## Original Contribution

# Time-Course of Cause-Specific Hospital Admissions During Snowstorms: An Analysis of Electronic Medical Records From Major Hospitals in Boston, Massachusetts

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With global climate change, more frequent severe snowstorms are expected; however, evidence regarding their health effects is very limited. We gathered detailed medical records on hospital admissions ($n$ = 433,037 admissions) from the 4 largest hospitals in Boston, Massachusetts, during the winters of 2010–2015. We estimated the percentage increase in hospitalizations for cardiovascular and cold-related diseases, falls, and injuries on the day of and for 6 days after a day with low (0.05–5.0 inches), moderate (5.1–10.0 inches), or high (>10.0 inches) snowfall using distributed lag regression models. We found that cardiovascular disease admissions decreased by 32% on high snowfall days (relative risk (RR) = 0.68, 95% confidence interval (CI): 0.54, 0.85) but increased by 23% 2 days after (RR = 1.23, 95% CI: 1.01, 1.49); cold-related admissions increased by 3.7% on high snowfall days (RR = 3.7, 95% CI: 1.6, 8.6) and remained high for 5 days after; and admissions for falls increased by 18% on average in the 6 days after a moderate snowfall day (RR = 1.18, 95% CI: 1.09, 1.27). We did not find a higher risk of hospitalizations for injuries. To our knowledge, this is the first study in which the time course of hospitalizations during and immediately after snowfall days has been examined. These findings can be translated into interventions that prevent hospitalizations and protect public health during harsh winter conditions.

cardiovascular diseases; cold temperature; electronic medical records; risk; snow

Abbreviations: IHD, ischemic heart disease; MI, myocardial infarction.

Major snowstorms cause social and economic disruption and pose hazards to human health (1, 2). The United States experienced several major winter storms in recent years, such as those in New England in 2015 and in the Mid-Atlantic and eastern regions in 2016, that resulted in missed work, road closures, power loss, and adverse health events, including carbon monoxide poisoning, traffic accidents, and deaths (3, 4). With global climate change, greater frequency of heavy precipitation is expected, particularly in the northeastern United States (5), and severe snowstorms are likely to become increasingly common (6, 7).

In 2015, Boston, Massachusetts, experienced extreme winter weather, with the highest recorded snowfall in a season of 110.6 inches (280.9 centimeters); 4 major snowstorms, of

which 2 ranked in the top 10 for snow accumulation; and a record-breaking number of consecutive days below 20°F (−6.7°C). We hypothesized that the high snow accumulation and frigid temperatures caused by severe snowstorms were associated with an increase in hospital admissions due to cardiovascular diseases, cold-related diseases, injuries, and falls on the day of the snowfall and on the following days.

Severe snowstorms have been associated with an increase in rates of mortality, mainly due to ischemic heart disease (IHD) (8, 9). Previous studies were primarily focused on a single health outcome (e.g., cardiac arrest (10) or myocardial infarction (MI) (11)) or a particular snowstorm event (8, 12), with the majority of these considering the Northeastern Blizzard of 1978. The present study fills 4

gaps in the literature on adverse health effects attributable to extreme weather. First, although there have been many studies in which investigators used claims data to estimate associations of extreme cold temperature with mortality and hospital admissions (13–15), none provided a detailed characterization of the adverse health outcomes that occurred during and immediately after major snowfall while also adjusting for temperature. Second, to our knowledge, there has been no study in which researchers investigated the health effects associated with the intensity of the snowstorm (inches of snow accumulation). Third, because of challenges such as road closures, power loss, and frigid temperatures on days of high snow accumulation and because outcomes are expected to vary in severity (potentially ranging from a fall with a fracture to hypothermia), we anticipated a delay in hospitalization for some causes but not others. However, to our knowledge, the time course of hospitalization by cause of admission and whether these time courses differ depending on the intensity of snow accumulation has not been characterized. Understanding the time course of hospitalization is critical both to evaluate the full health impact of severe winter weather and to potentially prevent these adverse health events. Fourth, most studies on the health effects of cold and heat waves in the United States have relied on administrative claims and mortality data from governmental agencies (13, 16, 17), but few have used data from electronic medical records obtained directly from hospitals. Access to detailed and well-validated medical records in a city that can be severely affected by snowstorms provides a unique opportunity to examine the number of hospitalizations that occur during and immediately after major snow events with an unprecedented level of accuracy.

## METHODS

### Data acquisition

We obtained de-identified individual-level hospitalization data from electronic medical records from the 4 largest hospitals in Boston (Beth Israel Deaconess Medical Center, Brigham and Women's Hospital, Boston Medical Center, and Massachusetts General Hospital) for each day during the months of November through April for the years 2010–2015. We included in our study all admissions of adults (≥18 years of age) with inpatient or observation status (including observation admissions in the emergency department). For each admission, we obtained individual-level data that included the date of hospitalization, the primary and first 2 secondary discharge diagnosis codes (*International Classification of Diseases, Ninth Revision*) for the hospitalization, and the patient's age, race, sex, and discharge vital status. These data were obtained directly from the hospitals.

We considered 6 outcomes in our analysis: 3 cardiovascular disease categories (severe arrhythmias/cardiac arrest, MI and IHD, and cardiovascular disease, which was measured as the combination of all arrhythmias, IHD, and MI), cold-related diseases (e.g., frostbite), injuries, and falls. Each outcome was defined based on the primary *International Classification of Diseases, Ninth Revision*, code assigned to

the admission except in cases of falls, which were defined based on E codes. E codes, which can only be assigned as secondary (not primary) codes, are supplemental codes that capture the external cause of injury or poisoning, as well as the intent and the place where the event occurred (Web Table 1, available at http://aje.oxfordjournals.org/). For each outcome, we derived the daily number of admissions by adding the individual admissions across the 4 hospitals.

We obtained daily weather data (minimum, maximum, and average temperature, as well as daily amount of snow accumulation) from the Weather Source, which provided data from the monitoring station at Boston Logan Airport and included daily snow accumulation data for 95% of the days in our study period (18). We imputed missing snowfall data by taking the average of the snow accumulation from the day before and the day after the missing day. The study protocol was approved by the institutional review boards at the Harvard T.H. Chan School of Public Health (which covers Beth Israel Deaconess Medical Center, Massachusetts General Hospital, and Brigham and Women's Hospital) and at the Boston Medical Center.

### Statistical analysis

The outcome variable was the daily number of cause-specific hospital admissions. The exposure variable (independent variable) was defined as an indicator of category of snowfall: high (>10.0 inches of snow accumulation), moderate (5.1–10.0 inches), and low (0.05–5.0 inches), with no snowfall as the reference group. We used generalized linear models assuming a Poisson outcome with log link. We fit the models using quasi-likelihood methods to allow for overdispersion (19). For each outcome, we estimated the relative risk of hospital admission on days with low, moderate, or high snowfall compared with days without snowfall. We fit 3 separate models that included the subset of days with low versus no snowfall, moderate versus no snowfall, and high versus no snowfall. To account for secular trends in hospital admissions, we adjusted for calendar year, calendar month, and day of the week as categorical variables. To account for potentially delayed associations between snowfall and hospital admissions, we fit unconstrained distributed lag models (20–23) to estimate lag-specific relative risks on the day of snowfall (lag 0) and for the 6 days after the snowfall day (lags 1–6).

