferential measurement errors/misclassification had occurred, it would likely have attenuated the observed associations. Fourth, we could not completely rule out the possibility of unmeasured or residual confounding by other environmental determinants of externalizing behaviors. However, we conducted several sensitivity analyses (Table 5), and the temperature-aggression associations persisted after statistical adjustment for multiple spatial covariates correlated with the exposure. Also, the lack of association between temperature and delinquency implied the specificity of the relationship between temperature and aggressive behaviors was less likely a mere reflection of residual confounding by other environmental factors. Last, although our analyses revealed a possibly stronger association among families of low SES, we could not further explore potential effect modification by other home characteristics (e.g., use of air conditioning) because such data were not available.

In conclusion, this longitudinal cohort study provides the first individual-level evidence that residing in locations with higher ambient temperatures might increase aggressive behavior among urban-dwelling adolescents. These adverse associations were almost absent in places with high levels of neighborhood green space. Future studies are needed to replicate our findings and identify mechanisms linking ambient temperature with higher levels of aggressive behaviors. Similar epidemiologic approaches to studying violent crimes may further inform the scientific debates on climate changes and violence.

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REFERENCES

1. Krug EG, Mercy JA, Dahlberg LL, et al. The world report on violence and health. *Lancet*. 2002;360(9339):1083–1088.
2. Burke M, Hsiang SM, Miguel E. Climate and conflict. *Annu Rev Econ*. 2015;7:577–617.
3. Burke MB, Miguel E, Satyanath S, et al. Warming increases the risk of civil war in Africa. *Proc Natl Acad Sci USA*. 2009;106(49):20670–20674.
4. Van Lange PAM, Rinderu MI, Bushman BJ. Aggression and violence around the world: a model of CLimate, Aggression, and Self-control in Humans (CLASH). *Behav Brain Sci*. 2017;40:e75.
5. Hsiang SM, Burke M, Miguel E. Quantifying the influence of climate on human conflict. *Science*. 2013;341(6151):1235367.
6. Ranson M. Crime, weather, and climate change. *J Environ Econ Manage*. 2014;67(3):274–302.
7. Hipp JR, Curran PJ, Bollen KA, et al. Crimes of opportunity or crimes of emotion? Testing two explanations of seasonal change in crime. *Soc Forces*. 2004;82(4):1333–1372.
8. Baron RA, Bell PA. Aggression and heat: the influence of ambient temperature, negative affect, and a cooling drink on physical aggression. *J Pers Soc Psychol*. 1976;33(3):245–255.
9. Cohen LE, Felson M. Social change and crime rate trends: a routine activity approach. *Am Sociol Rev*. 1979;44(4):588–608.
10. Anderson CA, Deuser WE, DeNeve KM. Hot temperatures, hostile affect, hostile cognition, and arousal: tests of a general model of affective aggression. *Pers Soc Psychol Bull*. 1995;21(5):434–448.
11. Baron RA. Aggression as a function of ambient temperature and prior anger arousal. *J Pers Soc Psychol*. 1972;21(2):183–189.
12. Baron RA, Bell PA. Aggression and heat: mediating effects of prior provocation and exposure to an aggressive model. *J Pers Soc Psychol*. 1975;31(5):825–832.
13. Cayan DR, Dettinger MD, Kammerdiener SA, et al. Changes in the onset of spring in the western United States. *Bull Am Meteorol Soc*. 2001;82(3):399–415.
14. Cayan D. Climate Change—What Should Southern California Prepare for? In: *Climate Change and the Future of Southern California*. Los Angeles, CA: Southern California Association of Governments; 2009:10–21. http://scag.ca.gov/Documents/ClimateChange_Full_lores.pdf. Accessed June 1, 2016.
15. Baker LA, Tuvblad C, Wang P, et al. The Southern California Twin Register at the University of Southern California: III. *Twin Res Hum Genet*. 2013;16(1):336–343.
16. Achenbach TM. *Achenbach System of Empirically Based Assessment (ASEBA): Development, Findings, Theory, and Applications*. Burlington, VT: University of Vermont, Research Center of Children, Youth & Families; 2009.
