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Heat-related morbidity and mortality in New England: Evidence for local policy

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ABSTRACT

Background: Heat-related morbidity and mortality is a recognized public health concern. However, public health officials need to base policy decisions on local evidence, which is often lacking for smaller communities.
Objectives: To evaluate the association between maximum daily heat index (HI) and morbidity and mortality in 15 New England communities (combined population: 2.7 million) in order to provide actionable evidence for local officials.
Methods: We applied overdispersed Poisson nonlinear distributed lag models to evaluate the association between HI and daily (May-September) emergency department (ED) admissions and deaths in each of 15 study sites in New Hampshire, Maine, and Rhode Island, controlling for time trends, day of week, and federal holidays. Site-specific estimates were meta-analyzed to provide regional estimates.
Results: Associations (sometimes non-linear) were observed between HI and each health outcome. For example, a day with a HI of 95°F vs. 75°F was associated with a cumulative 7.5% (95% confidence interval [CI]: 6.5%, 8.5%) and 5.1% (95% CI: 0.2%, 10.3%) higher rate of all-cause ED visits and deaths, respectively, with some evidence of regional heterogeneity. We estimate that in the study area, days with a HI≥95°F were associated with an annual average of 784 (95% CI: 658, 908) excess ED visits and 22 (95% CI: 3, 39) excess deaths.
Conclusions: Our results suggest the presence of adverse health impacts associated with HI below the current local guideline criteria of HI≥100°F used to issue heat advisories. We hypothesize that lowering this threshold may lead to substantially reduced heat-related morbidity and mortality in the study area.

1. Introduction

There is a well-established relationship between warm ambient temperatures (i.e., “heat”) and higher risk of mortality in many parts of the world, with excess risk of death observed during periods of both moderate and extreme heat (Anderson and Bell, 2011; Basu, 2009; Bobb et al., 2014b; Curriero et al., 2002; Gasparrini et al., 2015b; Guo et al., 2014; Lee et al., 2014; Nordio et al., 2015). Recent evidence suggests that while the relative risk for death is greatest in association with extreme heat events (i.e., heat waves), the absolute number of deaths attributable to more moderate warm temperatures can be much larger than the number of deaths attributable to extreme heat (Gasparrini et al., 2015b). The association between heat and risk of non-fatal health outcomes as reflected by hospital or emergency department (ED) admissions has been less thoroughly studied, but the current evidence suggests that both extreme and moderate heat are associated with substantial morbidity as well (Basu et al., 2012; Bobb et al., 2014a; Green et al., 2010; Gronlund et al., 2014, 2016; Kingsley et al., 2016; Knowlton et al., 2009).

Given the abundant evidence linking extreme heat to morbidity and mortality, many communities in the US and Europe have implemented heat communication plans, warning systems and/or heat response plans aimed at reducing the public health burden of future events (Bittner et al., 2014; White-Newsome et al., 2014). In the US, most communities rely on the National Weather Service (NWS) to provide primary communication about unsafe levels of heat to officials and the public. Moreover, public health communication and response plans are often triggered only after the NWS issues a heat advisory or warning.

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The thresholds at which heat advisories and warnings are issued are the same across most of the US Northeast, Ohio, and West Virginia. Specifically, local NWS field offices in this broad region typically issue heat advisories when the heat index (HI) is forecast to be between 100°F and 104°F for 2 or more hours, and excessive heat warnings are issued when the HI is forecast to be ≥105°F. HI combines temperature and humidity to provide a measure of thermal comfort (Anderson et al., 2013) or "how hot it really feels when relative humidity is factored in with the actual air temperature" (NWS, 2017).

Prior work highlights that the shape and magnitude of the exposure-response curve relating temperature to health outcomes can vary considerably by geographic location, local climate, population and housing characteristics, and a number of area-level factors (Curriero et al., 2002; Gasparrini et al., 2015b; Guo et al., 2014; Klein Rosenthal et al., 2014; Nordio et al., 2015; Reid et al., 2009). Given this evidence of geographic variability, some jurisdictions have adopted heat advisory and warning criteria based on local conditions (e.g. Philadelphia (Ebi et al., 2004)) or have conducted local evaluations of the heat-health relationship (e.g. New York City (Metzger et al., 2010)). In the case of New York City, the NWS changed the criteria for issuing local heat advisories in response to local evidence such that the current criteria for New York City is that a heat advisory is issued when the HI is forecast to exceed 95°F for two or more days or to exceed 100°F for any length of time; the criteria for issuing excessive heat warnings was left unchanged.

Given the clear importance of such local information, public health and emergency preparedness officials need to develop risk communication strategies, warning systems, and/or heat response plans based on evidence of adverse health effects in the local population. While generating and acting on local evidence is often possible in larger metropolitan areas, smaller cities and towns typically do not individually have sufficient data or other resources needed to obtain the necessary evidence to directly support policy changes. Moreover, the populations of these smaller communities are typically underrepresented or excluded in large analyses spanning broader geographic areas (Anderson and Bell, 2011; Basu et al., 2012; Bobb et al., 2014a, 2014b; Curriero et al., 2002; Gronlund et al., 2014).