Specifically, our model was of the form

$$\log E(Y_t) = \alpha + \sum_{l=0}^{6} \beta_l snow_{t-l} + \sum_{i=1}^{6} \gamma_i dow_{it} + \sum_{j=1}^{5} \delta_j month_{jt} + \sum_{k=1}^{4} \delta_k winter_{kt}, \quad (1)$$

where $Y_t$ is the number of hospitalizations for a particular outcome on day $t$, $snow_{t-l}$ is an indicator for whether a day at lag $l$ from day $t$ belongs to the snowfall category or was a day without snowfall (reference group), $dow_{it}$ is an indicator variable for day of the week (where Monday is the reference day), $month_{jt}$ is an indicator variable for the calendar month (December–April versus the reference month of November), and $winter_{kt}$ is an indicator variable for the winter season (for which 2010–2011 is the reference

category). We examined the correlation of snowfall days across lags and did not find high correlations (the highest was 0.30 between lag 0 and lag 2 for low snowfall days); we therefore did not impose constraints on the distributed lag parameters $\beta_l$, which is recommended when there is concern of multicollinearity ([24]).

In the model, the lag-specific relative risks are given by the coefficients $\exp(\beta_l)$. We also estimated the overall relative risk of hospital admissions by adding the lag-specific estimates. Specifically, the overall relative risk compares the total number of hospitalizations in the weeklong period after a snowfall day with the total number of hospitalizations in the weeklong period after a day without snowfall and is given by $\frac{1}{7}\sum_{l=0}^{6}\exp(\beta_l)$. The standard error for the overall relative risk was calculated using the delta method.

To explore whether risks varied by age, we repeated the analysis stratified by age group (18–64 years vs. ≥65 years). We also conducted 2 sensitivity analyses. First, we evaluated whether the association of snowfall with health outcomes remained after controlling for temperature by including in the model a smooth function of average daily temperature that was modeled using natural cubic splines with 3 degrees of freedom ([25]). Second, we considered an alternative approach to adjusting for secular trends in which we included a smooth function of day within the winter season (from 0 to 181), where the coefficients of the smooth function were allowed to differ across each winter season. Specifically, for this alternative specification, rather than include the month and season-specific categorical variables, we included terms for the interaction between winter season and natural cubic splines of the day within the season with 4 degrees of freedom.

## RESULTS

Over the study period (the months of November–April in 2010–2015), there were 433,037 hospitalizations for the 4 outcomes (cardiovascular disease, cold-related diseases, injuries, and falls) considered across the 4 hospitals (Table 1). Figure 1 shows the daily snow accumulations during the study period (daily hospitalization data are shown in Web Figure 1). Of the 906 days, 110 (12.1%) had low snowfall, 11 (1.2%) had moderate snowfall, and 10 (1.1%) had high snowfall (Table 2). There were fewer days with no snowfall in later winters, and of the 10 high snowfall days, only 1 occurred during the first 2 winters, whereas 4 occurred during the 2014–2015 winter.

### Primary analysis

Figure 2 shows the lag-specific relative risk of hospitalization for 6 outcomes comparing low (0.05–5.0 inches), moderate (5.1–10.0 inches), and high (>10.0 inches) snowfall days with days without snowfall from the primary model (estimates from unadjusted model are in Web Figure 2; numerical values are in Web Table 2). Figure 3 shows the corresponding overall relative risk of hospitalizations obtained by summing the lag-specific relative risks for each snowfall category and each outcome (numerical results are in Web Table 3). The relative risks can be

interpreted as the percentage increase in hospitalizations on low, moderate, and high snowfall days compared with days without snowfall.

*Cardiovascular disease admissions.*  For high snowfall days, admissions for cardiovascular disease (all arrhythmias, IHD, and MI) were 32% lower on the day of the snowfall (lag 0) than on days without snowfall (relative risk = 0.68, 95% confidence interval: 0.54, 0.85), increased slightly on the next day (lag 1), and had the largest increase 2 days after the snowfall (lag 2), with a relative risk of 1.22 (95% confidence interval: 1.01, 1.49). The increase in admissions for cardiovascular disease 2 days after a high snowfall day was driven by an increase in MIs and IHD. We found a statistically significant increase of the overall relative risk on moderate snowfall days.

*Cold-related diseases.*  For high snowfall days, cold-related admissions were 23% higher 2 days after the snowfall day (at lag 2, relative risk = 1.23, 95% confidence interval: 1.01, 1.49). For moderate snowfall days, we observed a significant increase in cold-related disease admissions on the day of snowfall but estimates on subsequent days were not statistically significant. We observed an overall increased risk of cold-related disease hospitalizations for all snowfall categories, with a larger overall relative risk on days with more intense snowfall.

*Injuries and falls.*  We did not find evidence of a statistically significant increase in hospitalizations for injuries. For fall-related injuries, we found small but statistically significant relative risks on days 4, 5, and 6 after low snowfall days and on days 4 and 6 after moderate snowfall days. We also found an overall higher risk of hospitalizations on low and moderate but not high snowfall days.

### Sensitivity analysis

Adjustment for the average daily temperature did not change the estimated overall relative risks, except for cold-related illness hospitalizations, which had lower but still significant risks (Figure 4; Web Table 3). This suggests that for days with similar average temperatures, the presence of snow accumulation was associated with additional cold-related hospitalizations. In the sensitivity analysis that was adjusted for secular trends using splines, estimates for cardiovascular disease hospitalizations remained very similar, whereas estimates for cold-related hospitalizations associated with moderate and high snowfall days were slightly attenuated, and estimates for injuries requiring hospitalization after high snowfall days became statistically significant.

The analysis stratified by age group (Figure 5) indicated that the higher risk of cold-related hospitalizations on moderate and high snowfall days and cardiovascular disease hospitalizations on moderate snowfall days did not differ considerably across the 2 groups, whereas the increase in hospitalizations for falls was driven primarily by persons in the 18–64 years of age category.