17. Achenbach TM. *Manual for the Child Behavior Checklist/4–18 and 1991 Profile*. Burlington, VT: Department of Psychiatry, University of Vermont; 1991.
18. Achenbach TM, Rescorla L. *ASEBA School-Age Forms and Profiles*. Burlington, VT: University of Vermont, Research Center of Children, Youth & Families; 2001.
19. Howards PP, Schisterman EF, Poole C, et al. "Toward a clearer definition of confounding" revisited with directed acyclic graphs. *Am J Epidemiol*. 2012;176(6):506–511.
20. Diggle P, Heagerty P, Liang K-Y, et al. *Analysis of Longitudinal Data*. 2nd ed. New York, NY: Oxford University Press; 2002.
21. Weiss B. Neurobehavioral toxicity as a basis for risk assessment. *Trends Pharmacol Sci*. 1988;9(2):59–62.
22. Crijnen AA, Achenbach TM, Verhulst FC. Problems reported by parents of children in multiple cultures: the Child Behavior Checklist syndrome constructs. *Am J Psychiatry*. 1999;156(4):569–574.
23. Office of Women's Health. California Adolescent Health 2009. Sacramento, CA: California Department of Health Care Services and California Department of Public Health; 2009. http://www.dhcs.ca.gov/dataandstats/reports/Documents/OWHReports/AdolHealthReport09.pdf. Accessed October 28, 2015.
24. Eley TC, Lichtenstein P, Moffitt TE. A longitudinal behavioral genetic analysis of the etiology of aggressive and nonaggressive antisocial behavior. *Dev Psychopathol*. 2003;15(2):383–402.
25. Burt SA, Neiderhiser JM. Aggressive versus nonaggressive antisocial behavior: distinctive etiological moderation by age. *Dev Psychol*. 2009;45(4):1164–1176.
26. Niv S, Tuvblad C, Raine A, et al. Aggression and rule-breaking: heritability and stability of antisocial behavior problems in childhood and adolescence. *J Crim Justice*. 2013;41(5):285–291.
27. Burt SA, Donnellan MB. Personality correlates of aggressive and non-aggressive antisocial behavior. *Pers Individ Dif*. 2008;44(1):53–63.
28. Burt SA, Larson CL. Differential affective responses in those with aggressive versus non-aggressive antisocial behaviors. *Pers Individ Dif*. 2007;43(6):1481–1492.
29. Davidson RJ, Putnam KM, Larson CL. Dysfunction in the neural circuitry of emotion regulation—a possible prelude to violence. *Science*. 2000;289(5479):591–594.
30. Bowler DE, Buyung-Ali L, Knight TM, et al. Urban greening to cool towns and cities: a systematic review of the empirical evidence. *Landsc Urban Plan*. 2010;97(3):147–155.
31. Kleeman MJ. A preliminary assessment of the sensitivity of air quality in California to global change. *Clim Change*. 2008;87(suppl 1):273–292.
32. Lurmann F, Avol E, Gilliland F. Emissions reduction policies and recent trends in Southern California's ambient air quality. *J Air Waste Manage Assoc*. 2015;65(3):324–335.
33. Bratman GN, Hamilton JP, Hahn KS, et al. Nature experience reduces rumination and subgenual prefrontal cortex activation. *Proc Natl Acad Sci USA*. 2015;112(28):8567–8572.
34. Bratman GN, Daily GC, Levy BJ, et al. The benefits of nature experience: improved affect and cognition. *Landsc Urban Plan*. 2015;138:41–50.
35. Rook GA. Regulation of the immune system by biodiversity from the natural environment: an ecosystem service essential to health. *Proc Natl Acad Sci USA*. 2013;110(46):18360–18367.
36. Bowler DE, Buyung-Ali LM, Knight TM, et al. A systematic review of evidence for the added benefits to health of exposure to natural environments. *BMC Public Health*. 2010;10:456.

37. Barbaro N, Shackelford TK. Dimensions of environmental risk are unique theoretical constructs. *Behav Brain Sci*. 2017;40:e76.
38. Heuser I, Lammers C-H. Stress and the brain. *Neurobiol Aging*. 2003;24(suppl 1):S69–S76.
39. DeWall CN, Anderson CA, Bushman BJ. The general aggression model: theoretical extensions to violence. *Psychol Violence*. 2011;1(3):245–258.
40. Raleigh C, Linke A, O'Loughlin J. Commentary: extreme temperatures and violence. *Nat Clim Change*. 2014;4(2): 76–77.
41. Nguyen JL, Schwartz J, Dockery DW. The relationship between indoor and outdoor temperature, apparent temperature, relative humidity, and absolute humidity. *Indoor Air*. 2014;24(1):103–112.