Heat-related Emergency Hospitalizations for Respiratory Diseases in the Medicare Population

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***Rationale*: The heat-related risk of hospitalization for respiratory diseases among the elderly has not been quantified in the United States on a national scale. With climate change predictions of more frequent and more intense heat waves, it is of paramount importance to quantify the health risks related to heat, especially for the most vulnerable.**
***Objectives*: To estimate the risk of hospitalization for respiratory diseases associated with outdoor heat in the U.S. elderly.**
***Methods*: An observational study of approximately 12.5 million Medicare beneficiaries in 213 United States counties, January 1, 1999 to December 31, 2008. We estimate a national average relative risk of hospitalization for each 10°F (5.6°C) increase in daily outdoor temperature using Bayesian hierarchical models.**
***Measurements and Main Results*: We obtained daily county-level rates of Medicare emergency respiratory hospitalizations (International Classification of Diseases, Ninth Revision, 464–466, 480–487, 490–492) in 213 U.S. counties from 1999 through 2008. Overall, each 10°F increase in daily temperature was associated with a 4.3% increase in same-day emergency hospitalizations for respiratory diseases (95% posterior interval, 3.8, 4.8%). Counties' relative risks were significantly higher in counties with cooler average summer temperatures.**
***Conclusions*: We found strong evidence of an association between outdoor heat and respiratory hospitalizations in the largest population of elderly studied to date. Given projections of increasing temperatures from climate change and the increasing global prevalence of chronic pulmonary disease, the relationship between heat and respiratory morbidity is a growing concern.**

AT A GLANCE COMMENTARY

Scientific Knowledge on the Subject

Although outdoor heat is known to increase rates of respiratory mortality in the elderly, the relationship between heat and respiratory morbidity has been little studied in the United States at a national level.

What This Study Adds to the Field

We investigate the relationship between outdoor temperature and emergency respiratory hospitalizations in the largest population of elderly studied to date: approximately 12.5 million Medicare beneficiaries in 213 urban United States counties. We find a clear and consistent increase in respiratory hospitalizations with increasing outdoor temperature across the United States.

Keywords: chronic obstructive pulmonary disease; hospitalization; hot temperature; respiratory tract infections; weather

Outdoor heat can cause spikes in respiratory deaths (1, 2), but considerably less is known about heat's impacts on respiratory morbidity. Given that: (*1*) climate change will increase exposure to extreme heat (3), (*2*) the prevalence of chronic respiratory diseases is increasing (4), and (*3*) the elderly will likely be most affected by heat-related problems (5), there is a pressing need to improve our understanding of respiratory heat effects among the elderly for both fatal and nonfatal outcomes.

There are two major limitations to current research on the relationship between heat and respiratory hospitalizations. First, this relationship has not been adequately studied worldwide to confidently identify a consistent link between respiratory hospitalizations and heat. The few studies that have investigated heat and respiratory hospitalizations have found somewhat conflicting results (6). For example, studies of Brisbane, Australia (7, 8) and Athens, Greece (9) found hospitalization rates decreased slightly during hot weather, whereas studies of California (10, 11), New York (12, 13), and 12 European cities (14) found respiratory hospitalizations increased with heat. Although a metaanalysis of current research estimated a positive relationship between heat and respiratory hospitalizations across all studies, it lacked sufficient power to distinguish this effect from a null effect (6).

Second, outside of California and New York, little research has been done in the United States. U.S. studies of heat and respiratory morbidity have been limited to single cities (12, 15) or single states (California [10, 11, 16], New York [13]) or were retrospective studies of single heat waves (17–19). Worldwide, large heterogeneity exists between temperature-morbidity studies from different locations (6, 20). Therefore, although the

(*Received in original form November 2, 2012; accepted in final form February 25, 2013*)

Supported by the National Institute for Environmental Health Sciences grants R01ES019560 and R21ES020152 (G.B.A., F.D., Y.W., M.L.B., R.D.P.), R01ES012054 (F.D., Y.W.), and R01ES015028 and R21ES021427 (M.L.B.); U.S. Environmental Protection Agency grants RD-83479801 (F.D., Y.W., M.L.B.) and R834894 (F.D., Y.W.); National Institutes of Health grant K23ES016819 and P01ES018176 (M.C.M.); and a grant from the Health Effects Institute (F.D., Y.W.).