### DISCUSSION

To our knowledge, this is the first study in which the time course of hospital admissions after low, moderate, and

**Table 1.** Characteristics of Study Population Admitted to 4 Hospitals From November to April Over the Entire Study Period During Days With or Without Snowfall, Boston, Massachusetts, 2010–2015

| Variable | Total (n = 433,037) | | None (n = 373,603) | | Low (0.05–5.0 inches) (n = 51,413) | | Moderate (5.1–10.0 inches) (n = 4,476) | | High (>10.0 inches) (n = 3,545) | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | No. | % | No. | % | No. | % | No. | % | No. | % |
| Admission type | | | | | | | | | | |
| Inpatient | 330,082 | 76.2 | 284,643 | 76.2 | 39,218 | 76.3 | 3,501 | 78.2 | 2,720 | 76.7 |
| Observation | 102,955 | 23.8 | 88,960 | 23.8 | 12,195 | 23.7 | 975 | 21.8 | 825 | 23.3 |
| Age, years[a] | 55.5 (19.1) | | 55.5 (19.1) | | 55.6 (19.1) | | 54.4 (19.4) | | 54.6 (19.1) | |
| Age group, years | | | | | | | | | | |
| 18–45 | 137,363 | 31.7 | 118,440 | 31.7 | 16,231 | 31.6 | 1,506 | 33.6 | 1,186 | 33.5 |
| 46–65 | 152,346 | 35.2 | 131,514 | 35.2 | 17,975 | 35.0 | 1,593 | 35.6% | 1,264 | 35.7 |
| >65 | 143,328 | 33.1 | 123,649 | 33.1 | 17,207 | 33.5 | 1,377 | 30.8 | 1,095 | 30.9 |
| Sex | | | | | | | | | | |
| Female | 241,123 | 55.7 | 207,929 | 55.7 | 28,730 | 55.9 | 2,496 | 55.8 | 1,968 | 55.5 |
| Male | 191,910 | 44.3 | 165,670 | 44.3 | 22,683 | 44.1 | 1,980 | 44.2 | 1,577 | 44.5 |
| Unknown/unspecified | 4 | 0.0 | 4 | 0.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 |
| Race | | | | | | | | | | |
| Asian | 14,559 | 3.4 | 12,525 | 3.4 | 1,732 | 3.4 | 169 | 3.8 | 133 | 3.8 |
| Black | 68,807 | 15.9 | 59,173 | 15.8 | 8,391 | 16.3 | 709 | 15.8 | 534 | 15.1 |
| Hispanic | 34,346 | 7.9 | 29,632 | 7.9 | 4,081 | 7.9 | 340 | 7.6 | 293 | 8.3 |
| White | 276,230 | 63.8 | 238,345 | 63.8 | 32,820 | 63.8 | 2,763 | 61.7 | 2,302 | 64.9 |
| Other/unknown | 39,095 | 9.0 | 33,928 | 9.1 | 4,389 | 8.5 | 495 | 11.1 | 283 | 8.0 |
| Discharge vital status | | | | | | | | | | |
| Alive | 424,810 | 98.1 | 366,546 | 98.1 | 50,431 | 98.1 | 4,367 | 97.6 | 3,466 | 97.8 |
| Dead | 8,224 | 1.9 | 7,056 | 1.9 | 981 | 1.9 | 109 | 2.4 | 78 | 2.2 |
| Missing | 3 | 0.0 | 1 | 0.0 | 0 | 0.0 | 0 | 0.0 | 1 | 0.0 |
| Outcome category | | | | | | | | | | |
| Cardiovascular disease[b] | 11,338 | 2.6 | 9,751 | 2.6 | 1,364 | 2.7 | 136 | 3.1 | 87 | 2.4 |
| MI and IHD | 5,726 | 1.3 | 4,889 | 1.3 | 713 | 1.4 | 80 | 1.8 | 44 | 1.2 |
| Severe arrhythmias and cardiac arrest | 5,612 | 1.3 | 4,862 | 1.3 | 651 | 1.3 | 56 | 1.3 | 43 | 1.2 |
| Cold-related diseases | 162 | 0.0 | 117 | 0.0 | 30 | 0.1 | 6 | 0.1 | 9 | 0.3 |
| Injuries | 20,538 | 4.7 | 17,714 | 4.7 | 2,391 | 4.7 | 245 | 5.5 | 188 | 5.3 |
| Fall E code[c] | 5,402 | 1.2 | 4,576 | 1.2 | 699 | 1.4 | 83 | 1.9 | 44 | 1.2 |

Abbreviations: IHD, ischemic heart disease; MI, myocardial infarction.

[a] Data are express as mean (standard deviation).

[b] Including all arrhythmias, IHD, and MI.

[c] E codes, which can only be assigned as secondary codes (not primary), are supplemental codes from the *International Classification of Diseases, Ninth Revision*, that capture the external cause of injury or poisoning, as well as the intent and the place where the event occurred.

high snowfall have been examined in an area affected by severe winter weather across several disease causes. We found that the risk of hospitalization varied depending on the cause of the admission, the intensity of snow accumulation, and the time lag from the snowfall day. The study period included the extreme weather events experienced in Boston in the winter of 2014–2015, as well as 3 of the largest winter storms ever recorded in Boston (winter storms Nemo, February 8–9, 2013; Juno, January 26–28, 2015; and Marcus, February 7–10, 2015).

**Cardiovascular disease admissions**

The mechanisms by which snowstorms and severe winter weather lead to adverse cardiovascular events have not been resolved. Exposure to low temperatures has been associated with excess cardiovascular mortality (13) and an increased risk of acute MI (26), but our estimates of the overall relative risk of hospitalizations for cardiovascular disease did not change substantially (and remained statistically significant) after flexible adjustment for daily temperature, which
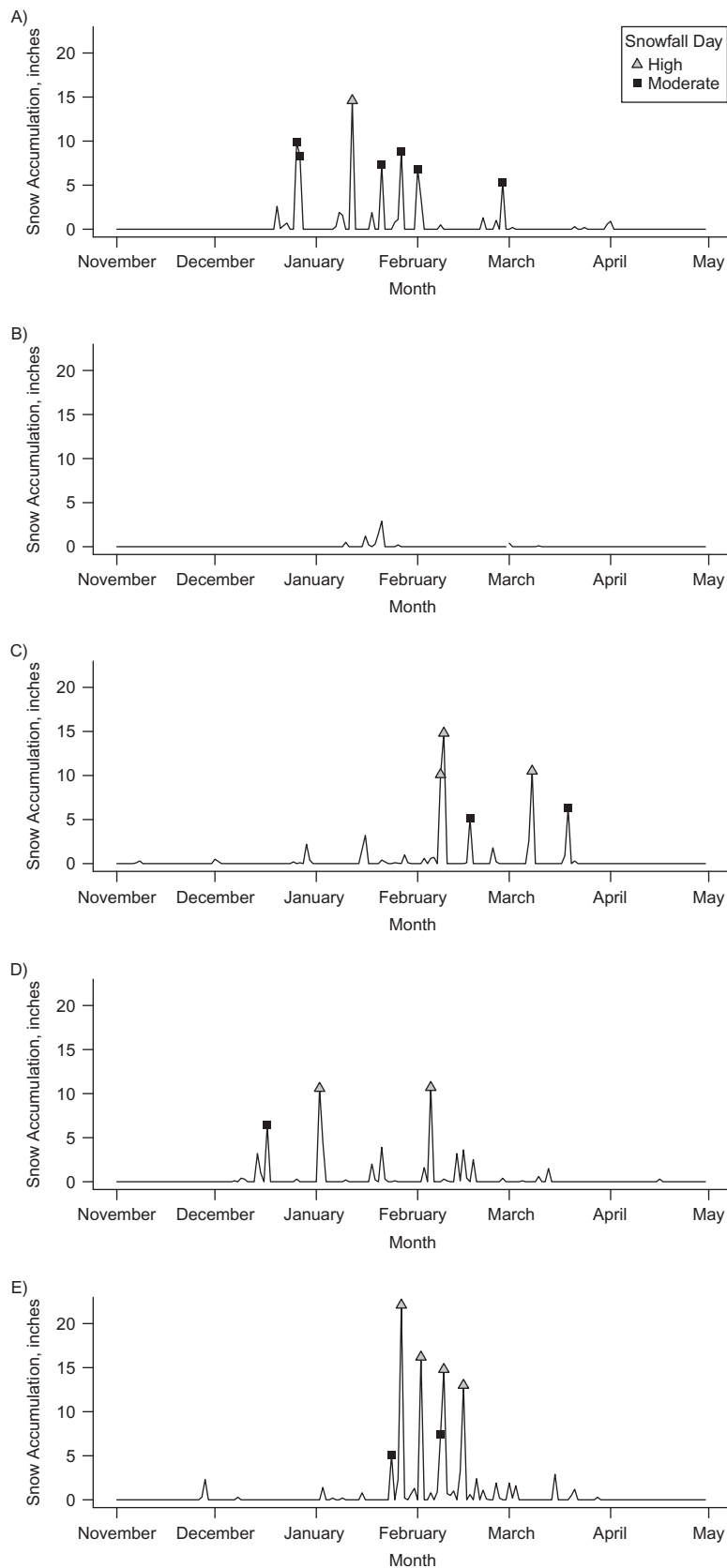
**Figure 1.** Daily snow accumulation by winter season and type of snowfall day, Boston, Massachusetts. A) 2010–2011; B) 2011–2012; C) 2012–2013; D) 2013–2014; and E) 2014–2015.

