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The impact of personal and outdoor temperature exposure during cold and warm seasons on lung function and respiratory symptoms in COPD

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ABSTRACT

Rationale: Chronic Obstructive Pulmonary Disease (COPD) patients often report aggravated symptoms due to heat and cold, but few studies have formally evaluated this.

Methodology: We followed 30 Boston-based former smokers with COPD for 4 non-consecutive 30-day periods in over 12 months. Personal and outdoor temperature exposure was measured using portable and Boston-area outdoor stationary monitors. Participants recorded daily morning lung function and reported any worsening breathing (breathlessness, chest tightness, wheeze) and bronchitis symptoms (cough, sputum color and amount) compared to baseline. Using linear and generalized linear mixed-effects models, we assessed associations between personal and outdoor temperature (1-3-day moving averages) exposure and lung function and symptoms, respectively, adjusting for humidity, smoking pack-years, and demographics. We also stratified by warm and cold season.

Results: Participants were on average 71.1 (±8.4) years old, with 54.4 (±30.7) pack-years of smoking. Each 5°C higher personal temperature exposure was associated with a 1.85 (95% CI, 0.99-3.48) higher odds of worsening breathing symptoms. In the warm season, each 5°C higher personal and outdoor temperature exposure were associated with a 3.20 (95% CI, 1.05-9.72) and a 2.22 (95% CI, 1.41-3.48) higher odds of worsening breathing symptoms, respectively. Lower outdoor temperature was associated with higher odds of worsening bronchitis symptoms (OR 1.25 per 5°C, 95% CI 1.04-1.51). There were no associations between temperature and lung function.

Conclusions: Our findings suggest that higher temperature, including outdoor warm season and personal temperature exposure year-round, may worsen dyspnea, while colder outdoor temperature may trigger cough and phlegm symptoms among COPD patients.

Background

Chronic Obstructive Pulmonary Disease (COPD) is the third leading cause of death in the world, with global burden and mortality estimated to continue to rise in the coming decades[1]. Symptoms of COPD include chronic cough, production of phlegm (mucus), and dyspnea[2]. The disease course often involves a progressive, inexorable functional decline with acute episodes of exacerbation[3].

There is increasing attention given to the effects of weather exposure in the context of climate change[4]. Extremes of temperature such as heat waves, hot weather, and extended periods of cold may negatively affect lung function and symptom burden in COPD. In fact, COPD patients often report susceptibility to temperature and weather changes.[5–8] Both summer heat[5,6,8] and winter cold[7,9,10] have been associated with increased COPD hospitalizations and symptom burden. For example, McCormack et al.[6] found that higher maximal indoor temperature during the warm season in Baltimore was associated with worsened breathlessness, cough, sputum, and increased rescue inhaler use among COPD patients. Similarly, McCormack et al. found that colder temperatures in the cold season were associated with respiratory symptoms and lower lung function.[7]

Few studies have evaluated whether temperature affects individual-level COPD morbidity indictors, including daily changes in respiratory symptoms and lung function, that may precede healthcare utilization for COPD.[6,7] Most studies have relied on community-level monitors or brief sampling periods to estimate exposure to temperature, which may not capture personal exposure to temperature, especially among COPD patients who spend most of their time at home. New methods, using portable monitors that patients bring along during their indoor and outdoor activities, allows for daily evaluation of personal exposure to temperature[11]. This study examines how daily personal and outdoor temperature in the warm (May-September) and cold (October-April) seasons affect daily lung function, breathing and bronchitis symptoms among community-dwelling COPD patients, using both portable and stationary monitors in the greater Boston area.

Materials and Methods

Study population

The study population includes 30 former smokers with COPD who were recruited as part of the Study of Air Pollution and COPD Exacerbation (SPACE) at the Beth Israel Deaconess Medical Center in Boston, Massachusetts, United States of America. This study was conducted in accordance with the Declaration of Helsinki and was approved by the Committee on Clinical Investigations at Beth Israel Deaconess Medical Center (IRB protocol number: 2015P000336/06). To be eligible, study participants were required to: 1) have a home address within 50 km of the Harvard Supersite air pollution and temperature monitor at Harvard Medical School in Boston; and 2) have a clinical diagnosis of COPD with at least moderate (GOLD Stage II) airflow obstruction, defined as forced expiratory volume in 1-second (FEV_1)/forced vital capacity

(FVC) ratio of <0.70 and FEV_1 <80% predicted, using NHANES III prediction formulas[12]. Participants with a history of lung cancer, interstitial lung disease, or bronchiectasis were ineligible to participate.

Data collection

Participants entered the study between 2/24/2017 and 01/17/2019. At study entry, demographic information, height, weight, past medical history, medication history, and baseline measures of lung function were obtained, and participants were instructed on how to use a portable spirometer and personal air quality monitor (PAM). They were then observed for up to four non-consecutive 30-day periods in four different seasons over 12 months. Participants measured their lung function daily in the morning before taking any medications, using a portable EasyOne™ Plus Diagnostic Spirometer. This device meets American Thoracic Society guidelines and has built-in quality assurance and incentive software. At the end of follow-up, the 30 participants had contributed a total of 3,314 observation days.

Exposure assessment

We measured personal daily exposure to temperature and relative humidity using the portable PAMs, and outdoor exposure using the temperature and relative humidity monitor on the rooftop of Countway Library, Harvard Medical School, Boston, MA. The PAMs were developed by Atmospheric Sensors Ltd (model 520) and were equipped with sensors for temperature and relative humidity. All exposure measures from the PAMs were calibrated to stationary monitors in the Boston area. During repeated calibration periods in different seasons, 24-hour averages of temperature and relative humidity from a reference PAM were compared to a state-owned stationary monitor in Boston using linear regression models. Mean adjusted R^2 was 0.8 for temperature, and 0.9 for relative humidity. Daily personal exposure to air pollutants, including fine particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2), and ozone (O_3), was also measured by the PAMs, as previously described[13]. Additional information about the PAM technology, reproducibility of pollutant measurements, and agreement with stationary monitors in diverse settings have been published by other investigators.[14,15] Outdoor exposure to pollutants was measured using state-owned stationary monitors in Boston, as previously described.[13] Finally, we evaluated if associations between temperature and COPD-related symptoms departed from linearity. **Statistical analysis**

We calculated mean previous-day 24-hour exposure to temperature from the PAMs (personal exposure) and outdoor state-owned stationary monitors in the Boston area (outdoor exposure).