Although the research described in this article has been funded in part by the U.S. Environmental Protection Agency, it has not been subjected to the agency's required peer and policy review and therefore does not necessarily reflect the views of the agency, and no official endorsement should be inferred. The contents of this article do not necessarily reflect the views and policies of the Health Effects Institute.

Author Contributions: Study concept and design: G.B.A., F.D., M.L.B., R.D.P. Acquisition of data: F.D., Y.W., R.D.P. Analysis or interpretation of data: G.B.A., F.D., M.C.M., M.L.B., R.D.P. Drafting of manuscript: G.B.A., F.D., Y.W., M.C.M., M.L.B., R.D.P. Critical revision of the manuscript for important intellectual content: G.B.A., F.D., Y.W., M.C.M., M.L.B., R.D.P. Statistical analysis: G.B.A., F.D., M.L.B., R.D.P. Obtained funding: F.D., M.L.B., R.D.P. Administrative, technical, or material support: F.D., R.D.P. Study supervision: F.D., R.D.P.

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This article has an online supplement, which is accessible from this issue's table of contents at www.atsjournals.org

Am J Respir Crit Care Med Vol 187, Iss. 10, pp 1098–1103, May 15, 2013

Originally Published in Press as DOI: 10.1164/rccm.201211-1969OC on March 14, 2013
Internet address: www.atsjournals.org

relationship between heat and respiratory hospitalizations has been well studied in California and New York (10, 11, 13), temperature effect estimates based only on these states are unlikely to be representative of national U.S. effects.

In this study we estimate the risk of emergency hospital admissions for respiratory diseases associated with outdoor heat exposure for approximately 12 million elderly individuals in 213 U.S. urban counties from 1999 to 2008. We investigate whether this association is confounded by exposure to air pollution or modified by individual (age, sex) or county (average summer temperature) characteristics. This is, to date, the largest elderly population investigated to estimate acute heat-related risks of respiratory hospitalizations and the first national study of these risks in the United States.

METHODS

This study used a dataset created for environmental health research by aggregating Medicare hospitalization rates by county and linking them with ambient air pollution and temperature data (21). This dataset includes daily hospitalizations for 1999 to 2008 for 221 U.S. counties, based on Medicare inpatient claims for all fee-for-service Medicare beneficiaries 65 years and older. Hospitalization rates are aggregated by sex, age (65–74 yr, 75–84 yr, ≥85 yr), and medical condition (chronic obstructive pulmonary disease [COPD], International Classification of Diseases, Ninth Revision, Clinical Modification principal discharge diagnosis codes 490–492; respiratory tract infections: 464–466, 480–487). The dataset includes measurements of weather (temperature, dew point temperature) and air pollution (tropospheric ozone [O_3], particulate matter with aerodynamic diameter ≤10 μm [PM_{10}] and ≤2.5 μm [$PM_{2.5}$]). Analysis was limited to the 213 study counties within the contiguous 48 states and, to ensure adequate information to estimate model parameters and for convergence of model-fitting algorithms, with 5 or more years of weather data. Further data details are in the online supplement.

We modeled the relationship between daily hospitalization rate and outdoor heat for May to September within each county using an overdispersed Poisson generalized linear model (1, 2). Models controlled for day of week and dew point temperature (adjusted for temperature to limit collinearity). Models adjusted for long-term and seasonal trends in county hospitalization rates and temperature using smooth spline functions of time (1). Further details on model development are in the online supplement.

For each county, we estimated the percentage increase in daily emergency respiratory hospitalizations associated with each 10°F (5.6°C) increase in daily average temperature (10, 11). To estimate the national average association between heat and respiratory hospitalizations, we combined county-level estimates with a two-stage Bayesian hierarchical model, incorporating variation within and between county-level estimates (22). We estimated national average associations separately for COPD and respiratory tract infections and jointly for both causes (total respiratory hospitalizations). To investigate differences in susceptibility, we estimated heat–hospitalization associations after stratifying data by age (65–74 yr, 75–84 yr, ≥85 yr) and sex. We estimated national average heat effects at single-day lags of 0, 1, and 2 days and cumulatively for lags 0 to 6. Finally, we investigated whether counties with cooler summers on average for the entire study period have statistically significant larger relative risks of heat-related hospital admissions than counties with warmer summers. We provide evidence toward this question using a two-level hierarchical Bayesian model (1, 22). Details are given in the online supplement.