Accordingly, the aim of this study was to assess heat-related morbidity and mortality in 15 communities across three New England states (Maine, New Hampshire, and Rhode Island) in order to provide actionable evidence to local forecast, public health, and emergency preparedness officials in the study area. New England is a region in the Northeast US that consists of 6 states with a combined population of approximately 14.4 million residents; this analysis leverages data from population centers in three of those states (Fig. 1). The Northeast US is particularly interesting in this regard due to the number of smaller cities and towns with distinct population centers surrounded by undeveloped land. Specifically, the population density of New England is higher than that of the US as a whole (US Census Bureau, 2014), with most New England residents living along a near continuum of coastal urban centers and smaller towns. In addition, evidence suggests that populations in the Northeast may be simultaneously more susceptible to heat-related mortality (Anderson and Bell, 2011; Nordio et al., 2015) and poised to experience some of the biggest increases in summer-time temperatures and temperature-related mortality in the US due to projected climate change (Schwartz et al., 2015). Specifically, we sought to: 1) estimate the association between maximum daily HI and rates of emergency department (ED) visits and deaths in these communities, 2) quantify the public health burden associated with excess heat across the study area, and 3) assess how NWS heat advisories or excessive heat warnings might be modified to better protect the public's health.

2. Methods

Daily counts of ED visits and deaths for May through September of each year were extracted from hospital discharge and vital statistics databases in Rhode Island, New Hampshire, and Maine. Specifically, we obtained from the Rhode Island Department of Health individual-level data on all ED admissions between 2005 and 2012 to Rhode Island hospitals, excluding the Veterans Affairs Hospital and psychiatric hospitals, and data on all deaths in the state from 1999 to 2011. In New Hampshire, data on ED admissions for any cause from all hospitals excluding Veterans Affairs hospitals and data on all-cause deaths were available for 2000–2009 from the New Hampshire Department of Health and Human Services. In Maine, these data were available from 2001 to 2010 from the Maine Department of Health and Human Services. Data available on each ED visit included sex, age, race, admission date, and primary and secondary discharge diagnoses using International Classification of Disease (ICD)-9 codes. Mortality records included information on sex, age, race, date of death, and primary and secondary cause of death using ICD-10 codes. Records of ED admissions and deaths included information on the location of residence: census tract of residence in Rhode Island and town of residence in New Hampshire and Maine. Each partner institution determined that this analysis did not require approval by local institutional review boards.

We obtained hourly data on ambient temperature and relative humidity for 15 first-order weather stations (Supplemental Table 1) from the National Oceanic and Atmospheric Administration's (NOAA) Integrated Surface Database (NOAA, 2014). These stations were chosen for being in close proximity to population centers and having nearly complete hourly data on temperature and relative humidity over the entire time period. We calculated hourly HI as a function of temperature and relative humidity using the approach used by the NWS (NWS, 2016) and described in detail in the Supplemental Material. Maximum daily HI was calculated for each day at each weather station. This method of calculating HI has been shown to correlate well with apparent temperature (Anderson et al., 2013) and is consistent with the approach currently used by most local NWS offices for determining when to issue heat advisories or excessive heat warnings.

Each study sites consisted of multiple small towns. Sites in New Hampshire and Maine included the population living in towns with any portion within 16.1 km (10 miles) of the selected NWS weather station. In New Hampshire and Maine, some towns were within the radius of more than one weather station. In such cases, to avoid double counting of ED admissions and deaths, the population of that town was assigned to the study area where the majority of ED admissions from that town were admitted (New Hampshire) or to the weather station nearest to the town centroid (Maine). The entire state of Rhode Island was considered as a single site given the small geographic extent and limited topographical variation across the state. The location of study sites is shown in Fig. 1, with additional details provided in the Supplemental Material. We obtained population estimates for each study site from the 2010 US Census (US Census Bureau, 2014).

Our primary analyses focused on all-cause ED admissions or deaths, including external injury. We additionally defined "heat-related" ED admissions as those with a primary or secondary diagnosis of ICD-9 992 (effects of heat and light), E900 (accident caused by excessive heat), or 276.5 (volume depletion disorder, including dehydration and hypovolemia) or a primary diagnosis of ICD-9 580–589 (nephritis, nephrotic syndrome, and nephrosis). This represents a composite outcome, which groups multiple conditions that have been previously shown to be strongly associated with excess heat (Basu et al., 2012; Bobb et al., 2014a; Gronlund et al., 2014; Kingsley et al., 2016; Knowlton et al., 2009). We additionally identified ED admissions with a primary diagnosis of cardiovascular disease, respiratory disease, renal disease, or asthma (Supplemental Table 3).

We used a two-stage analytic approach to estimate the association between HI and ED admissions or deaths across the region. In the first stage, we used over-dispersed Poisson distributed lag non-linear