We constructed multi-level linear mixed-effects models to assess for associations between 1-, 2-, and 3-day 24-hour exposure to personal and outdoor temperature and lung function FEV_1 and FVC,

$$Y_{imt}=b_0 + b_1\, temp_{imt} + b_2\, c_{imt} + w_i + v_{im} + e_{imt},$$

where Y_{imt} is any continuous indicator of lung function for participant i at observation month m on day t; $temp_{imt}$ indicates personal or outdoor temperature exposure average, and c_{imt} represents a vector of potential confounders (personal or outdoor exposure to relative humidity, age, sex, race, height, weight, total pack-year smoking history, education, and season). Season was categorized as winter, spring, summer, and fall based on the calendar start dates of each observation month. The term w_i denotes a participant-specific random effect and was used to account for intra-individual correlations between repeated measurements among the same person, v_{im} denotes a participant-observation month specific random effect that allows daily observations from a single observation month within the same person to be more highly correlated than observations from a different observation month on the same person. The residuals e_{imt} are normally distributed errors, assumed to follow an autoregressive [AR(1)] process, modeling the serial correlation among the daily time series within the same person's observation month.

For binary symptom outcomes, we constructed similar generalized logistic mixed-effects models using the PROC GLIMMIX function in SAS with a participant-observation month specific random effect to assess for associations between exposure to personal and outdoor temperature, and odds of worsening breathing symptoms (breathlessness, chest tightness, wheeze)[16] and bronchitis symptoms (cough, sputum color, and sputum amount)[17].

To allow evaluation of differential effects of heat and cold, we ran all models using stratum-specific associations for warm (May-September) and cold (October-April) seasons. This distinction is relevant for the Boston-area and aligns with cold and warm seasons defined in previous research[18]. When assessing the association between exposure to temperature (personal or outdoor) and morning lung function and symptom outcomes, in separate models we examined temperature based on previous 1- , 2- and 3-day moving averages of temperature.

To test if any associations were explained by differences in exposure to pollutants, we performed sensitivity analyses additionally adjusting all previous-day (1-day moving average) temperature models for previous-day $PM_{2.5}$, NO_2 and O_3 in separate models. For this analysis, we adjusted for individual personal pollutant exposure when examining personal temperature exposure, and outdoor pollutant exposure when examining outdoor temperature exposure and associations with lung function and symptoms.

Using generalized additive mixed models (GAMM) with a binomial distribution, we plotted penalized splines to evaluate the shape of the associations of personal and outdoor temperature exposure with COPD-related symptoms, including data for all seasons.

All statistical analyses were performed using SAS 9.4 (Cary, North Carolina, United States of America, etc.), and spline plots were produced using R version 3.5.1 (R Foundation for Statistical Computing, Vienna, Austria)

Results

Characteristics of study participants

We collected 3,314 observations among 30 participants. Baseline participant characteristics are summarized in Table 1. Participants had an average age of 71.1±8.4 years, most had some level of college education or associate degree or higher (73.3%), were predominantly White (80.0%), were slightly more female (53.3%) and had on average 54.4 (±30.7) pack-years of smoking. There was also a near even distribution of participants across the income categorizations.

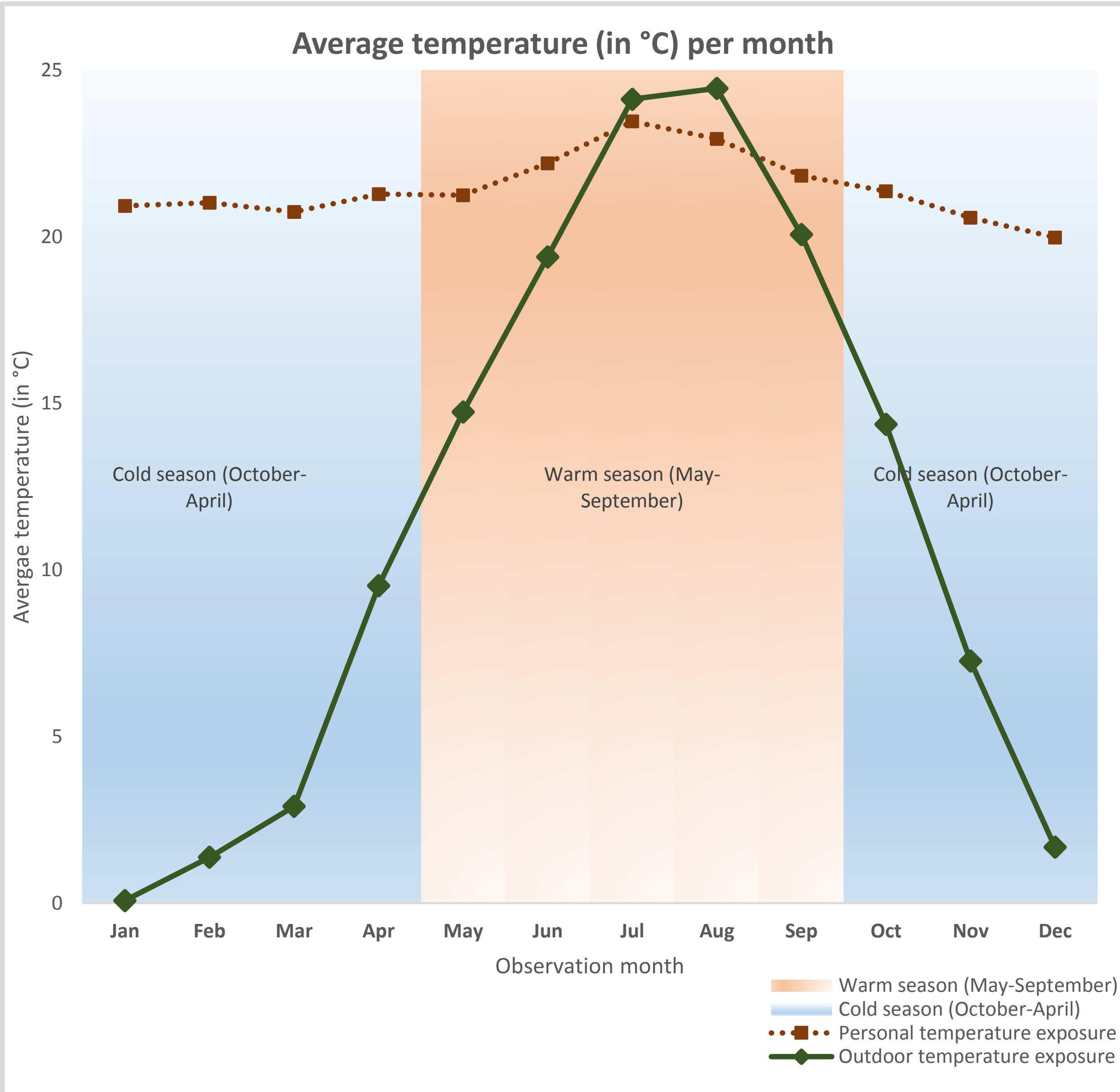
Table 1: Baseline characteristics of study participants (n=30)