We assessed the sensitivity of model results to the degree of adjustment for seasonality and long-term trends as well as to the metric used for heat exposure (maximum temperature, minimum temperature, heat index). We also investigated sensitivity to air pollutant control (O_3, PM_{10}, and $PM_{2.5}$). Details on these sensitivity analyses are in the online supplement.

RESULTS

Our final dataset included 213 urban counties, covering approximately 12.5 million Medicare beneficiaries across the United States (>30% of the U.S. population ≥65 yr of age [23]) (Table 1) and including locations with a variety of climates (Figure 1; *see* Figure E1 in the online supplement).

On average across the 213 counties, respiratory hospitalizations increased 4.3% (95% posterior interval [PI], 3.8, 4.8%) for each 10°F increase in daily mean summer temperature (Figure 2). Results were similar for COPD (4.7%; PI, 3.9, 5.5%) and respiratory tract infections (4.1%; PI, 3.4, 4.7%) (Figure 2). Results were robust to changes in adjustment for seasonality (Figure E2) and were similar using different temperature metrics (e.g., minimum and maximum temperature, heat index) (Table E1).

Across counties, we found small to moderate correlations between temperature and air pollutants (median across counties: O_3, 0.39; PM_{10}, 0.42; $PM_{2.5}$, 0.45) (Figure E3, Table E2). However, both county-level and national average estimates were very similar for models with and without the adjustment for O_3, PM_{10}, and $PM_{2.5}$ (Figure 3, Table E3). Therefore, we did not find evidence that the association between outdoor temperature and respiratory admissions is attributable to exposure to air pollution.

Heat and respiratory hospitalizations were most strongly associated on the day of exposure (lag 0) (Figure E4). One day after exposure (lag 1), the association was smaller but still positive and statistically significant (2.3%; PI, 1.8, 2.8%), whereas at lag 2, there was no evidence of an association (0.1%; PI, −0.3, 0.5%) (Figure E4). When we modeled cumulative effects up to 1 week after exposure (lags 0–6), we found a cumulative effect of a 2.2% (PI, 1.3, 3.1%) increase in respiratory hospitalizations associated with a 10°F increase in the previous week's daily mean temperature (Figure E4).

The association between heat and respiratory hospitalizations was consistently positive and statistically significant in all subpopulations (i.e., age and sex) considered (Figure 2). Relative risk estimates were very similar for men and women (4.3%; PI, 3.6, 5.0% for men and 4.4%; PI, 3.7, 5.1% for women) (Figure 2) and for the different age groups (65–74 yr, 4.8%; PI, 4.0, 5.6%; 75–84 yr, 4.2%; PI, 3.5, 4.9%; ≥85 yr, 4.2%; PI, 3.2, 5.2%) (Figure 2).

We investigated whether differences between county-specific risks of heat-related hospital admissions could be explained by differences between the counties' average summer temperature, defined as average May to September temperature for 1999 to 2008 (Figures 1 and 4). For a county with average summer temperature 10°F cooler than the national average summer temperature, the county was estimated to have a 1.4% (PI, 0.4, 2.3%) higher relative risk of heat-related respiratory hospitalization than the national relative risk.

DISCUSSION

We investigated the acute relationship between short-term exposure to outdoor heat and hospitalizations for respiratory diseases among the elderly in 213 U.S. counties, geographically spread across the United States and with a variety of climates. Across these counties, daily rates of Medicare respiratory hospitalizations increased 4.3% (PI, 3.8, 4.8%) per 10°F increase in daily temperature. To translate this association to number of excess hospitalizations, each 10°F increase in daily temperature, for example, translates to approximately 30 excess respiratory Medicare hospitalizations per day across these 213 study counties, based on county-specific effect estimates and hospitalization rates for the most current year of this study (2008). Note that a larger increase in daily temperature would result in more excess hospitalizations and a lower increase in fewer hospitalizations (e.g., approximately 15 excess respiratory Medicare hospitalizations/d

TABLE 1. STUDY POPULATION, TOTAL HOSPITALIZATIONS, AND DAILY HOSPITALIZATION COUNTS AND RATES FOR 213 U.S. COUNTIES, 1999–2008