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**Table 2.** Summary Statistics of Daily Data by Snowfall Category, Boston, Massachusetts, 2010–2015

| Variable | Total | | | None | | | Snowfall Category | | | | | | | | | P Value[a] |
| | | | | | | | Low (0.05–5.0 inches) | | | Moderate (5.1–10.0 inches) | | | High (>10.0 inches) | | | |
| | No. | % | Mean (SD) | No. | % | Mean (SD) | No. | % | Mean (SD) | No. | % | Mean (SD) | No. | % | Mean (SD) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. of days | 906 | 100 | | 775 | 85.5 | | 110 | 12.1 | | 11 | 1.2 | | 10 | 1.1 | | |
| Daily weather | | | | | | | | | | | | | | | | |
| Snowfall, inches | | | 0.4 (1.7) | | | 0.0 (0.0) | | | 1.0 (1.0) | | | 7.0 (1.6) | | | 13.7 (3.7) | <0.0001 |
| Average daily temperature, °F[b] | | | 38.0 (11.3) | | | 39.7 (10.9) | | | 28.5 (6.8) | | | 25.7 (4.8) | | | 22.0 (8.2) | <0.0001 |
| Minimum daily temperature, °F | | | 30.7 (10.9) | | | 32.2 (10.6) | | | 22.3 (8.0) | | | 20.5 (6.4) | | | 15.3 (10.2) | <0.0001 |
| Maximum daily temperature, °F | | | 45.2 (12.3) | | | 47.1 (12.0) | | | 34.7 (6.7) | | | 30.9 (3.9) | | | 28.5 (7.7) | <0.0001 |
| Winter season | | | | | | | | | | | | | | | | 0.002 |
| 2010–2011 | 181 | 20 | | 155 | 20 | | 19 | 17.3 | | 6 | 54.5 | | 1 | 10.0 | | |
| 2011–2012 | 182 | 20.1 | | 172 | 22.2 | | 10 | 9.1 | | 0 | 0.0 | | 0 | 0.0 | | |
| 2012–2013 | 181 | 20.0 | | 151 | 19.5 | | 25 | 22.7 | | 2 | 18.2 | | 3 | 30.0 | | |
| 2013–2014 | 181 | 20 | | 152 | 19.6 | | 26 | 23.6 | | 1 | 9.1 | | 2 | 20.0 | | |
| 2014–2015 | 181 | 20 | | 145 | 18.7 | | 30 | 27.3 | | 2 | 18.2 | | 4 | 40.0 | | |
| Month | | | | | | | | | | | | | | | | <0.0001 |
| November | 150 | 16.6 | | 146 | 18.8 | | 4 | 3.6 | | 0 | | | 0 | | | |
| December | 155 | 17.1 | | 135 | 17.4 | | 17 | 15.5 | | 3 | 27.3 | | 0 | | | |
| January | 155 | 17.1 | | 113 | 14.6 | | 36 | 32.7 | | 3 | 27.3 | | 3 | 30.0 | | |
| February | 146 | 15.6 | | 99 | 12.8 | | 32 | 29.1 | | 4 | 36.4 | | 6 | 60.0 | | |
| March | 155 | 17.1 | | 134 | 17.3 | | 19 | 17.3 | | 1 | 9.1 | | 1 | 10.0 | | |
| April | 150 | 16.6 | | 148 | 19.1 | | 2 | 1.8 | | 0 | | | 0 | | | |
| Day of the week | | | | | | | | | | | | | | | | 0.83 |
| Monday | 130 | 14.3 | | 112 | 14.5 | | 15 | 13.6 | | 1 | 9.1 | | 2 | 20.0 | | |
| Tuesday | 130 | 14.3 | | 108 | 13.9 | | 18 | 16.4 | | 3 | 27.3 | | 1 | 10.0 | | |
| Wednesday | 129 | 14.2 | | 113 | 14.6 | | 14 | 12.7 | | 0 | 0.0 | | 2 | 20.0 | | |
| Thursday | 129 | 14.2 | | 107 | 13.8 | | 20 | 18.2 | | 1 | 9.1 | | 1 | 10.0 | | |
| Friday | 129 | 14.2 | | 114 | 14.7 | | 12 | 10.9 | | 1 | 9.1 | | 2 | 20.0 | | |
| Saturday | 130 | 14.3 | | 109 | 14.1 | | 19 | 17.3 | | 1 | 9.1 | | 1 | 10.0 | | |
| Sunday | 129 | 14.2 | | 112 | 14.5 | | 12 | 10.9 | | 4 | 36.4 | | 1 | 10.0 | | |