Demographic and clinical characteristics	Mean±SD or n (%)
Age	71.1±8.4
Sex	
Male	14 (46.7)
Female	16 (53.3)
Race	
Black	6 (20.0)
White	24 (80.0)
Income	
<$24,999	10 (33.3)
$25,000-49,999	10 (33.3)
$50,000->$150,000	9 (30.0)
did not provide	1 (3.3)
Education	
High school or less	8 (26.7)
Some college	13 (43.3)
College degree or higher	9 (30.0)
Height	165.1±10.2
Weight	85.3±17.7
Total Pack Year History	54.4±30.7
Baseline FEV_1 L	1.3±0.5
Baseline FEV_1 % Pred.	54.3±14.2
Baseline FVC L	2.6±0.8
Baseline FVC % Pred.	79.9±15.7

Data are presented as mean (SD, standard deviation) or as n (%, column percentage), as indicated. FEV_1: forced expiratory volume in 1 second; FVC: forced vital capacity.

The mean±SD personal temperature exposure was 21.5±2.2°C for all seasons, 20.8±2.1°C for the cold season (October-April) and 22.3±2.0°C for the warm season (May-September). The mean±SD outdoor temperature was 12.0±9.6°C for all seasons, 5.6±7.1°C for the cold season and 20.3±5.2°C for the warm season. Figure 1 shows the mean daily temperature per month as measured by personal and outdoor community-level monitors.

Figure 1: Distribution of daily personal and outdoor temperature exposure per month



Temperature exposure and lung function

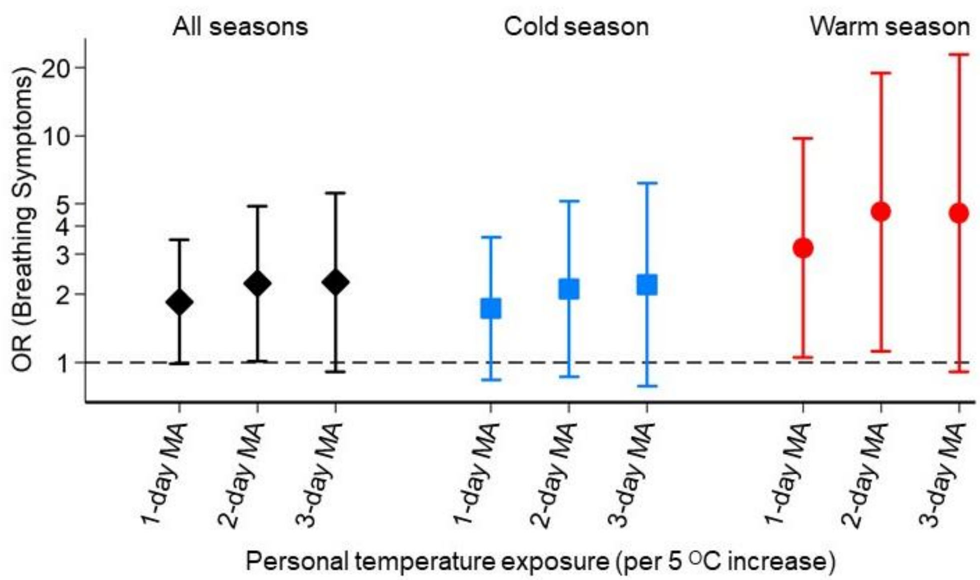
Using linear mixed-effects models, we found no associations between 1-, 2-, and 3-day moving average personal and outdoor exposure to temperature and morning lung function (FEV_1 and FVC) across all seasons, nor for cold or warm seasons (see Appendix 1).

Temperature exposure and breathing symptoms

Higher temperature exposure measured by personal monitor was associated with higher odds of worsened breathing symptoms, as shown in Figure 2. For example, in fully adjusted mixed-effects models, each 5^{o}C higher previous-day personal exposure to temperature was associated with a 1.85-fold (95% CI, 0.99-3.48; P=0.055) higher odds of worsening breathing symptoms overall. These results were similar for 2-day (2.23 (95% CI: 1-01-4.89; P=0.046)) and 3-day (2.26 (95% CI, 0.91- 5.58; P=0.078)) moving averages of temperature. We also found positive associations between each 5^{o}C higher 1-day moving average personal temperature exposure and odds of worsening breathing symptoms in the warm season (3.20 (95% CI, 1.05-9.72; P=0.040), with similar results for 2-day moving averages (4.61 (95% CI, 1.12-18.94; P=0.034)) and 3-day moving average of temperature (4.56 (95% CI 0.91-22.81; P=0.065)). We found no associations between personal exposure to temperature and breathing symptoms within the cold season.