Category	No. (Range) of Medicare Beneficiaries (in Millions)*	Total Hospitalizations, May–September, 1999–2008*	Hospitalization Count/d (Range)†	Daily Hospitalization Rate (Range) per 100,000 Beneficiaries†
All respiratory	12.5 (11.5, 13.1)	1,141,458	2.3 (0.6, 31.9)	5.8 (3.4, 11.7)
By cause				
Respiratory tract infections	12.5 (11.5, 13.1)	756,395	1.6 (0.4, 21.6)	3.9 (2.5, 7.2)
Chronic obstructive pulmonary disease	12.5 (11.5, 13.1)	385,063	0.8 (0.1, 10.3)	2.0 (0.4, 4.5)
By sex				
Male	5.2 (4.5, 5.4)	499,373	1.1 (0.3, 13.9)	6.3 (3.7, 12.6)
Female	7.3 (7.0, 7.7)	642,085	1.3 (0.3, 17.9)	5.5 (3.0, 11.0)
By age				
65–74 yr	6.4 (6.0, 6.7)	358,830	0.8 (0.2, 10.1)	3.6 (1.8, 6.9)
75–84 yr	4.4 (4.1, 4.7)	468,002	1.0 (0.2, 13.0)	6.7 (3.9, 12.9)
⩾85 yr	1.6 (1.4, 1.8)	314,626	0.6 (0.1, 9.6)	12.1 (7.5, 22.9)

*Total across all 213 study counties.
†Average values across all study days were computed for each county, and shown here are the median and range (in parentheses) of these county-specific values.

for a 5°F increase, approximately 45 for a 15°F increase). Across all study counties, the average within-county range between the hottest and coolest temperatures over the 10 study years for a specific date of the summer (e.g., June 1) was 15.1°F, whereas the average interquartile range was 5.8°F (*see* online supplement for more details on this calculation).

We investigated this association for lags of a week or less and found the association was strongest at a same-day lag. The association was robust to control for air pollution, changes in control for long-term and seasonal trends, and changes in the metric used to estimate heat exposure. By jointly investigating this large set of locations, this study identified a consistent increase in respiratory hospitalizations associated with heat across a variety of U.S. locations and also identified heterogeneity between county-specific associations based on differences in local climate.

These acute heat effects are smaller than those found in several previous time series studies. Each 10°F increase in outdoor heat was found to increase respiratory hospitalization rates 12.3% in Mediterranean cities (14), 16.1% in New York, NY (12), and 19.3% in a metaanalysis of worldwide heat-morbidity studies (6). This difference cannot be explained by differences in exposure metrics, because our estimates changed little with alternate exposure metrics. The smaller effect size found in this study may result from differences in modifying factors, including population characteristics, housing structures, and air conditioning prevalence. Our findings are more consistent with two California studies, which identified increases of 2.0% (11) and 2.6% (10) in respiratory hospitalizations per 10°F increase in daily outdoor heat. Although the effect found in our study is higher, our study was restricted to a more susceptible population (people ⩾65 yr of age), whereas these California studies included all ages.

Although epidemiological studies cannot definitively determine the pathway of heat's effects on respiratory health, a large multicommunity study can evaluate consistency between epidemiological health endpoints and potential pathways through close investigation of effect modification by age, sex, and local climate, as well as the role of air pollution. Our research helps clarify the link between outdoor heat and acute respiratory health outcomes by providing support for or against several plausible pathways for heat's effects on respiratory health.

First, we extensively tested sensitivity of heat effect estimates to controlling for three pollutants linked to both outdoor heat and respiratory health (O_3, PM_{10}, and $PM_{2.5}$) (21, 24). Our results provide evidence that increased respiratory risks during hot weather are not explained solely by increases in air pollution concentration—associations between heat and respiratory hospitalizations were almost unchanged with adjustment for pollutants. Pollen and mold concentrations have also been linked to