**Table continues**

**Table 2.** Continued

| Variable | Total | | | None | | | Snowfall Category | | | | | | | | | P Value[a] |
| | | | | | | | Low (0.05–5.0 inches) | | | Moderate (5.1–10.0 inches) | | | High (>10.0 inches) | | | |
| | No. | % | Mean (SD) | No. | % | Mean (SD) | No. | % | Mean (SD) | No. | % | Mean (SD) | No. | % | Mean (SD) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Same-day[c] (lag 0) admissions | | | | | | | | | | | | | | | | |
| Cardiovascular disease[d] | | | 12.5 (4.0) | | | 12.6 (3.9) | | | 12.4 (4.1) | | | 12.4 (5.2) | | | 8.7 (2.3) | 0.023 |
| MI and IHD | | | 6.3 (2.7) | | | 6.3 (2.7) | | | 6.5 (2.7) | | | 7.3 (3.5) | | | 4.4 (2.2) | 0.081 |
| Severe arrhythmia and cardiac arrest | | | 6.2 (6.2) | | | 6.3 (2.6) | | | 5.9 (2.7) | | | 5.1 (2.6) | | | 4.3 (2.5) | 0.028 |
| Cold-related diseases | | | 0.2 (0.5) | | | 0.2 (0.4) | | | 0.3 (0.6) | | | 0.5 (1.0) | | | 0.9 (1.4) | <0.0001 |
| Injuries | | | 22.7 (22.7) | | | 22.9 (5.7) | | | 21.7 (5.2) | | | 22.3 (4.8) | | | 18.8 (5.0) | 0.033 |
| Falls | | | 6.0 (2.9) | | | 5.9 (2.9) | | | 6.4 (3.2) | | | 7.5 (4.5) | | | 4.4 (1.9) | 0.039 |
| Total admissions over 1 week[e] (lags 0–6) | | | | | | | | | | | | | | | | |
| Cardiovascular disease[d] | | | 87.6 (10.4) | | | 87.8 (10.4) | | | 86.0 (10.3) | | | 89.3 (10.0) | | | 88.9 (12.9) | 0.36 |
| MI and IHD | | | 44.3 (7.1) | | | 44.2 (7.0) | | | 44.6 (7.8) | | | 46.6 (5.5) | | | 47.1 (8.1) | 0.38 |
| Severe arrhythmia and cardiac arrest | | | 43.3 (7.5) | | | 43.6 (7.6) | | | 41.4 (6.9) | | | 42.6 (7.7) | | | 41.8 (9.2) | 0.038 |
| Cold-related diseases | | | 1.3 (1.6) | | | 1.0 (1.4) | | | 2.3 (1.8) | | | 3.4 (1.6) | | | 4.3 (2.1) | <0.0001 |
| Injuries | | | 158.5 (16.5) | | | 158.8 (16.6) | | | 156.6 (15.6) | | | 165.5 (19.6) | | | 149.1 (19.0) | 0.076 |
| Falls | | | 41.9 (11.2) | | | 41.0 (10.6) | | | 45.9 (12.7) | | | 56.2 (11.3) | | | 47.2 (9.4) | <0.0001 |
| In-hospital mortality rate[f] | | | | | | | | | | | | | | | | |
| Same-day (lag 0) | | | 0.020 (0.008) | | | 0.020 (0.007) | | | 0.020 (0.008) | | | 0.025 (0.011) | | | 0.023 (0.011) | 0.056 |
| Over 1 week (lags 0–6) | | | 0.019 (0.003) | | | 0.019 (0.003) | | | 0.020 (0.003) | | | 0.021 (0.003) | | | 0.020 (0.004) | <0.001 |

Abbreviations: IHD, ischemic heart disease; MI, myocardial infarction; SD, standard deviation.

[a] Tests for a difference in distribution across snowfall categories: for continuous variables, Wilcoxen rank sum test; for categorical variables, either Fisher's exact test (variables with 2–3 categories) or analysis of variance (variables with ≥4 categories).

[b] Conversion: °C = (°F − 32)/1.8.

[c] Number of daily admissions on the snowfall day.

[d] Including all arrhythmias, IHD, and MI.

[e] Number of admissions summed over a weeklong period that included the snowfall day and up to 6 days after.

[f] Equal to number of admissions that resulted in death divided by the total number of admissions.
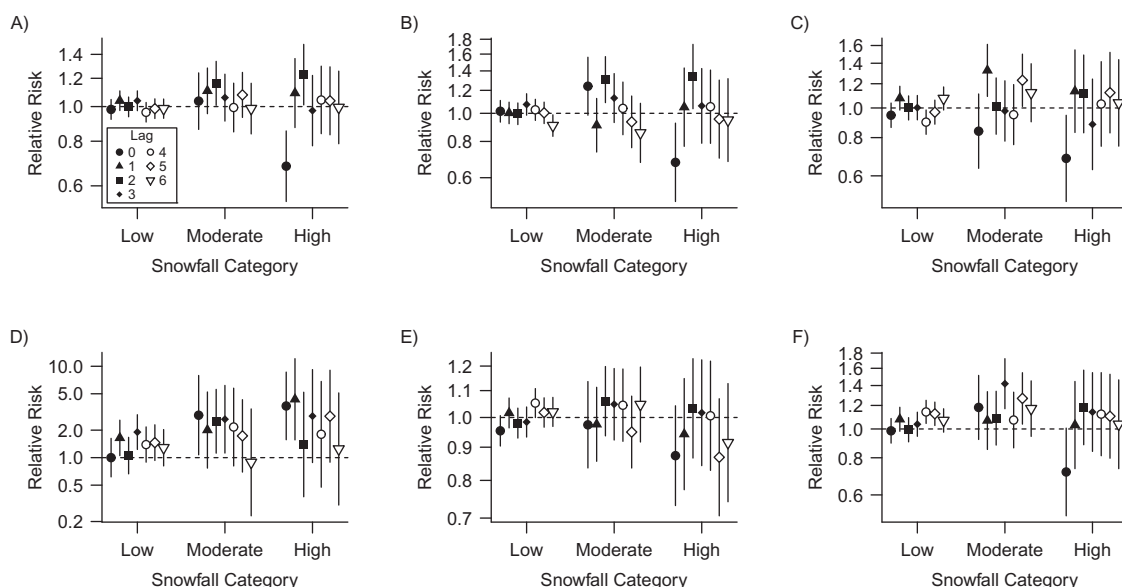
**Figure 2.** Lag-specific relative risk of hospital admission for 6 outcomes comparing low (0.05–5.0 inches), moderate (5.1–10.0 inches), and high (>10.0 inches) snowfall days to days without snowfall, Boston, Massachusetts, 2010–2015. A) Cardiovascular disease; B) myocardial infarction and ischemic heart disease; C) arrhythmias/cardiac arrest; D) cold-related diseases; E) injuries; and F) falls. Lags correspond to the day of the snowfall (lag 0) and up to 6 days after (lags 1–6). The model is adjusted for calendar year, day of the week, and winter month. Cardiovascular disease includes all arrhythmias, ischemic heart disease, and myocardial infarction. One inch = 2.54 cm.

suggests that additional factors beyond temperature likely play a role. Snow shoveling may be one such factor. This possibility derives from case studies of "snow-shoveler's infarction" (11, 27), which found that heavy snow shoveling resulted in cardiorespiratory demands that were comparable to or higher than the demands of maximal treadmill testing (28). Findings from other studies have also shown increased mortality for several days after a snowstorm (8). Similarly, we found an elevated risk of MI/IHD 2 days after and severe arrhythmias/cardiac arrest 1 day after moderate snowfall days, with an overall increased risk for cardiovascular hospitalization across all lags after moderate snowfall.

### Falls and injuries

In prior studies, investigators have examined the associations of snowfall with emergency department visits (29) and motor vehicle collisions (30). In 1, researchers identified clusters of emergency department visits resulting from falls and found that these clusters occurred during periods of snowfall or freezing rain (29). This result supports our finding that snowfall is associated with an increased risk of hospitalizations from falls. In another study, the risk of motor vehicle collisions on snowfall days compared with dry days was estimated, and the results were mixed: Snowfall days were associated with a higher risk of nonfatal injuries from crashes but a lower risk of fatal crashes (29). We did not observe any association between snowfall and an increased risk of hospitalization from injuries. One possibility could be that, because our data excluded outpatient visits, we might have missed less severe injuries that did not lead to hospitalization. Another explanation could

be that our injuries outcome category, which is heterogeneous with a large number of diagnoses, includes several types of injury not affected by snow, diluting the associations of specific injuries that may increase with snowfall. Future work should investigate diagnosis-specific outcomes within the broader outcome categories considered here.