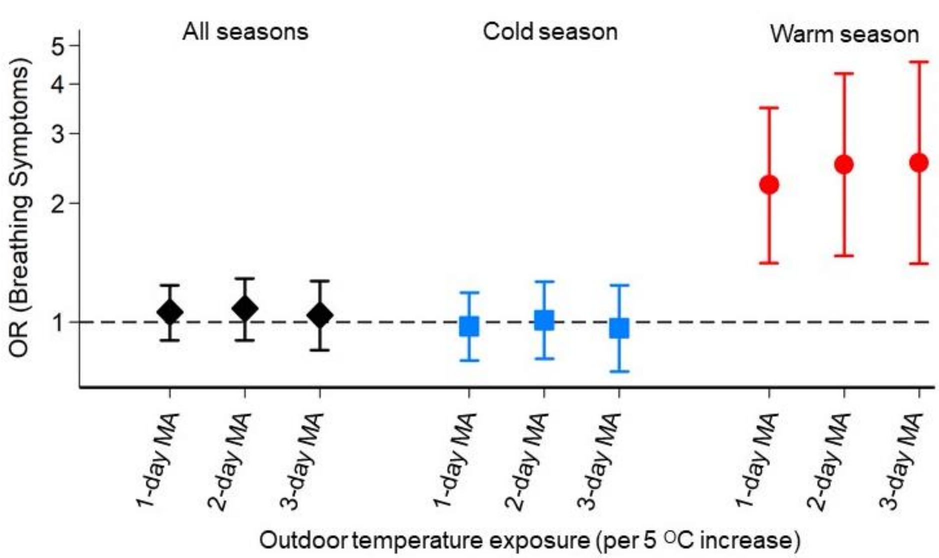
Higher outdoor temperature exposure was associated with worsened breathing symptoms in the warm season (see Figure 3). Each 5^{o}C higher previous-day outdoor temperature was associated with a 2.22 (95% CI, 1.41-3.48; P=0.001) higher odds of worsening breathing symptoms in the warm season. These results were similar by 2-day (2.50 (95% CI, 1.47-4.24; P=0.001) and 3-day (2.53 (95% CI, 1.40-4.55; P=0.002)) moving averages of outdoor temperature exposure in the warm season. Outdoor temperature exposure was not associated with worsening breathing symptoms overall, or in the cold season specifically.

***Figure 2**: The association between personal temperature exposure and breathing symptoms (per 5^{o}C higher temperature)*



Legend: mixed-model analysis showing odds ratios for breathing symptoms per 5^{o}C higher personal temperature exposure, adjusted for previous-day humidity, age, sex, height, weight, total pack-years of smoking, and education; Black: results for all seasons, blue: results for cold season (October-April), red: results for warm season (May-September). Abbreviations: OR: odds ratio, MA: moving average.

***Figure 3**: The association between outdoor temperature exposure and breathing symptoms (per 5^{o}C higher temperature)*



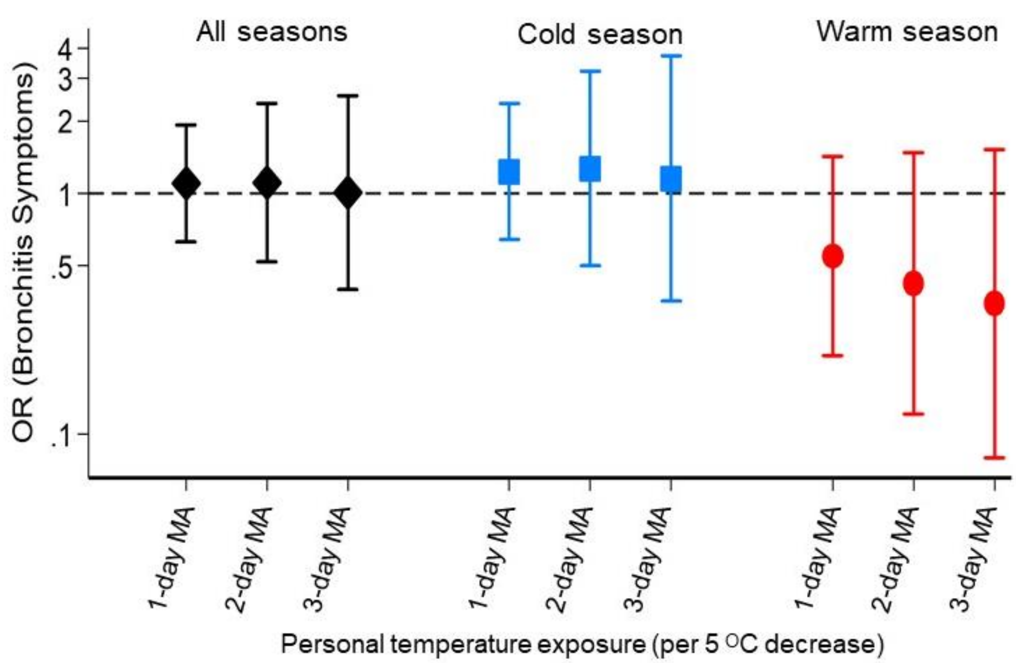
Legend: mixed model analysis showing odds ratios for breathing symptoms per 5°C higher outdoor temperature exposure, adjusted for previous-day humidity, age, sex, height, weight, total pack years of smoking, and education; Black: results for all seasons, blue: results for cold season (October-April), red: results for warm season (May-September). Abbreviations: OR: odds ratio, MA: moving average.

Temperature exposure and bronchitis symptoms

Personal exposure to temperature was not associated with worsening bronchitis symptoms overall, nor for season-stratified models (Figure 4).

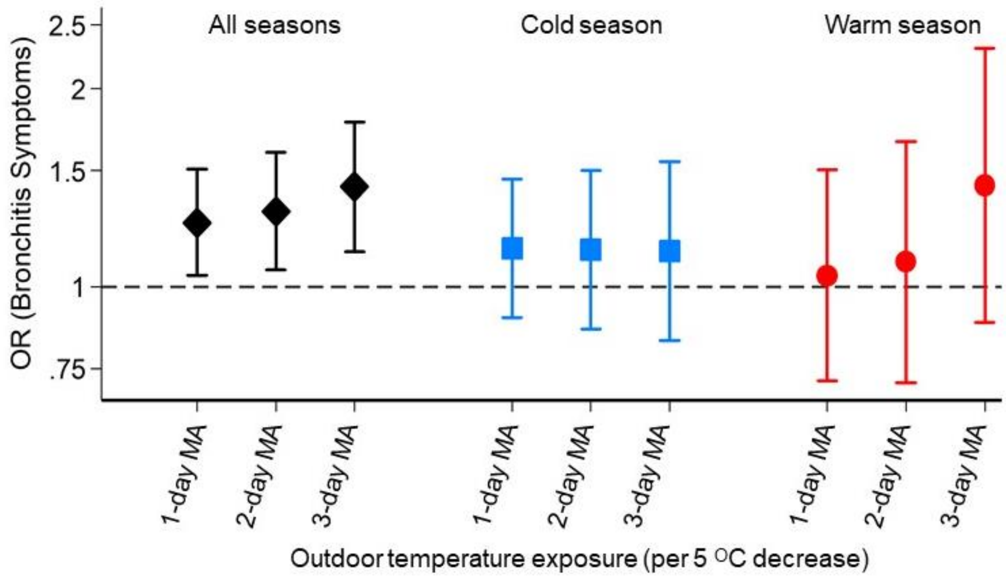
Lower outdoor temperature exposure was associated with worsening bronchitis symptoms. In fully adjusted models, each 5°C lower previous-day outdoor temperature exposure was associated with a 1.25 (95% CI, 1.04-1.51; P=0.016) higher odds of worsening bronchitis symptoms, with similar associations for 2-day (1.30 (95% CI, 1.06-1.60; P=0.014)) and 3-day (1.42 (95% CI, 1.13-1.78; P=0.003)) moving averages. We found no associations between outdoor temperature exposure and bronchitis symptoms in season-stratified models (Figure 5).