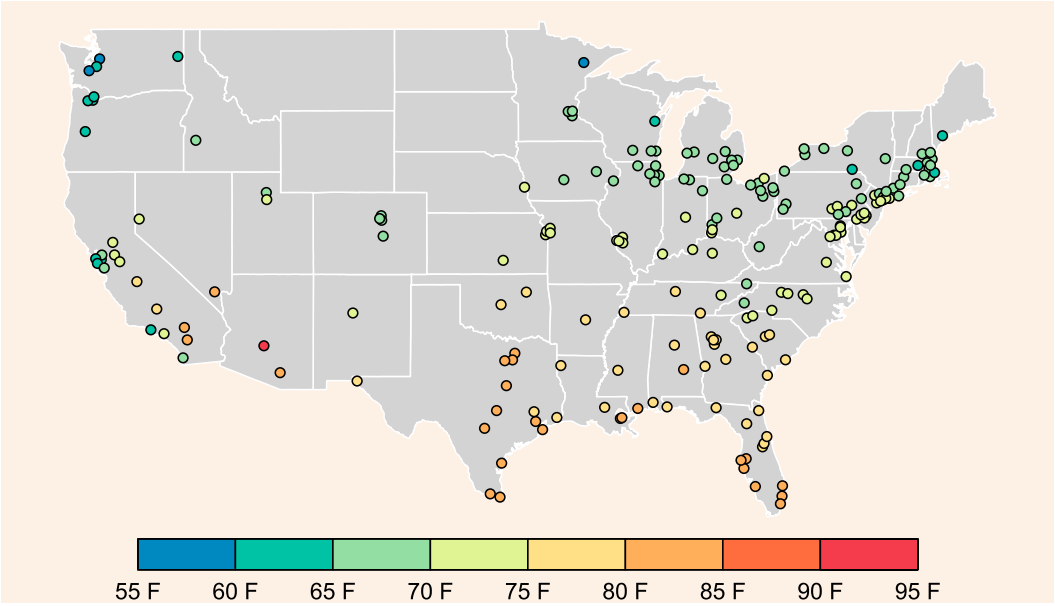

Figure 1. Two hundred thirteen U.S. study counties and their average summer temperatures. Colors correspond to the county's daily mean temperatures, averaged from May to September (1999–2008).

both outdoor heat (25, 26) and respiratory health (27, 28). Nationally representative data for these aeroallergens were not available to definitively address this question in the current study (29), but future research could investigate this pathway for heat effects at the community or regional level.

Our findings also provide evidence that increases in acute respiratory outcomes during heat are probably not caused by indoor crowding to avoid the heat. Although indoor crowding may help spread respiratory infections (30), respiratory diseases take several days to progress from exposure to symptoms. We found, conversely, the strongest association between respiratory hospitalizations and heat was on the same day as exposure (lag 0). Several city- or state-level studies in the United States (10–12), as well as international studies (6, 20), have similarly found same-day associations between respiratory hospitalizations and heat. These results suggest heat may aggravate existing respiratory infections rather than spread new infections through indoor crowding.

Although epidemiologic evidence cannot definitively determine biological pathways, our results suggest that the pathway for acute respiratory heat effects may differ somewhat from the pathway for cardiovascular heat effects. Heat-related cardiovascular outcomes are likely caused by stress to the cardiovascular system from thermoregulatory responses to heat (31). Our results suggest that, although adverse systemic effects related to thermoregulation may play a role in respiratory heat effects, these effects are likely also caused by the direct effect of breathing hot air.

Thermoregulation helps humans maintain safe body temperatures in heat but is associated with systemic inflammation, increases in cardiac output, increases in skin blood flow, and increases in pulmonary ventilation (32, 33). Additionally, although humans primarily lose body heat through surface sweating, hyperthermia can increase ventilation and cause thermal hyperpnea (second-phase panting, during which tidal volume and respiratory rate both increase) (32). These thermoregulatory responses could contribute to the observed increase in hospitalizations for respiratory infections and COPD exacerbations, especially because COPD is a disease characterized by ventilatory impairment, persistent pulmonary and systemic inflammation (33, 34), and coexisting cardiovascular disease (34, 35).

However, if heat effects on respiratory health were mediated exclusively by a thermoregulatory pathway, risks would likely differ substantially by age, county climate and, possibly, sex. First, age and, to some degree, sex are linked to physiological differences in thermoregulation (36–38), and so we would expect differences in susceptibility by age and sex if respiratory heat effects were mediated exclusively by a thermoregulatory pathway. However, here we found little difference in respiratory susceptibility to heat by either age or sex. Second, if effects were mediated exclusively by a thermoregulatory pathway, heat effects would likely differ substantially based on a location's climate, because thermoregulatory response improves with repeated heat exposure (38). However, although respiratory heat effects were generally lower in counties with hotter average summer temperatures, heat–hospitalization associations remained positive across the range of county climates. Furthermore, county climate modified respiratory heat effects much less than in similar research on heat and cardiorespiratory mortality (1).