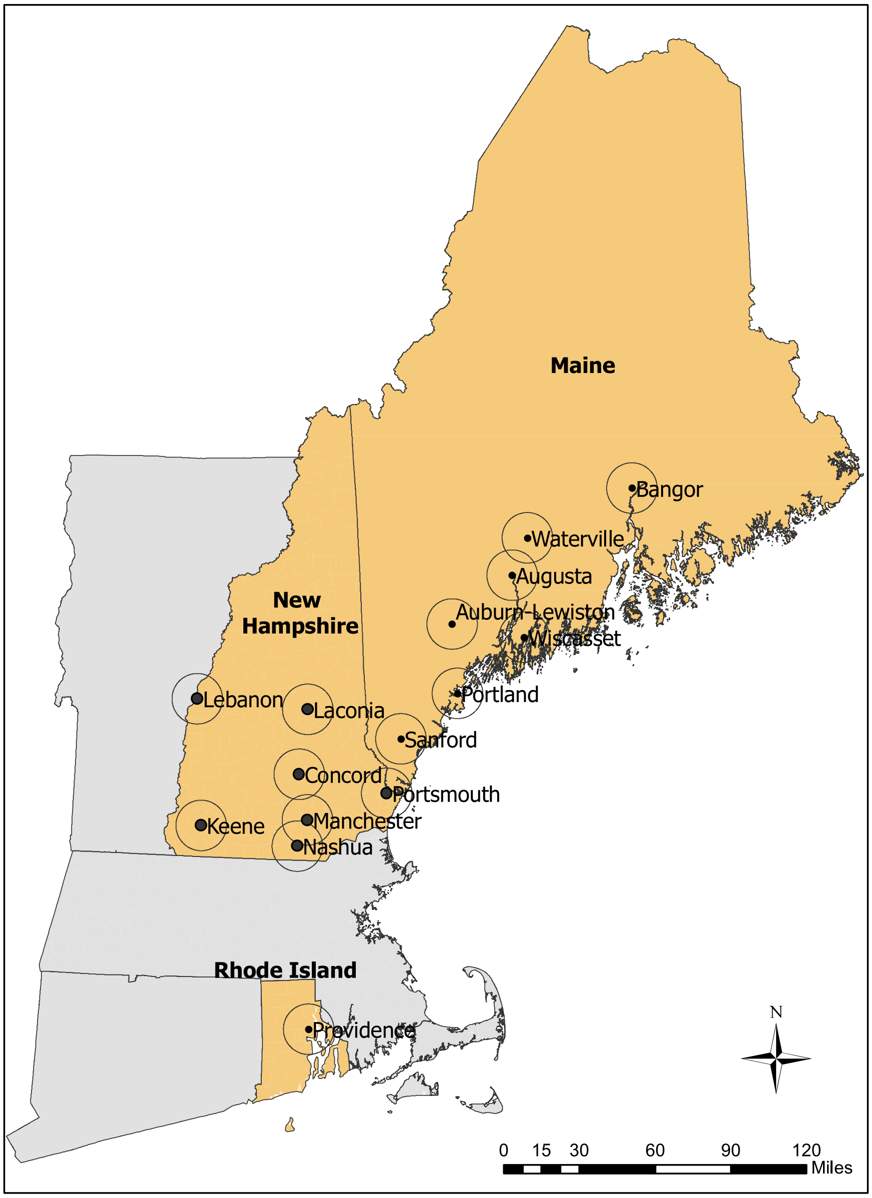

Fig. 1. Map of study region showing location of individual study sites. Each circle denotes a 10-mile radius around an included weather station (dots). Sites in New Hampshire and Maine included the population living in towns with any portion within 16.1 km (10 miles) of the selected NWS weather station. For study sites where a town was within the radius of more than one weather station, the population of that town was assigned to the study area where the majority of ED admissions from that town were admitted (New Hampshire) or to the weather station nearest to the town centroid (Maine). The entire state of Rhode Island was considered as a single site given the small geographic extent and limited topographical variation of the state.

models (Gasparrini et al., 2010) to evaluate the association between maximum daily HI and daily morbidity and mortality between May and September separately for each study site. In each model we considered HI on the same day and the previous seven days (lags 0–7 days) and adjusted for temporal trends (using a natural cubic spline with 5 degrees of freedom per year), day of week (factor), and federal holiday (yes versus no). HI was modeled as a natural cubic spline with internal knots at the median and 75th percentiles of the distribution of HI across all locations over the entire study period. We modeled the lag function for HI using a natural cubic spline with 5 degrees of freedom. While many studies have focused on the association between high heat and morbidity and mortality on the same day (lag 0), other studies suggest that there can be lagged effects of high heat (Gasparrini et al., 2015a). We thus aimed to choose a distributed lag model that properly accounts for same day (lag 0) and potentially lagged effects (lags 0–7 days) of heat. Of note, we did not adjust for ambient levels of ozone or other air pollutants in our analyses. This is appropriate in this setting because the primary goal of interest in this study is to quantify the total effect of temperature on morbidity and mortality, following Reid et al. (2012) which showed that ozone and other air pollutants are more likely to be mediators between temperature and health endpoints rather than confounders. In this setting, adjusting analyses for air pollutants would instead yield estimates of the direct effect of temperature not mediated through air pollutants, which are not relevant to our causal questions of interest in this study. In the second stage, we obtained summary estimates of the regional association from the site-specific estimates using a multivariable, random-effects (assuming a compound symmetry between-site covariance structure) meta-analytic approach derived for this purpose (Gasparrini and Armstrong, 2013; Gasparrini et al., 2012).

Using this approach, we estimated the association between HI and all-cause ED admissions and all-cause mortality across the region. We present results as a relative rate (i.e., incidence rate ratio) of each outcome associated with a day of a given HI compared to a day with a HI of 75°F as the reference. To quantify the public health burden of excess heat we estimated the number of ED admissions and deaths attributable to days with HI above varying thresholds using methods appropriate for the distributed lag nonlinear models we used, as previously described (Gasparrini and Leone, 2014). Briefly, Gasparrini and Leone (2014) describe a generalization to the standard epidemiologic definitions of attributable fraction and attributable number suitable for use in the context of time-varying exposures with lagged, potentially non-linear health effects. We estimated the attributable number above specific values of HI for each study site using the best linear unbiased prediction (BLUP) with 95%CI of the overall same-day or cumulative exposure-response association. The BLUP is a compromise between the location-specific association (first stage) and the pooled association (second stage). We then divided the site-specific attributable number by the number of years in our study period to obtain average annual estimates.

We performed a number of additional analyses suggested by key stakeholders with whom we shared initial results. First, to gain insights into the consistency of the associations across study sites, we graphically compared the shape of the summary exposure-response functions from each state with each other and with the overall regional estimate. We calculated state-specific summary estimates for Maine and New Hampshire by applying the multivariate random-effects meta-analytic approach described above to the locations within each state. These curves were graphically compared to the overall regional estimate and the curve for Rhode Island obtained from the first stage analysis. Second, we considered separately the association between HI and ED visits for heat-related conditions, cardiovascular diseases, respiratory diseases, asthma, and renal diseases. Third, we assessed whether the association between HI and all-cause ED visits differed among individuals aged ≥65 years versus <65 years in separate models. Fourth, we assessed whether the association between HI and all-cause ED visits was more pronounced during the early part of the season (May and June) as compared to later in the season (July or August), as suggested by prior studies (Sheridan and Lin, 2014).