***Figure 4**: The association between personal temperature exposure and bronchitis symptoms (per 5°C lower temperature)*



Legend: mixed model analysis showing odds ratios for bronchitis symptoms per 5°C lower personal temperature exposure, adjusted for previous-day humidity, age, sex, height, weight, total pack years of smoking, and education; Black: results for all seasons, blue: results for cold season (October-April), red: results for warm season (May-September). Abbreviations: OR: odds ratios, MA: moving average.

Figure 5: *The association between outdoor temperature exposure and bronchitis symptoms (per 5^{O}C lower temperature)*



Legend: mixed model analysis showing odds ratios for bronchitis symptoms per 5^{O}C lower outdoor temperature exposure, adjusted for previous-day humidity, age, sex, height, weight, total pack years of smoking, and education; Black: results for all seasons, blue: results for cold season (October-April), red: results for warm season (May-September). Abbreviations: OR: odds ratios, MA: moving average.

Secondary analyses

In secondary analyses, we did not find that any associations between temperature exposure and symptoms were explained or confounded by personal or outdoor pollutant exposures. In models examining associations between previous-day personal and outdoor temperature exposure and lung function, breathing and bronchitis symptoms, additional adjustment for personal or outdoor $PM_{2.5}$, NO_2, or O_3 exposure did not change any of the associations between temperature exposure and these outcomes (see Appendix 2-5).

Penalized spline plots demonstrated linear-shaped associations between previous-day personal temperature exposure and breathing symptoms, and between previous-day personal and outdoor temperature exposure and bronchitis symptoms. However, the association between outdoor temperature exposure and breathing symptoms showed a non-linear, U-shaped relationship, in which extremes of both warmer and colder outdoor temperature exposure were associated with higher odds of breathing symptoms (Appendix 6). Splines for cold and warm season followed similar patterns as those for all seasons (data not shown).

Discussion

In this prospective study of people with moderate-to-severe COPD residing in the Boston area, higher personal and outdoor temperature exposure was associated with worsened breathing symptoms (i.e., breathlessness, wheeze, and tightness of the chest), especially in the warm (May-September) season. In contrast, lower outdoor temperature exposure was associated with worsening bronchitis symptoms (cough, sputum color, and sputum amount), regardless of season. We found no associations between temperature exposure and morning lung function. Associations with temperature were not explained by differences in exposure to air pollutants.

Our findings are consistent with a growing number of studies reporting adverse health effects of indoor and outdoor heat in the warm season in older patients with COPD[6,19]. For example, McCormack et al.[6], using longitudinal individual-level exposure and symptom assessment data in a Baltimore-based cohort of COPD patients, a 10°F (5.5°C) increase in daily maximum indoor home temperature was associated with a worsening of symptoms based on average Breathlessness, Cough and Sputum Scale score as well as increased inhaler use in the warmer months. A New York City-based study[20] on COPD morbidity using hospitalization data found that the same-day risk of COPD hospitalization increased by 7.6% for every one-degree Celsius increase above a threshold temperature of 29.8 °C, and that there was a detectable but smaller association between temperature and respiratory hospitalization when applying a 1-day lag.

We found that higher personal exposure to heat was associated with breathlessness, but not lung function, regardless of season. This may indicate that worsened breathing symptoms are not a result of a bronchoconstrictive effect of heat but, rather, a thermoregulatory response where the metabolic demands of cooling the body in the setting of fixed airflow limitation, results in exertional dyspnea[8]. Our findings suggest that heat can result in a greater burden of breathing symptoms among COPD patients whether it is due to hot weather or other sources of (indoor) heat. In the cold season, we found associations between personal exposure to heat and breathlessness, but not with outdoor temperature exposure suggesting that higher temperatures from indoor heating sources during the cold season also have an adverse effect on breathing symptoms. Our findings suggest thus an opportunity for clinical, housing and policy measures to prevent exposure to high temperatures among patients with COPD, both during warm and cold seasons.

Although the results of our primary (linear) models demonstrated that higher outdoor temperature exposure was associated with worsened breathing symptoms in the warm season only, in secondary analyses we evaluated non-linear relationships and found that both extremes of outdoor temperature (not only very warm but also very cold) were associated with a higher odds of worsening breathing symptoms[7]. Interestingly, for personal temperature exposure, we found that only higher temperatures were associated with greater odds of breathing symptoms in a linear fashion across the range of exposures. A potential explanation could be that during periods of extremely cold weather, our participants spent most of their time indoors (reflected in the much narrower range of recorded personal temperatures throughout the year, averaged over 24-hour periods, compared to outdoor temperatures). Therefore, these results may suggest that even brief exposure to outdoor cold temperatures may cause dyspnea in the COPD population who spend most of their time indoors in a temperature-controlled environment[7].Our finding that colder outdoor temperature was associated with bronchitis symptoms is consistent with epidemiological studies finding adverse health effects of cold weather such as risk of acute bronchitis and exacerbations of asthma and COPD[7,21]. One of the few studies to evaluate associations of colder temperature with daily sub-clinical measures, by McCormack et al.[7], reported that during the winter season, colder outdoor temperatures were associated with increased respiratory symptoms (measured by the Breathlessness, Sputum and Cough scale), increased rescue inhaler use and decreased lung function in former smokers with COPD. We found an effect of colder temperature on bronchitis symptoms (cough, sputum color, and sputum amount), while we found the opposite for breathing symptoms. This may indicate mucous hypersecretion as a potential mediator of the response to cold temperature in COPD.[22] Despite evidence that colder temperatures can trigger bronchoconstriction in COPD[23,24], We did not find any associations between personal or outdoor cold temperature exposure and lung function in this study, even within the cold season. The reasons for the lack of association are unclear. Our findings suggest that COPD patients experience changes in bronchitis symptoms in association with temperature in the absence of lung function change.[16,25]

Our study has several limitations. Since our study population consists of former smokers with COPD living in an urban environment, our findings may not be generalizable to current smokers or those living in other settings. While we collected a large number of repeated measures (up to 120 observation-days per participant and 3,314 observation-days in total), our study only included 30 unique individuals in the Boston area, which limits the generalizability of our findings to other populations with COPD, such as those with milder disease or those living in other climates. We also did not account for characteristics of participant's homes and behaviors, such as types of insulation used in the home, heating sources, or window-opening behavior of people living in the home, which may influence participant's personal exposure to temperature. Future research may assess how such factors influence personal temperature exposure, and whether there are health benefits of interventions to reduce exposure to heat and cold in this population.