### Intensity of snow accumulation

It is interesting that moderate but not high snowfall was associated with an overall increase in cardiovascular admissions and that low and moderate but not high snowfall were associated with an overall increase in falls that required hospital admission. One explanation could be that the individuals most susceptible to cardiovascular events or falls tend to stay inside during the most severe weather conditions and therefore would not be exposed to the health hazards posed by these conditions. Our age-stratified results, which showed that the increase in hospital admissions for falls was driven predominantly by younger adults, support this possibility. The lower risk of cardiovascular hospitalization on high snowfall days (lag 0, >10.0 inches) may be related to individuals staying indoors and not engaging in activities that lead to adverse events.

### Lag-specific results

We found that the time lag with the highest risk of admissions differed depending on the cause of disease and the severity of the snowfall. For example, hospitalizations for cardiovascular disease decreased sharply on high snowfall days (lag 0, >10.0 inches) compared with days without
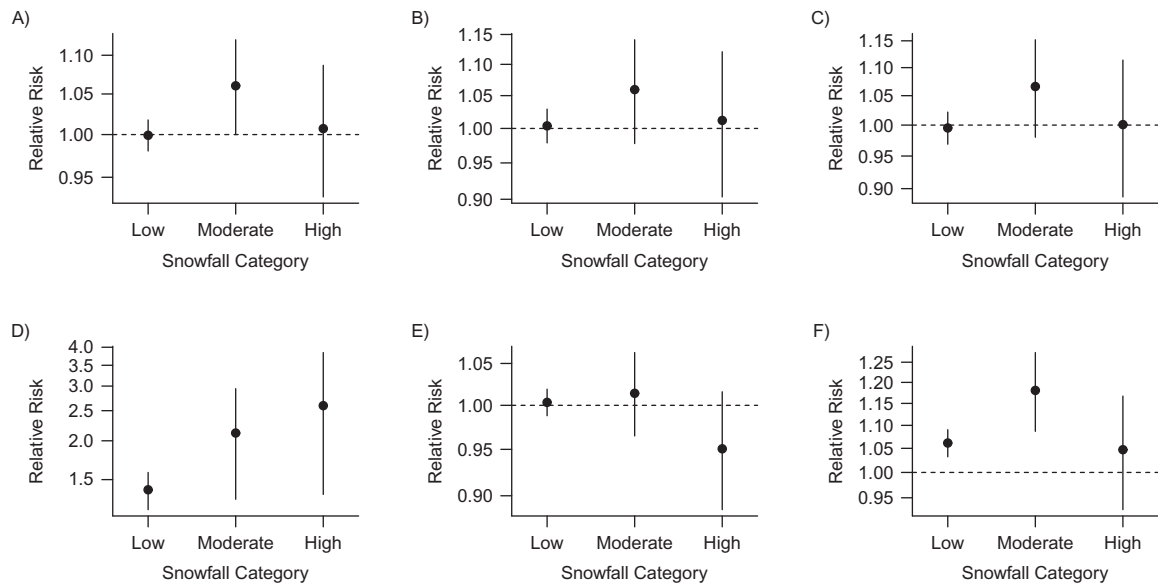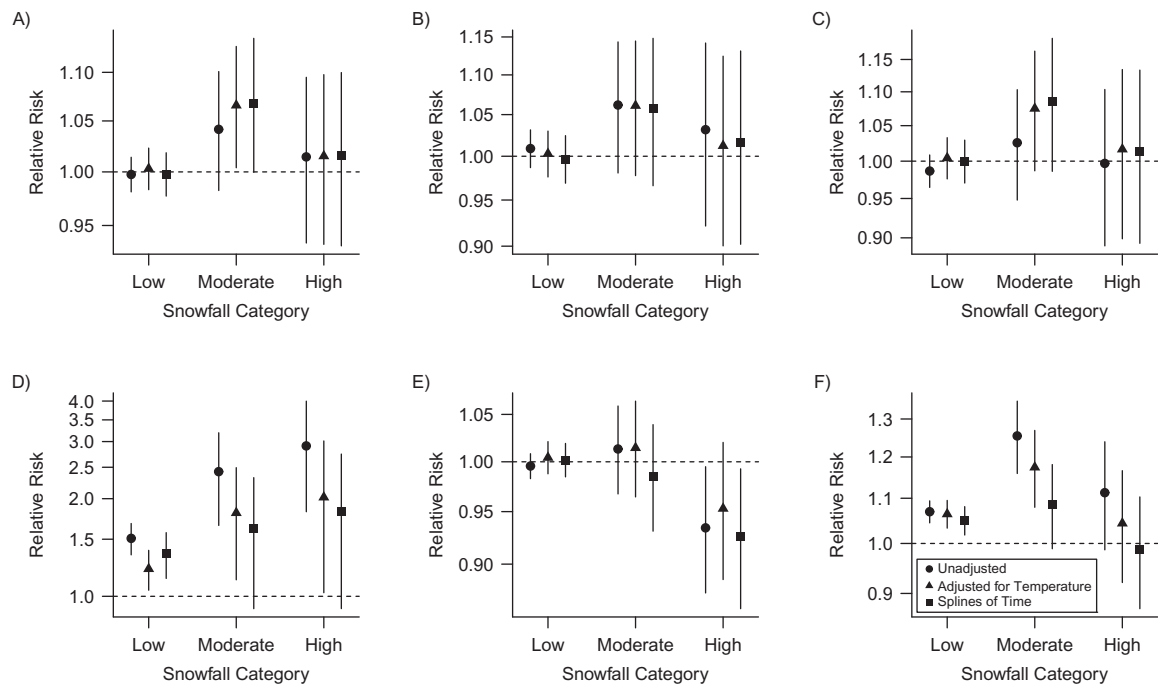
**Figure 3.** Overall relative risk of hospital admission summed over lags 0–6 for 6 outcomes comparing low (0.05–5.0 inches), moderate (5.1–10.0 inches), and high (>10.0 inches) snowfall days to days without snowfall, Boston, Massachusetts, 2010–2015. A) Cardiovascular disease; B) myocardial infarction and ischemic heart disease; C) arrhythmias/cardiac arrest; D) cold-related diseases; E) injuries; and F) falls. Estimates are from the primary model that was adjusted for secular trends. Cardiovascular disease includes all arrhythmias, ischemic heart disease, and myocardial infarction. One inch = 2.54 cm.