All analyses were performed in R version 3.2.1 using the dlnm version 2.2.6 and mvmeta version 0.4.7 packages (Gasparrini, 2011; Gasparrini et al., 2012). We considered a two-sided p-value <0.05 as statistically significant.

3. Results

The 15 study sites ranged in population (2010 estimates) from 39,891 in Lebanon, New Hampshire (average of 6291 ED visits and 114 deaths per year) to 1.05 million in the state of Rhode Island (average of 145,927 ED visits and 3681 deaths per year) (Supplemental Table 1). The total population in the study area was 2.7 million, representing 100%, 66%, 62%, and 19% of the 2010 population of Rhode Island, New Hampshire, Maine, and New England, respectively. Across the study region, those admitted to the ED were substantially younger than those that died, with a similar ratio of males to females (Supplemental Table 4).

Across the study region, HI was statistically significantly associated with higher morbidity, as reflected by a higher relative rate of same-day (lag 0) all-cause ED visits (Fig. 2A). For example, the rate of all-cause ED visits was 1.8% (95% confidence interval [CI]: 1.3%, 2.2%) higher on a day with a HI of 95°F versus 75°F adjusting for temporal trends, day of week, and federal holidays (Table 1). This association was more pronounced when considering the cumulative effect over the following 7 days (lag 0–7, Fig. 2B). For example, the rate of all-cause ED visits over the following 7 days was 7.5% (95% CI: 6.5%, 8.5%) higher comparing days with a HI of 95°F versus 75°F. Interestingly, the shape of the exposure-response function between HI and ED visits flattened out at higher levels of HI when considering same day ED visits (lag 0), but continued to increase approximately linearly when considering the cumulative association over the following 7 days (lags 0–7 days).

We also observed an association between HI and the relative rate of mortality on the same day (lag 0, Fig. 2D and Table 1). For example, the rate of all-cause deaths was 5.5% (95% CI: 2.5%, 8.6%) higher comparing days with a HI of 95°F versus 75°F (Table 1). This association was similar but less precisely estimated when we considered the cumulative effects over the subsequent 7 days (lag 0–7 days, Fig. 2E and Table 1). We note that the shape of the exposure-response function is approximately linear when considering same-day deaths (lag 0), but steeper at higher levels of HI when considering the cumulative association (lags 0–7 days).

We observed that the time course of these effects differed for all-cause ED visits versus mortality. Specifically, the results shown in Table 1 suggest that more than half of the cumulative increase in relative risk of ED visits associated with high HI days occurs on days after the initial heat event (comparing estimates for lag 0–7 vs lag 0). For example, a day with a HI of 95°F was associated with a 1.8% increase in the rate of ED visits on the same day (lag 0), but a cumulative 7.5% increase over the next week (lag 0–7 days). In contrast, the increased relative risk of death was predominantly observed on the same day as the heat event (lag 0), except at more extreme HI values where the cumulative relative risk exceeded the relative risk seen at lag 0. Consistent with these results, the distributed lag functions (Fig. 2C and F) suggest that the impact on ED admissions of a single day with a HI of 95°F versus 75°F is detectable up through the subsequent 5 days while the impact on death appears to be limited to the same day and next day.

To quantify the public health burden of excess heat we calculated the number of ED visits and deaths attributable to days with HI above varying thresholds (Table 2) and hence potentially preventable. We found that among the approximately 2.7 million residents of the study area, during this time period there were an average of 232 (95% CI: 187, 277) excess ED visits and 8 (95% CI: 2, 14) excess deaths per year attributable to days with a HI ≥100°F (lag 0–7 estimates). Days with less extreme HI occur more regularly and thus were associated with higher attributable numbers. For example, among the residents of the study area, during this time period there were an average of 784 (95% CI: 658, 908) excess ED visits and 22 (95% CI: 3, 39) excess deaths each year attributable to days with a HI ≥95°F(lag 0–7 estimates). Subtracting these numbers suggests that days with HI between 95 and 100°F account for approximately 550 excess ED visits and 14 excess deaths on average per year in the study area. Site-specific results are shown in Supplemental Table 5.

In secondary analyses we evaluated whether the association between HI and ED visits varied across the study region by graphically superimposing the cumulative exposure-response functions for each state (Fig. 3A). While the exposure-response curves for Rhode Island and New Hampshire appeared similar to the overall regional summary exposure-response curve, the exposure-response curve appeared somewhat more pronounced in Maine. Another way to visualize regional heterogeneity is to compare the relative rate for days with a HI of 95°F versus 75°F in each study site (Fig. 3B). This analysis suggests stronger associations between HI and all-cause ED visits across study sites in Maine compared to those in New Hampshire or Rhode Island, as well as compared to the regional average. Differences by state were less clear when instead considering the outcome of death given the smaller sample size and decreased precision of these estimates (Figs. 3C and D).

We additionally examined the association between HI and specific causes of ED admissions (Fig. 4). In this analysis we found a substantially stronger association with heat-related admissions, admissions for renal diseases, and admissions for respiratory diseases and asthma, with no harmful association observed for cardiovascular diseases. We also saw little evidence of differences in the exposure-response curves for all-cause ED visits in the spring (May-June) versus summer (July-August), by sex, or by age (Fig. 4).