Our study also has several strengths. Our unique longitudinal study design with daily exposure and health measures allowed us to evaluate how day-to-day variability in personal and outdoor temperature exposure relate to daily lung function, breathing symptoms and bronchitis symptoms in an older population with COPD, while accounting for within-person correlation of measurements, and adjusting for a robust list of potential individual-level and seasonal confounders. We used lightweight portable exposure monitors, calibrated to gold standard stationary monitors, to measure exposure at the individual level for a prolonged period (a total of four months) across different seasons. Our findings suggest the value of measuring personal temperature exposure in this population, as we found that personal temperature exposure was associated with both breathing and bronchitis symptoms.

Conclusion

Our findings suggest that exposure to higher temperature year-round may worsen breathing symptoms, especially in the warm season, and exposure to colder temperature independent of season may trigger cough and phlegm symptoms among COPD patients, without impacting lung function. These findings suggest an opportunity to address personal exposure to warmer temperature as a risk factor for aggravated dyspnea in the warmer months, and outdoor colder temperatures as a risk factor for increased bronchitis symptoms in COPD throughout the year.

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Appendices

Appendix 1: The association between personal and outdoor temperature exposure (per 5°C higher temperature) and lung function

Temperature average	Unit	Difference in FEV_1 mL (95% Confidence Interval)*	P Value	Difference in FVC mL (95% Confidence Interval)*	P Value
Personal exposure to temperature					
1-day moving average temperature	5°C	6.8 (-8.8-22.4)	0.392	5.2 (-24.9-35.3)	0.736
2-day moving average temperature	5°C	17.4 (-5.4-40.1)	0.135	26.1 (-17.6-69.7)	0.241
3-day moving average temperature	5°C	19.4 (-9.3-48.0)	0.185	15.9 (-39.2-70.9)	0.572
Outdoor exposure to temperature					
1-day moving average temperature	5°C	1.7 (-3.1-6.4)	0.497	2.3 (-6.7-11.3)	0.614
2-day moving average temperature	5°C	2.4 (-3.3-8.1)	0.410	5.4 (-5.2-15.8)	0.318
3-day moving average temperature	5°C	2.7 (-3.7-9.1)	0.407	7.3 (-4.6-19.1)	0.230
Data are presented as mean difference (95% CI) per 5°C increase personal and outdoor temperature exposure. Linear mixed models adjusted for relative humidity, age, sex, height, weight, total pack years of smoking, and education.					

Appendix 2: Sensitivity analysis: association of personal and outdoor temperature exposure (per 5°C degrees higher temperature) and FEV_1, adjusting for pollutants

Morning FEV_1	Unit	All seasons		Stratified by cold season		Stratified by warm season	
		Difference in FEV_1 mL (95% CI)	P Value	Difference in FEV_1 mL (95% CI)	P Value	Difference in FEV_1 mL (95% CI)	P Value
PERSONAL TEMPERATURE EXPOSURE							
1-day moving average	5 °C	6.8 (-8.8-22.4)	0.392	3.0 (-17.0-23.0)	0.756	11.0 (-13-35.5)	0.361
Adjusting for personal PM2.5	5 °C	7.3 (-8.3-22.9)	0.360	3.8 (-16.3-23.8)	0.712	11.7 (-12.5-35.8)	0.343
Adjusting for personal NO2	5 °C	3.9 (-11.8-19.6)	0.626	1.2 (-18.8-21.2)	0.906	6.6 (-17.7-30.9)	0.592
Adjusting for personal O3	5 °C	7.7 (-8.0-23.4)	0.337	3.1 (-16.9-23.1)	0.758	13.8 (-10.7-38.4)	0.270
2-day moving average	5 °C	17.4 (-5.4-40.1)	0.135	10.5 (-18.5-39.0)	0.483	26.5 (-8.0-61.0)	0.133
3-day moving average	5 °C	19.4 (-9.3-48.0)	0.185	18.0 (-19.0-55.0)	0.335	17.5 (-24.0-59.0)	0.405
OUTDOOR TEMPERATURE EXPOSURE							
1-day moving average	5 °C	1.7 (-3.1-6.4)	0.497	3.0 (-3.5-9.5)	0.345	-1.0 (-10.0-8.0)	0.799
Adjusting for outdoor PM2.5	5 °C	1.9 (-3.0-6.7)	0.451	3.1 (-3.3-9.4)	0.339	-0.8 (-10.1-8.6)	0.877
Adjusting for outdoor NO2	5 °C	1.6 (-3.1-6.4)	0.500	2.8 (-3.5-9.2)	0.379	-0.7 (-9.7-8.3)	0.877
Adjusting for outdoor O3	5 °C	1.0 (-4.2-6.2)	0.699	2.5 (-3.9-9.0)	0.443	-3.2 (-12.9-6.6)	0.529
2-day moving average	5 °C	2.4 (-3.3-8.1)	0.410	4.0 (-4.0-11.5)	0.333	-0.5 (-11.0-10.5)	0.960
3-day moving average	5 °C	2.7 (-3.7-9.1)	0.407	5.0 (-4.0-13.5)	0.278	-0.5 (-13.0-11.5)	0.926
Data are presented as mean difference (95% CI) FEV_1 (Forced Expiratory Volume in one second) in mL per 5°C increase personal or outdoor temperature exposure. Linear mixed effect models adjusted for participant age, sex, height, weight, total pack-years of smoking, education, and humidity.							