Our findings are consistent with the hypothesis that acute respiratory heat effects are likely also caused by a direct effect of breathing hot air. We found limited effect modification of respiratory heat effects by climate, which could be explained if respiratory heat effects are triggered by very brief exposure to heat, because even widespread use of air conditioning cannot eliminate brief (e.g., ≤10 min) outdoor heat exposure. Although an hour or more of exposure is required for some thermoregulatory responses to heat (39), a few minutes of heat exposure can trigger direct human airway responses to inhaling hot air. This rapid response has been demonstrated in studies of asthma (40, 41), and it likely operates through the cholinergic reflex pathway (40, 42, 43).

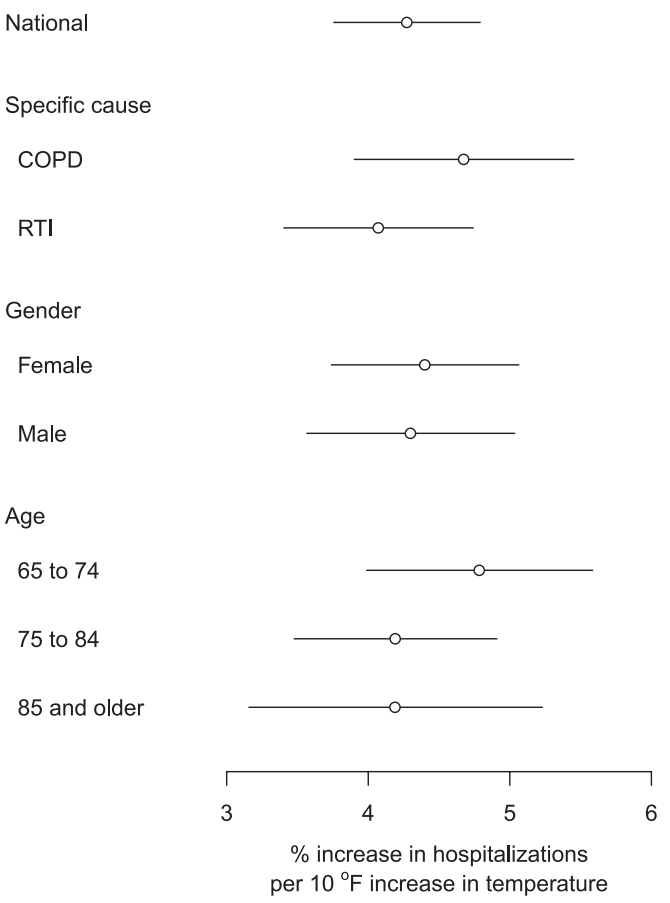

Figure 2. Percent increase in respiratory hospitalizations for each 10°F daily outdoor heat increase, 1999 to 2008 (lag 0). Estimates are pooled across all 213 study counties; outdoor heat is measured as daily mean temperature, May to September. *Horizontal lines* show 95% posterior intervals. COPD = chronic obstructive pulmonary disease; RTI = respiratory tract infections.

Studies of the association between heat and human mortality have found evidence of decreasing effects over decades (44, 45) and smaller effects in hotter climates (1), suggesting protective adaptation to heat, possibly related to differences in housing stock or behavior during hot weather. Given this study's timeframe, we were unable to explore temporal adaptation, but we did investigate evidence of differences in heat–hospitalization associations between hotter and milder counties. Although our results are consistent with evidence of adaptation—smaller effects in counties where summers are typically very hot—this adaptation did not completely remove risk even in the hottest counties.

Any adaptations may take decades to realize or be impractical in certain communities. For example, architectural adaptations can only change slowly with changes in housing stock and may be impractical in dense urban communities like New York City. Adaptation could also bring its own risks and impacts. Higher use of air conditioning will draw on already-stressed power grids, which could cause power outages during severe heat waves and so create new health threats (46). Additionally, the energy use associated with increased use of air conditioning will