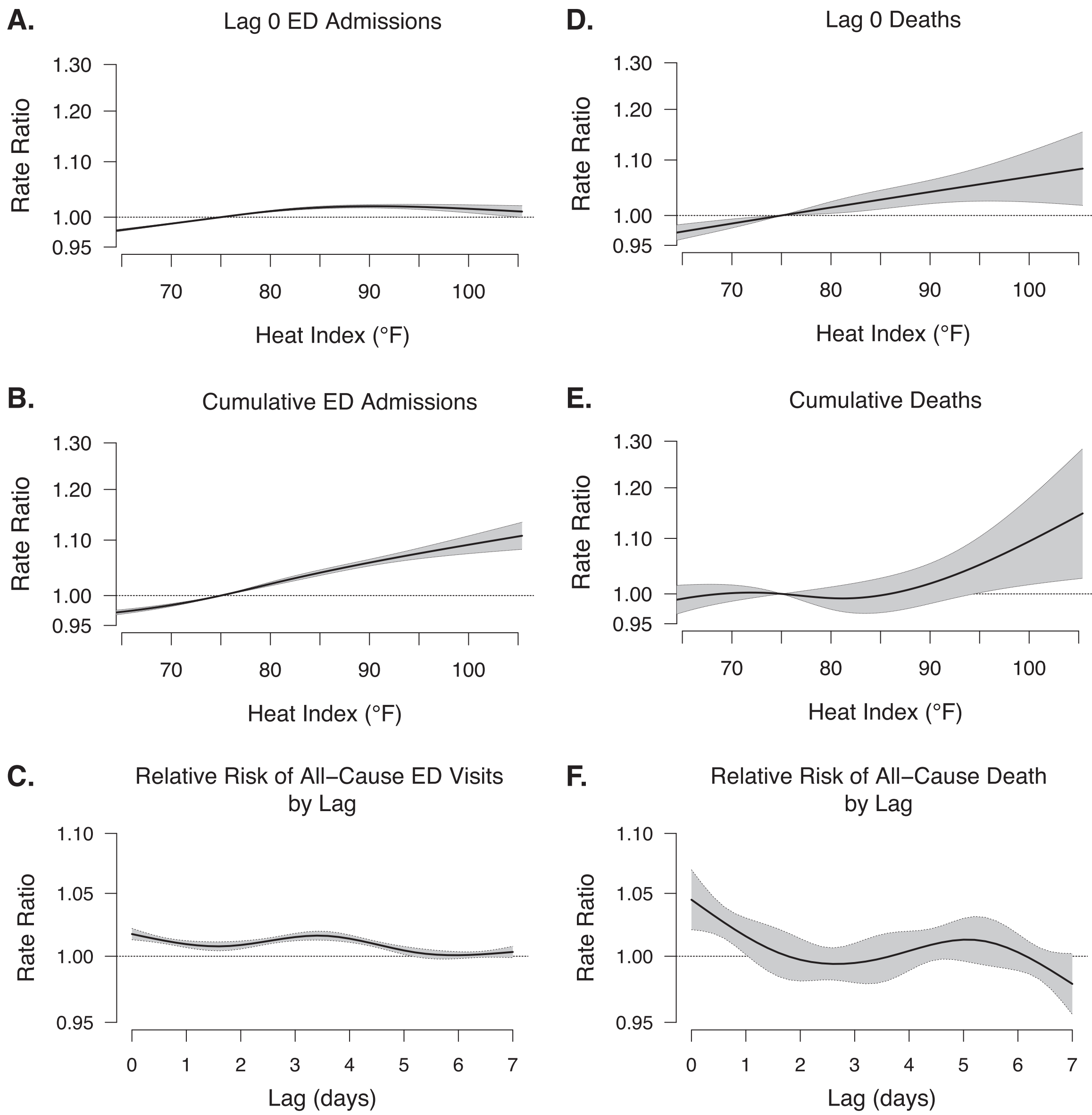

Fig. 2. Meta-analytic summary estimates of the association between maximum daily heat index (HI) and all-cause emergency department (ED) admissions on the same day (lag 0, **A.**) and on the subsequent 7 days (lag 0–7 days, **B.**). **C.** Distributed lag function of the association between HI and all-cause ED admissions comparing days with HI of 95°F versus 75°F. Meta-analytic summary estimates of the association between HI and all-cause deaths on the same day (lag 0, **D.**) and subsequent 7 days (lag 0–7 days, **E.**). **F.** Distributed lag function of the association between HI and all-cause deaths comparing days with HI of 95°F versus 75°F. The dark solid line in each panel represents the central estimate while the shading depicts 95% confidence intervals.

4. Discussion

The goal of this study was to provide forecast, public health and emergency preparedness officials in New England with local, actionable evidence regarding the association between HI and morbidity and mortality. Across 15 communities in three New England states representing an estimated 2.7 million people we found that HI was associated with higher rates of all-cause and heat-related ED admissions as well as all-cause deaths. Importantly, these associations were detectable even on days with more moderate HI values below the current threshold for NWS heat advisories or excess heat warnings in this region.

Our findings that HI is associated with higher rates of death are consistent with a large and growing body of evidence showing qualitatively similar effects in virtually every region of the globe (Anderson and Bell, 2011; Basu, 2009; Bobb et al., 2014b; Curriero et al., 2002; Gasparrini et al., 2015b; Guo et al., 2014). Relatively fewer studies have considered the association between measures of heat and morbidity, but our results are again broadly consistent with those of prior studies in Rhode Island (Kingsley et al., 2016), California (Basu et al., 2012; Green et al., 2010), New York (Lin et al., 2009; Sheridan and Lin, 2014), and across larger US regions (Bobb et al., 2014a; Gronlund et al., 2014). Direct comparison of our health effects estimates to those from previous studies is challenging given the typically nonlinear exposure-response function and the fact that most prior studies have used ambient temperature as the exposure metric, either with or without adjustment for humidity, rather than HI. Nonetheless, while there is heterogeneity in the shape and scale of the exposure-response function across studies, there is no evidence to suggest that these associations are not indicative of a causal effect of heat on health (USGCRP, 2016).