Appendix 3: Sensitivity analysis: association of personal and outdoor temperature exposure (per 5^{o}C degrees higher temperature) and FVC, adjusting for pollutants

Morning FVC	**Unit**	**All seasons**		**Stratified by cold season**		**Stratified by warm season**	
		Difference in FVC mL (95% CI)	**P Value**	**Difference in FVC mL (95% CI)**	**P Value**	**Difference in FVC mL (95% CI)**	**P Value**
PERSONAL TEMPERATURE EXPOSURE							
1-day moving average	5^{o}C	5.2 (-24.9-35.3)	0.736	-18.0 (-56.5-20.5)	0.357	32.0 (-14.0-78.5)	0.173
Adjusting for personal PM2.5	5^{o}C	5.4 (-24.8-35.5)	0.727	-17.9 (-56.4-20.6)	0.363	32.3 (-14.1-78.6)	0.172
Adjusting for personal NO2	5^{o}C	1.5 (-28.8-31.9)	0.921	-21.0 (-59.5-17.4)	0.284	25.0 (-21.6-71.6)	0.292
Adjusting for personal O3	5^{o}C	4.3 (-26.2-34.7)	0.784	-18.1 (-56.5-20.4)	0.357	32.7 (-14.4-79.9)	0.173
2-day moving average	5^{o}C	26.1 (-17.6-69.7)	0.241	-7.5 (-62.0-47.0)	0.789	65.0 (0.0-130.0)	0.050
3-day moving average	5^{o}C	15.9 (-39.2-70.9)	0.572	-5.0 (-75.0-64.5)	0.884	27.0 (-51.5-105.0)	0.501
OUTDOOR TEMPERATURE EXPOSURE							
1-day moving average	5^{o}C	2.3 (-6.7-11.3)	0.614	1.5 (-10.5-13.5)	0.810	-1.5 (-19.0-15.5)	0.853
Adjusting for outdoor PM2.5	5^{o}C	3.1 (-6.0-12.3)	0.503	1.6 (-10.4-13.6)	0.794	0.5 (-17.3-18.4)	0.953
Adjusting for outdoor NO2	5^{o}C	2.1 (-6.9-11.1)	0.643	0.8 (-11.3-12.9)	0.896	-0.5 (-17.7-16.8)	0.956
Adjusting for outdoor O3	5^{o}C	1.7 (-7.9-11.6)	0.708	1.1 (-11.2-13.4)	0.859	-3.8 (-22.5-14.9)	0.690
2-day moving average	5^{o}C	5.4 (-5.2-15.8)	0.318	2.0 (-12.5-16.0)	0.807	5.5 (-15.0-25.5)	0.598
3-day moving average	5^{o}C	7.3 (-4.6-19.1)	0.230	5.0 (-11.5-21.0)	0.550	4.0 (-19.5-27.0)	0.752

Data are presented as mean difference (95% CI) FVC (Forced Vital Capacity) in mL per 5^{o}C increase personal or outdoor temperature exposure. Linear mixed models adjusted for relative humidity, age, sex, height, weight, total pack-years of smoking, and education.

Appendix 4: Association of personal and outdoor temperature exposure (per 5^oC degrees higher temperature) and breathing symptoms, adjusting for pollutants in 1-day moving average models

Breathing symptoms (breathlessness, wheeze, tightness of the chest)	**All seasons**		**Stratified by cold season**		**Stratified by warm season**	
	Odds ratio (95% CI)	**P Value**	**Odds ratio (95% CI)**	**P Value**	**Odds ratio (95% CI)**	**P Value**
PERSONAL TEMPERATURE EXPOSURE						
1-day moving average	**1.85 (0.99-3.48)**	**0.055**	**1.73 (0.84-3.57)**	**0.139**	**3.20 (1.05-9.72)**	**0.040**
Adjusting for personal PM2.5	1.88 (1.00-3.52)	0.050	1.78 (0.86-3.68)	0.119	3.18 (1.04-9.66)	0.042
Adjusting for personal NO2	1.79 (0.95-3.39)	0.072	1.69 (0.81-3.5)	0.161	3.10 (1.02-9.45)	0.046
Adjusting for personal O3	1.83 (0.97-3.45)	0.062	1.73 (0.83-3.57)	0.141	3.08 (1.00-9.50)	0.051
2-day moving average	**2.23 (1.01-4.89)**	**0.046**	**2.21 (0.87-5.14)**	**0.101**	**4.61 (1.12-18.94)**	**0.034**
3-day moving average	**2.26 (0.91-5.58)**	**0.078**	**2.21 (0.79-6.17)**	**0.132**	**4.56 (0.91-22.81)**	**0.065**
OUTDOOR TEMPERATURE EXPOSURE						
1-day moving average	**1.06 (0.90-1.24)**	**0.509**	**0.98 (0.80-1.19)**	**0.799**	**2.22 (1.41-3.48)**	**0.001**
Adjusting for outdoor PM2.5	1.04 (0.88-1.22)	0.646	0.97 (0.80-1.19)	0.797	2.13 (1.34-3.39)	0.002
Adjusting for outdoor NO2	1.06 (0.90-1.24)	0.504	0.97 (0.80-1.19)	0.780	2.22 (1.41-3.50)	0.001
Adjusting for outdoor O3	0.97 (0.82-1.15)	0.755	0.96 (0.78-1.17)	0.653	1.89 (1.16-3.08)	0.011
2-day moving average	**1.08 (0.90-1.29)**	**0.407**	**1.01 (0.81-1.27)**	**0.921**	**2.50 (1.47-4.24)**	**0.001**
3-day moving average	**1.04 (0.85-1.27)**	**0.707**	**0.96 (0.75-1.24)**	**0.773**	**2.53 (1.40-4.55)**	**0.002**