**Figure 4.** Sensitivity analysis for the overall relative risk of hospital admission summed over lags 0–6 for 6 outcomes comparing low (0.05–5.0 inches), moderate (5.1–10.0 inches), and high (>10.0 inches) snowfall days to days without snowfall, Boston, Massachusetts, 2010–2015. A) Cardiovascular disease; B) myocardial infarction and ischemic heart disease; C) arrhythmias/cardiac arrest; D) cold-related diseases; E) injuries; and F) falls. The unadjusted model only included the snowfall day indicator variable; the primary model was adjusted for day of the week, month, and calendar year; the model adjusted for temperature was additionally adjusted for natural cubic splines of average daily temperature with 3 degrees of freedom (df); the splines of time model was adjusted for day of the week and terms for the interaction between calendar year and natural cubic splines of the day within the season with 4 df. Cardiovascular disease includes all arrhythmias, ischemic heart disease, and myocardial infarction. One inch = 2.54 cm.
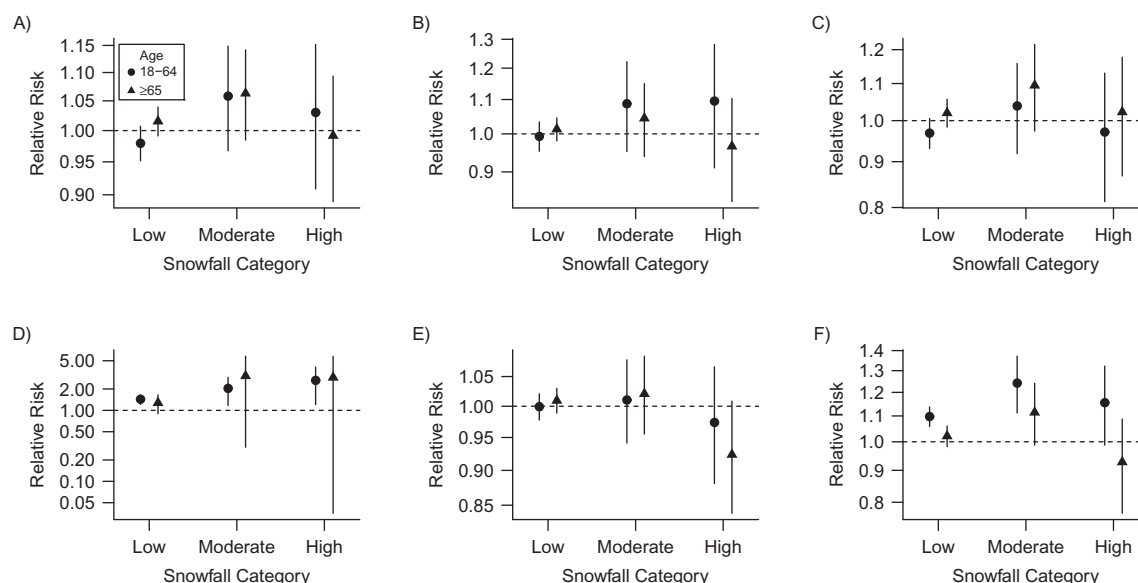
**Figure 5.** Age-stratified analysis for the overall relative risk of hospital admission summed over lags 0–6 for 6 outcomes comparing low (0.05–5.0 inches), moderate (5.1–10.0 inches), and high (>10.0 inches) snowfall days to days without snowfall, Boston, Massachusetts, 2010–2015. A) Cardiovascular disease; B) myocardial infarction and ischemic heart disease; C) arrhythmias/cardiac arrest; D) cold-related diseases; E) injuries; and F) falls. Estimates are from the primary model, which was adjusted for secular trends. Cardiovascular disease includes all arrhythmias, ischemic heart disease, and myocardial infarction. One inch = 2.54 cm.

snowfall, peaked 2 days after the high snowfall day (lag 2), and then returned to baseline levels on subsequent days. For cold-related disease admissions, the highest risks occurred on the day of (lag 0) and the day after (lag 1) a high snowfall, and for falls, the highest risks occurred a few days after a low or moderate snowfall day.

Our finding that cardiovascular admissions decreased on high snowfall days but increased on subsequent days prompts us to question whether these findings reflect excess hospitalizations resulting from weather conditions or if they are simply due to delays in getting to the hospital. Individuals may delay going to (or be unable to get to) the hospital during high snowfall days, especially when there is a declared snow emergency, travel ban, or shutdown of public transportation. Of the 4 days in the winter of 2014–2015 with more than 10 inches of snow, 3 days were declared a snow emergency, 1 of which had a 24-hour statewide travel ban (January 27, 2015; 22.1 inches of snow accumulation). Our estimates of the overall relative risk, which did not differ from the null, suggest that rather than leading to new hospitalizations, heavy snow accumulation may instead shift those admissions to a few days later when the snowstorm has subsided. This result highlights the importance of our methodology, which allows for estimating both the lag-specific and overall effects of snowfall on daily hospital admissions.

Given that snowstorms have been associated with higher rates of death from IHD on the day of the snowstorm (lag 0) (9), another possible explanation for the reduced number of same-day cardiovascular disease admissions is that those individuals with the highest risk of an acute cardiac event

who otherwise would have been hospitalized may have died suddenly during the storm and therefore never been hospitalized (16, 17).

A key feature of our modeling approach, in which we estimated the association between day-to-day changes in snowfall and day-to-day changes in hospital admissions, is that it controls for both measured and unmeasured factors that vary slowly over time but do not change daily (21, 31, 32), such as race/ethnicity and socioeconomic status. One factor that does vary daily is air pollution level; however, because air pollution is unlikely to cause snowfall, we do not need to adjusted for it to control for confounding (33). On the other hand, major storms may lead to higher air pollution levels, and therefore air pollution could be a mediator of adverse snowstorm-related health effects, which is a topic for future investigation.

Several limitations should be acknowledged. First, the snowfall data were measured at a single monitoring location in Boston and may differ from citywide average levels. Second, using billing codes to define outcomes has known limitations. For example, because diagnoses which result in the highest payout from patients or insurance providers are more likely to be identified as the primary diagnosis code, an admission may not be coded as a cold-related disease if other diagnoses are present. However, we would expect this outcome misclassification to occur on days with and without snowfall (i.e., nondifferential misclassification), and thus it would likely bias the relative risk estimates toward the null (34). Third, we only considered admissions and did not include other outcomes, such as emergency department volume, clinic volume, or treatment for falls and injuries

that did not require admission. Fourth, although our study included 4 major hospitals within the urban center of Boston, the severe winter weather affected a much broader region. Thus, our results may not be generalizable to more suburban or rural areas that differ across a range of factors, including demographic characteristics, accessibility to hospitals, and reliance on cars versus other modes of transportation (e.g., walking, public transit). Future multisite studies covering a broader geographical area with different weather patterns, age structures, and potential adaptations to severe winter weather are warranted to both replicate the findings of the current study and explore characteristics that might modify the association between snowfall and hospital admissions.

Study strengths include the large population-based sample and the use of electronic medical records, which provide more detailed information than do claims data and include all age groups, not just people older than 65 years of age. Additionally, the length of the study period allowed us to capture a range of severity across winters, including the historic 2014–2015 winter season, and our application of distributed lag models allowed us to measure delayed associations and the variations associated with the severity of the snowfall event and the cause of hospitalization. The 4 hospitals that participated in this study represent the largest in the city of Boston and provide 71% of all hospital beds in facilities that provide acute care for nonpediatric populations (35).