However, the purpose of our analyses was not to replicate the results of prior studies in a new location, but rather to use local data to estimate the morbidity and mortality attributable to excess heat in the study area. In an effort to reduce heat-related morbidity and mortality, NWS local forecast offices typically issue a heat advisory or an excessive

Table 1
Percent change (and 95% confidence interval) in rate of all-cause emergency department (ED) visits and all-cause deaths associated with a specific maximum daily heat index compared to days with a maximum daily heat index of 75°F.

Maximum Daily Heat Index (°F)	All-Cause ED Visits		All-Cause Deaths	
	Same Day (Lag 0)	Cumulative Effect over Next 7 days (Lag 0–7 days)	Same Day (Lag 0)	Cumulative Effect over Next 7 days (Lag 0–7 days)
75	0 (Reference)	0 (Reference)	0 (Reference)	0 (Reference)
80	1.0 (0.9, 1.2)	2.0 (1.6, 2.4)	1.4 (0.4, 2.4)	−0.7 (−2.6, 1.2)
85	1.7 (1.5, 1.9)	4.0 (3.5, 4.5)	2.8 (1.1, 4.4)	−0.3 (−3.2, 2.8)
90	1.9 (1.6, 2.2)	5.8 (5.2, 6.4)	4.1 (2.0, 6.3)	1.8 (−1.7, 5.3)
95	1.8 (1.3, 2.2)	7.5 (6.5, 8.5)	5.5 (2.5, 8.6)	5.1 (0.2, 10.3)
100	1.5 (0.8, 2.2)	9.1 (7.5, 10.8)	6.9 (2.3, 11.6)	9.4 (1.6, 17.9)
105	1.0 (0.1, 2.0)	10.7 (8.2, 13.2)	8.3 (1.8, 15.2)	14.4 (2.6, 27.5)

Table 2
Average annual number (and 95% confidence interval) of excess all-cause emergency department (ED) visits and all-cause deaths attributable to all days at or above each maximum daily heat index.

Maximum Daily Heat Index (°F)	All-Cause ED Visits		All-Cause Deaths	
	Same Day (Lag 0)	Cumulative Effect over Next 7 days (Lag 0–7 days)	Same Day (Lag 0)	Cumulative Effect over Next 7 days (Lag 0–7 days)
75	3346 (2905, 3786)	7191 (6387, 7,965)	93 (9, 177)	24 (−76, 120)
80	2908 (2514,3304)	6524 (5818, 7224)	84 (8, 160)	29 (−58, 113)
85	1675 (1407,1937)	4293 (3833, 4746)	44 (7, 107)	39 (−19, 95)
90	694 (539,849)	2127 (1863, 2391)	26 (2, 64)	36 (0.3, 70)
95	197 (127,268)	784 (658, 908)	12 (−1, 30)	22 (3, 39)
100	39 (16, 62)	232 (187, 277)	4 (−1, 9)	8 (2, 14)

heat warning to communicate risks to the public and local officials. These messages are typically issued approximately 12–24 h in advance of extreme heat events and contain recommendations that members of the public can use to protect their health, such as wearing light-colored clothing and drinking plenty of water. In addition, these NWS products may trigger specific actions detailed in heat response plans, such as additional messaging or the opening of cooling centers in the affected areas. The NWS offices in the study area typically issue heat advisories when the HI is forecast to exceed 100°F for 2 or more hours and excessive heat warnings when the HI is forecast to exceed 105°F for 2 or more hours. The results of our study suggest that moderately hot days with a HI below the threshold for issuing heat advisories are still associated with substantial excess morbidity and mortality. Specifically, we estimate that in the study area an average of 784 (95% CI: 658, 908) ED admissions and 22 (95% CI: 3, 39) deaths per year are attributable to days with a HI ≥95°F.

Our results also include some interesting findings regarding the time course of effects of high heat events. Specifically, we found that moderate to high HI was associated with deaths primarily on the same day (lag 0) with little or no additional heat-related deaths over the subsequent week, as can be seen by comparing results for lag 0–7 days versus lag 0 in Table 1. This is consistent with results from prior studies suggesting that the effects of heat on mortality have a short duration with few additional heat-related deaths and potentially some mortality displacement (i.e., harvesting) on subsequent days (Anderson and Bell, 2009; Gasparrini et al., 2015a; Hajat et al., 2005). In contrast, the relative risk between HI and ED admissions was substantially larger when considering the cumulative effect over the following 7 days versus the same day. Indeed, the results shown in Table 1 suggest that more than half of the excess relative rate of ED visits associated with high HI days occurs on days beyond the same day. Moreover, the exposure-response curve for ED visits (which flattens out at higher levels of HI when considering same-day exposures, but not cumulative exposures) potentially suggests that preventive measures or individual behaviors on high heat days protect individuals from heat-related ED visits on the same day but not on subsequent days. This finding is consistent with a prior analysis of heat-related hospitalizations among US Medicare beneficiaries (Bobb et al., 2014a), but to our knowledge, has not been previously reported for ED admissions.