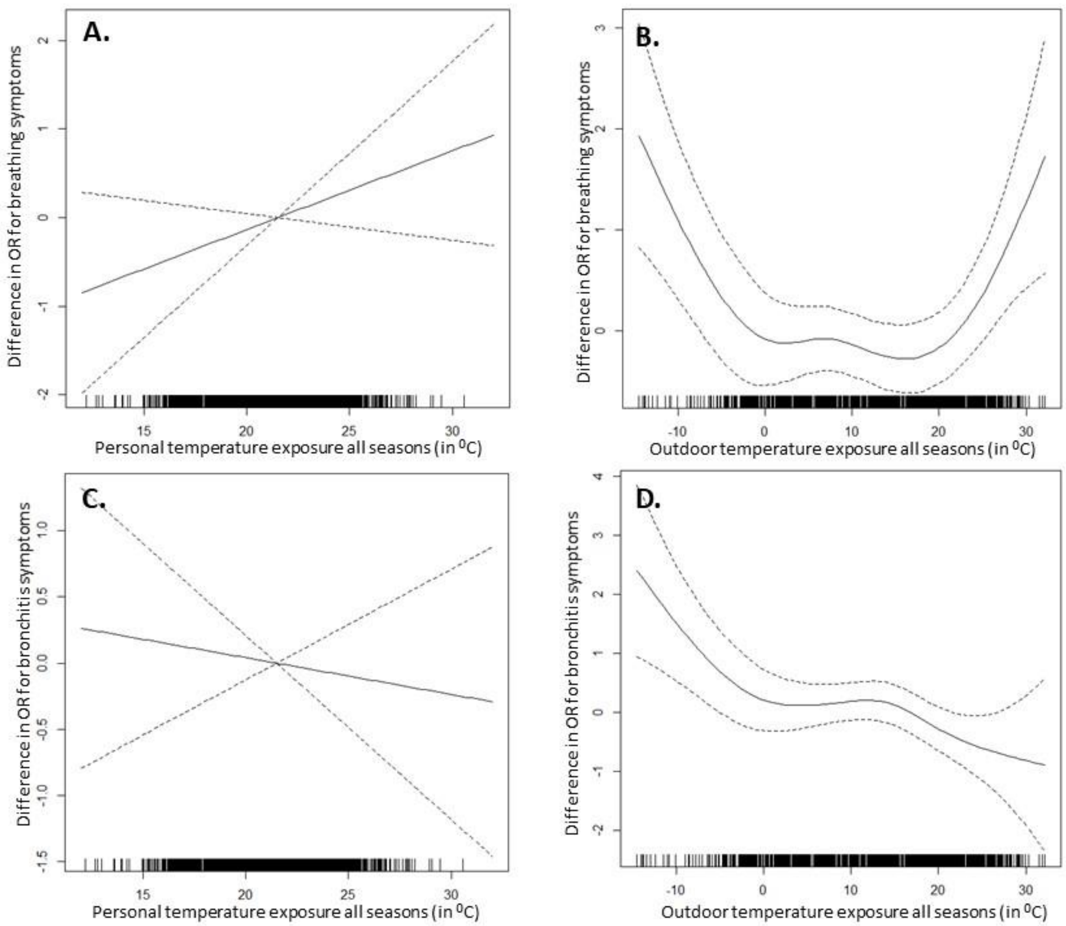
Represents odds ratio (95% confidence interval) per 5^oC increase in personal and outdoor temperature exposure. Mixed models are adjusted for relative humidity, age, sex, height, weight, total pack-years of smoking, and education. Data is shown for all seasons and stratified by temperature measured in the cold season (October-April) and the warm season (May-September).

Appendix 5: Association of personal and outdoor temperature exposure (per 5^{o}C degrees lower temperature) and bronchitis symptoms, adjusting for pollutants in 1-day moving average models

Bronchitis symptoms (cough, sputum color, and sputum amount)	**All seasons**		**Stratified by cold season**		**Stratified by warm season**	
	Odds ratio (95% CI)	**P Value**	**Odds ratio (95% CI)**	**P Value**	**Odds ratio (95% CI)**	**P Value**
PERSONAL TEMPERATURE EXPOSURE						
1-day moving average	**1.10 (0.63-1.93)**	**0.728**	**1.23 (0.64-2.36)**	**0.527**	**0.55 (0.21-1.42)**	**0.217**
Adjusting for personal PM2.5	*1.10 (0.63-1.93)*	*0.728*	*1.23 (0.64-2.36)*	*0.527*	*0.55 (0.21-1.42)*	*0.217*
Adjusting for personal NO2	*1.13 (0.65-1.99)*	*0.662*	*1.24 (0.65-2.38)*	*0.518*	*0.56 (0.21-1.47)*	*0.237*
Adjusting for personal O3	*1.03 (0.58-1.83)*	*0.913*	*1.21 (0.63-2.32)*	*0.562*	*0.48 (0.18-1.28)*	*0.142*
2-day moving average	**1.11 (0.52-2.37)**	**0.789**	**1.27 (0.50-3.21)**	**0.619**	**0.42 (0.12-1.48)**	**0.178**
3-day moving average	**1.01 (0.40-2.55)**	**0.986**	**1.15 (0.36-3.73)**	**0.811**	**0.35 (0.08-1.52)**	**0.161**
OUTDOOR TEMPERATURE EXPOSURE						
1-day moving average	**1.25 (1.04-1.51)**	**0.016**	**1.14 (0.90-1.46)**	**0.282**	**1.04 (0.72-1.50)**	**0.841**
Adjusting for outdoor PM2.5	*1.29 (1.07-1.56)*	*0.008*	*1.15 (0.90-1.47)*	*0.256*	*1.12 (0.76-1.64)*	*0.565*
Adjusting for outdoor NO2	*1.25 (1.04-1.50)*	*0.020*	*1.13 (0.88-1.44)*	*0.345*	*1.06 (0.73-1.53)*	*0.774*
Adjusting for outdoor O3	*1.25 (1.02-1.52)*	*0.030*	*1.15 (0.90-1.48)*	*0.259*	*1.00 (0.67-1.50)*	*0.995*
2-day moving average	**1.30 (1.06-1.60)**	**0.014**	**1.14 (0.86-1.50)**	**0.364**	**1.09 (0.71-1.66)**	**0.692**
3-day moving average	**1.42 (1.13-1.78)**	**0.003**	**1.13 (0.83-1.55)**	**0.435**	**1.43 (0.88-2.31)**	**0.148**

Represents odds ratio (95% confidence interval) per 5^{o}C decrease in personal or outdoor temperature exposure. Generalized mixed effects models are adjusted for relative humidity, age, sex, height, weight, total pack-years of smoking, and education. Data is shown for all seasons and stratified by temperature measured in the cold season (October-April) and the warm season (May-September).

Appendix 6 Splines assessing non-linearity between temperature exposure and COPD symptoms



Penalized splines demonstrating change in breathing (A and B) or bronchitis symptoms (C and D) as a function of all-season previous-day personal and outdoor temperature exposure. Using generalized additive mixed models (GAMM) with a binomial distribution, we plotted penalized splines to evaluate departures from linearity for the association of personal and outdoor temperature exposure and COPD-related symptoms. The solid line represents adjusted difference in symptoms and the dashed lines indicate the 95% confidence interval bands. The distribution of the exposure is displayed by the rug plot along the x axis. Breathing symptoms include breathlessness, chest tightness and wheeze. Bronchitis symptoms include cough, sputum colour, and amount; OR: odds ratios.

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