With global climate change, the frequency of snowstorms is expected to increase, and characterizing the health impact of snowstorms by degree of snow accumulation, disease outcomes, and their time course is paramount. The results of the present study can be directly translated into public health and clinical interventions that prevent hospital admissions caused by snowstorms and protect public health during harsh winter conditions.

## ACKNOWLEDGMENTS

## REFERENCES

1. Bell JE, Herring SC, Jantarasami L et al. Impacts of extreme events on human health. In: Crimmins A, Balbus J, Gamble JL, et al., eds. *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. Washington, DC: US Global Change Research Program; 2016:99–128.
2. Schwartz RM. Societal impacts of blizzards in the conterminous United States, 1959–2000. In: Janelle DG, Warf B, Hansen K, eds. *Worldminds: Geographical Perspectives on 100 Problems*. Dordrecht, Netherlands: Springer Netherlands; 2004:449–454.
3. Barron J, Rojas R. Swirling storm draws white curtain over east. *The New York Times*. January 24, 2016:A1.
4. Smith J, Fox JC. More snow, intense cold compound the misery. *The Boston Globe*. February 15, 2015:Weather. https://www.bostonglobe.com/metro/2015/02/15/snow/2IO1E0ibEJ1PK1sC1wPAyO/story.html. Accessed July 8, 2016.
5. Hartmann DL, Klein Tank AMG, Rusticucci M, et al. Observations: atmosphere and surface. In: Stocker TF, Qin D, Plattner G-K, et al., eds. *Climate Change 2013: The Physical Science Basis Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press; 2013:159–254.
6. Kunkel KE, Karl TR, Brooks H, et al. Monitoring and understanding trends in extreme storms: state of knowledge. *Bull Am Meteorol Soc*. 2013;94(4):499–514.
7. Walsh J, Wuebbles D, Hayhoe K, et al. Our changing climate. In: Melillo JM, Richmond TC, Yohe GW, eds. *Climate Change Impacts in the United States: The Third National Climate Assessment*. Washington, DC: US Global Change Research Program; 2014.
8. Glass RI, Zack MM Jr. Increase in deaths from ischaemic heart-disease after blizzards. *Lancet*. 1979;1(8114):485–487.
9. Gorjanc ML, Flanders WD, VanDerslice J, et al. Effects of temperature and snowfall on mortality in pennsylvania. *Am J Epidemiol*. 1999;149(12):1152–1160.
10. Spitalnic SJ, Jagminas L, Cox J. An association between snowfall and ED presentation of cardiac arrest. *Am J Emerg Med*. 1996;14(6):572–573.
11. Heppell R, Hawley SK, Channer KS. Snow shoveller's infarction. *BMJ*. 1991;302(6774):469–470.
12. Faich G, Rose R. Blizzard morbidity and mortality: Rhode Island, 1978. *Am J Public Health*. 1979;69(10):1050–1052.
13. Anderson BG, Bell ML. Weather-related mortality: how heat, cold, and heat waves affect mortality in the united states. *Epidemiology*. 2009;20(2):205–213.
14. Gasparrini A, Guo Y, Hashizume M, et al. Mortality risk attributable to high and low ambient temperature: a multicountry observational study. *Lancet*. 2015;386(9991):369–375.
15. Ye X, Wolff R, Yu W, et al. Ambient temperature and morbidity: a review of epidemiological evidence. *Environ Health Perspect*. 2012;120(1):19–28.
16. Armstrong B, Gasparrini A, Hajat S. Estimating mortality displacement during and after heat waves. *Am J Epidemiol*. 2014;179(12):1405–1406.

17. Braga AL, Zanobetti A, Schwartz J. The time course of weather-related deaths. *Epidemiology*. 2001;12(6):662–667.
18. Weather Source LLC. *Bulk Data Downloads*. http://weathersource.com/hyper-local-past-present-and-forecast-worldwide-weather-data-for-business-intelligence/bulk-data-downloads. Accessed November 21, 2016.
19. McCullagh P, Nelder JA. *Generalized Linear Models*. 2nd ed. Boca Raton, FL: Chapman and Hall/CRC; 1989.
20. Peng RD, Dominici F, Welty LJ. A Bayesian hierarchical distributed lag model for estimating the time course of risk of hospitalization associated with particulate matter air pollution. *J R Stat Soc Ser C Appl Stat*. 2009;58(1):3–24.
21. Peng RD, Dominici F. *Statistical Methods for Environmental Epidemiology in R: A Case Study in Air Pollution and Health*. New York, NY: Springer-Verlag; 2008.
22. Schwartz J. The distributed lag between air pollution and daily deaths. *Epidemiology*. 2000;11(3):320–326.
23. Welty LJ, Peng RD, Zeger SL, et al. Bayesian distributed lag models: estimating effects of particulate matter air pollution on daily mortality. *Biometrics*. 2009;65(1):282–291.
24. Bhaskaran K, Gasparrini A, Hajat S, et al. Time series regression studies in environmental epidemiology. *Int J Epidemiol*. 2013;42(4):1187–1195.
25. Hastie TJ, Tibshirani RJ. *Generalized Additive Models*. Boca Raton, FL: Chapman & Hall/CRC; 1990.
26. Bhaskaran K, Hajat S, Haines A, et al. Effects of ambient temperature on the incidence of myocardial infarction. *Heart*. 2009;95(21):1760–1769.
27. Janardhanan R, Henry Z, Hur DJ, et al. The snow-shoveler's ST elevation myocardial infarction. *Am J Cardiol*. 2010; 106(4):596–600.
28. Franklin BA, Hogan P, Bonzheim K, et al. Cardiac demands of heavy snow shoveling. *JAMA*. 1995;273(11):880–882.
29. Dey AN, Hicks P, Benoit S, et al. Automated monitoring of clusters of falls associated with severe winter weather using the BioSense system. *Inj Prev*. 2010;16(6):403–407.
30. Eisenberg D, Warner KE. Effects of snowfalls on motor vehicle collisions, injuries, and fatalities. *Am J Public Health*. 2005;95(1):120–124.
31. Dominici F, Wang C, Crainiceanu CM, et al. Model selection and health effect estimation in environmental epidemiology. *Epidemiology*. 2008;19(4):558–560.
32. Peng RD, Dominici F, Louis TA. Model choice in time series studies of air pollution and mortality. *J R Stat Soc Ser A Stat Soc*. 2006;169(2):179–203.
33. Buckley JP, Samet JM, Richardson DB. Commentary: does air pollution confound studies of temperature? *Epidemiology*. 2014;25(2):242–245.
34. Rothman KJ, Greenland S, Lash TL, eds. *Modern Epidemiology*. Philadelphia, PA: Lippincott Williams & Wilkins; 2008.
35. Division of Health Care Facility Licensure and Certification, Department of Public Health, Executive Office of Health and Human Services, Commonwealth of Massachusetts. *Health Care Facility Licensure and Certification*. http://www.mass.gov/eohhs/gov/departments/dph/programs/hcq/healthcare-quality/. Accessed January 19, 2016.