In additional exploratory analyses conducted after sharing initial results with local stakeholders, we evaluated whether the exposure-response function between HI and rates of ED admissions varies appreciably across the study area. We found that excess heat was more strongly associated with rates of ED admissions in Maine compared to New Hampshire, Rhode Island, and the regional average. These results may indicate that residents of Maine are more susceptible to the effects of moderate and extreme heat than other residents in the study area. Maine residents may be more susceptible to heat at least in part because rates of air conditioning usage in Maine homes is strikingly low for the region: 51% statewide in 2011 (Maine Center for Disease Control and Prevention, 2016) as compared to 86% in the rest of the Northeast in 2009. (US Energy Information Administration, 2009) Prior studies have demonstrated that susceptibility to heat varies across locations (Gronlund et al., 2014; Lee et al., 2014; Nordio et al., 2015), highlighting the need for local evidence in making policy decisions. Indeed, it is interesting to note that even across this relatively small geographic area there is potential benefit to exploring different policy responses for a given level of excess heat. Prior research has also demonstrated that people tend to adapt to their local climate such that the greatest risk is posed by large deviations from usual conditions rather than the absolute value of any metric (Shi et al., 2015). Interestingly, communities across Maine tended to have lower maximum daily HI compared to communities in New Hampshire and Rhode Island, but a similar number of days per year where the HI exceeded 95°F or 100°F.

We also explored whether the exposure-response function between HI and ED admissions varied in the early versus late portion of the warm-weather season, as has been reported in relation to mortality in some prior studies (Barnett et al., 2012; Lee et al., 2014), but not others (Metzger et al., 2010). In this study area we did not observe any appreciable differences in the effect of HI on ED admissions across the season, although this analysis may have been underpowered to detect differences of the expected magnitude. Similarly, we did not observe substantial variation of the association by age or gender, but again, this analysis may have been underpowered to detect small but potentially meaningful differences in vulnerability. These questions would be better addressed in a larger, more geographically extensive dataset.

Finally, we assessed how the relationship between HI and morbidity varied by cause of admission to the ED. Consistent with previous studies (Green et al., 2010; Gronlund et al., 2014; Kingsley et al., 2016), we found that heat-related and renal admissions were most strongly associated with HI, respiratory and asthma admissions were more weakly associated, and cardiovascular admissions were not associated with HI.

In regard to policy change, our results suggest that the current NWS criteria for issuing heat advisories in this region may not be sufficiently protective, and could be altered to better protect the public's health. Metzger et al. (2010) suggested that local jurisdictions should undertake the type of analysis we present before adopting new heat-alert criteria. Indeed, the NWS regional office covering New York City changed the

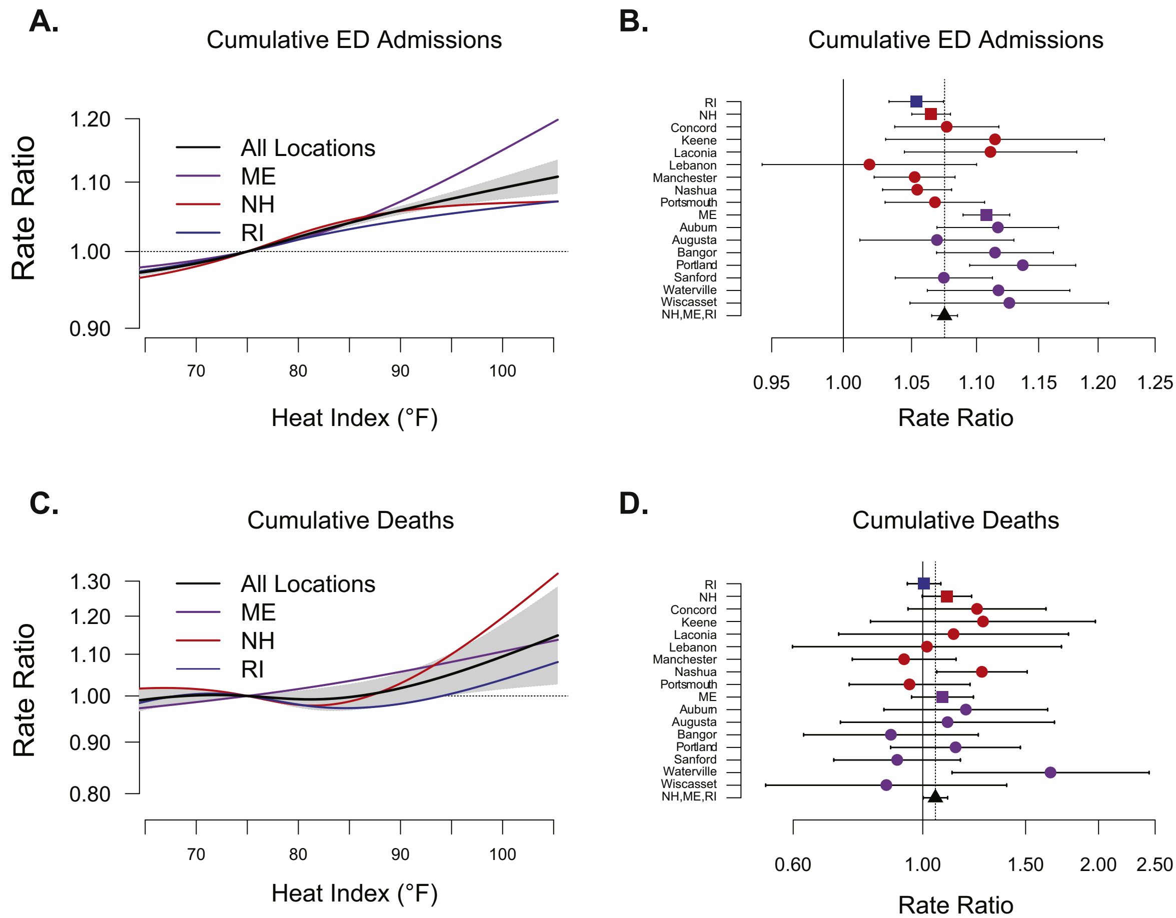

Fig. 3. How much does the association between maximum daily heat index (HI) and all-cause ED visits and death vary across the study region? Estimated cumulative (lag 0–7 days) exposure-response curves between HI and all-cause ED visits **(A.)** and deaths **(C.)**, overall (black line with 95% confidence interval shown in shaded region), and in each state. Estimated cumulative relative rate (and 95% confidence intervals, lag 0–7 days) of all-cause ED visits **(B.)** and deaths **(D.)** comparing days with HI of 95°F versus 75°F in each study site (circles), in each state (squares), and overall (triangle and dashed vertical line).