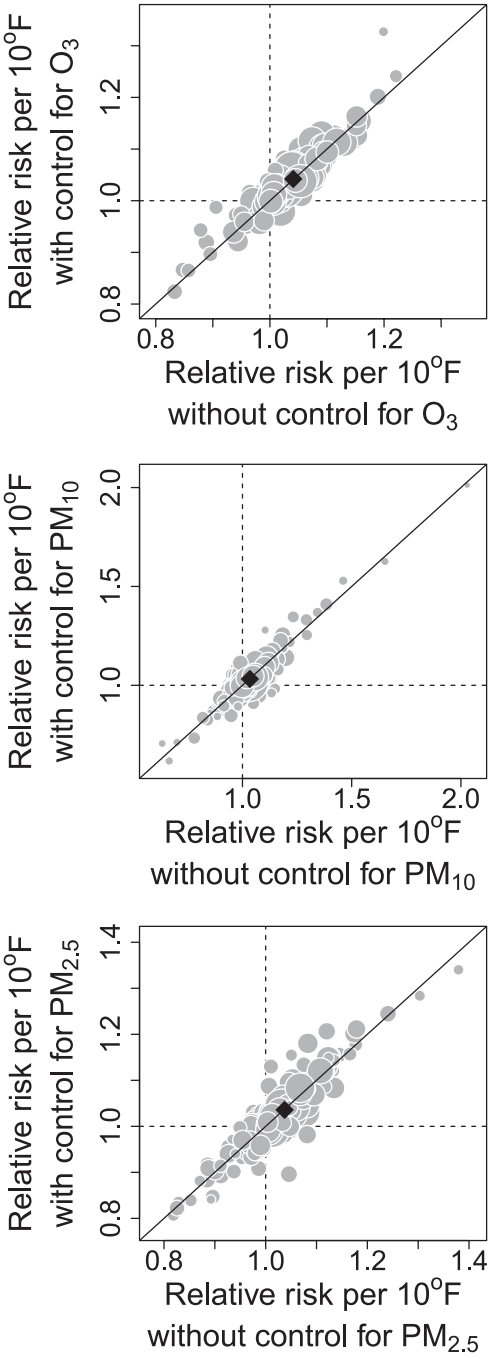

Figure 3. Relative risk of heat-related respiratory hospitalization with and without adjustment for air pollution, 1999 to 2008 (lag 0). Analysis for ozone (O_3) (n = 200), particulate matter with aerodynamic diameter less than or equal to 10 μm (PM_{10}) (n = 165), and particulate matter with aerodynamic diameter less than or equal to 2.5 μm ($PM_{2.5}$) (n = 196). *Circles* show community-level estimates. Larger circles indicate greater certainty. *Black diamond* shows estimate across all communities.

increase air pollution and accelerate climate change through release of greenhouse gases (47).

In the future, heat-related health hazards are likely to increase. Within this century, exposure to heat is expected to increase as the average global temperature rises at least 3°F (3), and heat waves are expected to become more frequent and severe (3). Also, a growing percentage of the population will likely be particularly

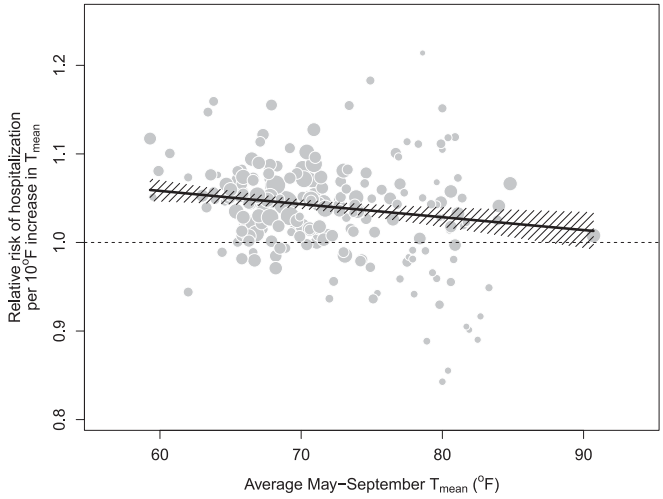

Figure 4. Modification of county-level relative risk of heat-related respiratory hospitalization by a county's average summer temperature (lag 0). Average county summer temperature for May to September, 1999 to 2008. *Circles* show county-level estimates. Larger circles indicate greater certainty. *Solid line* shows the predicted pooled estimate by average summer temperature (*shaded region* shows 95% posterior interval). T_{mean} = mean daily temperature.

susceptible to heat-related respiratory morbidity, given projected increases in the global prevalence of chronic respiratory diseases (4) and aging of the U.S. population (48).

In summary, in a 10-year study of Medicare respiratory hospitalizations and outdoor heat in 213 U.S. counties, we found risk of respiratory hospitalization significantly increased with daily outdoor heat. This relationship persisted across age categories, sexes, and county climates, and could not be explained by changing concentrations of air pollution. Heat-related respiratory hazards are likely to increase in the future with increasing prevalence of respiratory conditions (4) and rising temperatures from climate change (3).

Author disclosures are available with the text of this article at www.atsjournals.org.

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