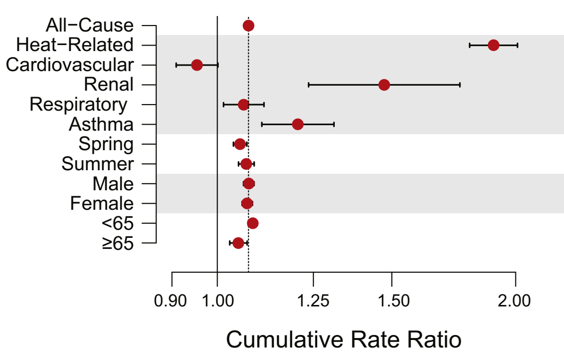

Fig. 4. Cumulative association (lag 0–7 days) between maximum daily heat index and emergency department (ED) visits for specific causes, age groups, and timing in the season. Background shading denotes analytic groupings. Each point represents the rate ratio (and 95% confidence interval) comparing days with maximum daily heat index of 95°F versus 75°F.

criteria used for issuing heat advisories in response to local evidence suggestive of adverse health effects at lower levels of HI (Metzger et al., 2010). Similarly, the NWS regional office for Philadelphia issues heat advisories based on the predicted number of deaths attributable to forecast heat events (Ebi et al., 2004). Analyses in Western Europe provide additional insights on how local evidence can be used to directly inform public health practice (e.g., Diaz et al., 2015; Masato et al., 2015; Pascal et al., 2013). These examples show how local policy and responses can be customized to better protect the public's health and highlight the need for local data to support these efforts.

There is also a need for more local data regarding the effectiveness of heat warning systems, as the available evidence remains scant (Nitschke et al., 2016; Toloo et al., 2013). A survey of 900 residents across four North American cities found that individuals' knowledge of heat events was essentially universal, that most respondents believed excess heat was potentially personally dangerous, but that most people did not alter their behavior in response to heat events (Sheridan, 2007). These findings that have been documented in other studies as well (Toloo et al., 2013). However, other evidence suggests that although fewer than 40% of US counties have a heat response plan in place (White-Newsome et al., 2014), jurisdictions that have implemented such plans have experienced fewer heat-related deaths and/or ambulance calls during extreme heat events occurring after such plans are implemented (Toloo et al., 2013). We are aware of only one study directly assessing the effectiveness of NWS heat warnings on mortality: Ebi et al. (2004) concluded that NWS excessive heat warnings issued for Philadelphia prevented an average of 2.6 lives, but the results did not reach statistical significance. We are not aware of any studies directly assessing the effectiveness of NWS heat warnings or advisories at reducing ED visits or hospitalizations; clearly an area where more research is needed. An interesting additional question is how improved knowledge of the exposure-response function for correlates of heat in a given study area can inform efforts to evaluate the effectiveness of heat warnings or advisories. For example, a more complete understanding of the exposure-response function may make it possible to estimate the maximum potential benefit of heat advisories and warnings (in terms of deaths or ED admissions averted) and whether it is feasible to actually measure this impact at a population level.

Our results need to be considered in the context of study limitations. Perhaps the most important limitation of this study is the relatively small sample size compared to the much larger sample sizes available from national studies. Many of the communities involved would on their own have an insufficient number of deaths and ED visits to conduct a meaningful analysis and the results from an analysis in a single community would be unlikely to substantially influence state or regional policy decisions. However, by pooling results from these 15 study sites we are able to quantify the morbidity and mortality attributable to excess heat across New England, thereby providing evidence directly relevant to local and regional policy. Nonetheless, the relatively small sample size of this study limited our ability to consider detailed analyses by specific causes of death or ED admissions or individual characteristics that may confer additional susceptibility to heat; questions that may be more appropriately addressed further in larger, more geographically extensive studies. In addition to statistical uncertainty from the limited sample size, there is also model uncertainty in terms of the number of lag days to include in estimation of cumulative effects. Another important limitation of this study is the reliance on NWS first-order weather stations for estimating community exposure to heat. These stations were chosen because of their nearly complete hourly data on temperature and humidity over the entire time period. Although this is common practice in the research literature, these stations are typically located at airports and may not provide an optimal representation of population exposure to heat across a town, city or metropolitan area. To limit the potential for misclassification of exposure we selected study sites with a substantial population living in relative proximity to a weather station, but some exposure misclassification likely remains.

5. Conclusions

In summary, the results of this study confirm the presence of an association between maximum daily heat index and rates of ED admissions and deaths across 15 New England communities with an estimated combined population of 2.7 million. Consistent with prior studies, we observed these effects on days with a maximum daily heat index below that which is currently used to trigger NWS heat advisories in the study area. If this association is causal, and assuming that heat advisories are at least partially effective in reducing heat-related morbidity and mortality, we estimate that lowering the threshold at which the NWS issues heat advisories from a heat index of ≥100°F to a heat index of ≥95°F may prevent up to 550 ED admissions and 14 deaths per year in the study communities alone based on the difference in excess cases between 95°F and 100°F. The number of excess ED admissions and deaths attributable to heat across the whole of New England is likely to be even higher. This research provides important information about the heat-health relationship in New England, where small and rural populations have been previously understudied, and provides quantitative support for a lowered threshold for issuing heat advisories. Additional research is needed to better optimize the effectiveness of heat warning systems and heat response plans in order to protect the public's health.

Competing financial interests

The authors declare that they have no conflicts of interest.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.envres.2017.02.005.

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