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LETTER

Future respiratory hospital admissions from wildfire smoke under climate change in the Western US

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Abstract

Background. Wildfires are anticipated to be more frequent and intense under climate change. As a result, wildfires may emit more air pollutants that can harm health in communities in the future. The health impacts of wildfire smoke under climate change are largely unknown. *Methods.* We linked projections of future levels of fine particulate matter ($PM_{2.5}$) specifically from wildfire smoke under the A1B climate change scenario using the GEOS-Chem model for 2046–2051, present-day estimates of hospital admission impacts from wildfire smoke, and future population projections to estimate the change in respiratory hospital admissions for persons ⩾65 years by county ($n = 561$) from wildfire $PM_{2.5}$ under climate change in the Western US. *Results.* The increase in intense wildfire smoke days from climate change would result in an estimated 178 (95% confidence interval: 6.2, 361) additional respiratory hospital admissions in the Western US, accounting for estimated future increase in the elderly population. Climate change is estimated to impose an additional 4990 high-pollution smoke days. Central Colorado, Washington and southern California are estimated to experience the highest percentage increase in respiratory admissions from wildfire smoke under climate change. *Conclusion.* Although the increase in number of respiratory admissions from wildfire smoke seems modest, these results provide important scientific evidence of an often-ignored aspect of wildfire impact, and information on their anticipated spatial distribution. Wildfires can cause serious social burdens such as property damage and suppression cost, but can also raise health problems. The results provide information that can be incorporated into development of environmental and health policies in response to climate change. Climate change adaptation policies could incorporate scientific evidence on health risks from natural disasters such as wildfires.

Introduction

Climate change is anticipated to increase the threat of wildfires with fires seasons that start earlier, burn larger areas, and occur more often [1–4]. Recent studies projected the future wildfire growth within various climate change scenarios in the Western US, estimating an increase in area burned by mid-21st century of 54%–900% [4–6]. Fine particulate matter ($PM_{2.5}$) levels during or after wildfire events can often exceed the US Environmental Protection Agency National Ambient Air Quality Standard for daily $PM_{2.5}$ (35 $\mu g\ m^{-3}$, reaching over 100 $\mu g\ m^{-3}$ for the 24 h average [7]. For example, the Bay area in California had to issue an air quality alert due to smoke transported from the Soberanes Fire in Monterey County starting on 22 July 2016 due to wildfire smoke [8]. The air quality is 'worse than Beijing' in affected areas such as Carmel Valley [8].

Our previous study found a statistically significant association between relatively more severe wildfire air pollution episodes and risk of respiratory admissions for persons ⩾65 years in the Western US in the present day [9]. In particular, health impacts of wildfire-specific $PM_{2.5}$ on respiratory admissions may be higher than those from $PM_{2.5}$ from non-wildfire sources [9]. $PM_{2.5}$ exposure due to wildfires is expected to increase under climate change by the 2050s [10]. In the context of climate change, some communities may suffer higher exposure to wildfire smoke, and thereby face higher health risks, due to fuel load, climate conditions such as humidity and temperature. The relative impact on communities will depend not only on their change in exposure to wildfire-specific $PM_{2.5}$, but also their population growth. Northern California, the Northwest, and Colorado are areas that are both highly populated and estimated to face high levels of wildfire-emitted air pollution in the future under a changing climate [10].

Estimates of the future health burden due to wildfire pollution are needed to better understand the health consequences of a changing climate and to help decision makers prepare for upcoming wildfire events and optimize resource allocation. However, to the best of our knowledge, the change in risk of hospital admissions associated with wildfire smoke under a changing climate has not previously been quantified. Most of the current, limited literature on the association between wildfire smoke and population health is based on present-day estimates from a single fire episode [7]. A few studies found significant associations between respiratory outcomes and total-mass $PM_{2.5}$ during or after wildfire events at the present day [11–15].

The aim of the present study is to develop innovative methods to estimate the changes in number of admissions due to wildfire smoke in the *future* under conditions of climate change, building on the previous two studies, one on present-day health effect of wildfire smoke and the other on future exposure to wildfire smoke [9, 10]. This study combines research on climate change, atmospheric chemistry modeling, wildfire schemes, population projections, and epidemiological analysis to investigate the health impacts of air pollution from wildfires under climate change. We estimated the increase in risk of respiratory hospital admissions for an older population (⩾65 years) from wildfire smoke with a changing climate for 2046–2051 in the Western US under the A1B scenario, the moderate growth scenario, from the Intergovernmental Panel on Climate Change (IPCC). Results of this study may provide insight into the public health impacts of climate change, and may serve as a useful reference for policy-makers in designing public health programs and climate change adaptation and mitigation strategies.

Methods

Estimates of wildfire-specific $PM_{2.5}$ under climate change

This study utilizes estimates of future (2046–2051) $PM_{2.5}$ levels directly attributable to wildfires (hereafter referred to as wildfire-specific $PM_{2.5}$) in all 561 Western US counties using GEOS-Chem simulation models based on the fire prediction scheme introduced by Yue *et al* and the A1B scenario from IPCC [16]. GEOS-Chem is a global atmospheric chemistry model that has been extensively used in simulations of wildfire-specific aerosols at present-day and in the future [4, 6]. The A1B scenario projects that with moderate growth, global carbon dioxide emissions would reach 522 ppm by 2050, global average surface temperature would increase 2.8 °C and the sea level would rise 0.21–0.48 m by the end of the 21st century [17]. The fire scheme predicted area burned in mid-21st century (2046–2051) by integrating 15 different general circulation models that projected future climate. Yue *et al* estimated that compared with present day (1981–2000), total area burned would increase by 60%–120%, length of fire season would increase by three weeks, and emissions of organic carbon would increase by 50%–70% by mid-21st century. This fire scheme can explain up to 60% of the observed variance in area burned in the Western US, and is ecosystem dependent. We projected future $PM_{2.5}$ emissions from wildfires using the area burned results from this fire scheme in the Western US by mid-21st century under the A1B scenario. This process estimated daily, gridded ($0.5° \times 0.667°$ latitude by longitude) $PM_{2.5}$ concentrations specifically from wildfires for 2046–2051. Wildfire-specific $PM_{2.5}$ concentrations were estimated for the present-day (2004–2009) using a similar simulation based on present-day climate conditions in order to estimate the difference in wildfire-specific $PM_{2.5}$ between the future and the present day. Details about the wildfire modeling can be found in [10].

Smoke wave

We use the term 'smoke wave' to describe episodes of high $PM_{2.5}$ from wildfires [10]. The air pollution episodes from wildfires tend to be intense, short-lived, and rare. It is challenging to study the characteristics of wildfire-specific $PM_{2.5}$ and its health effect due to its highly-skewed frequency distribution (about 90% daily wildfire-specific $PM_{2.5}$ levels are near zero). We created the smoke wave term to better quantify the characteristics of pollution episodes from wildfires, such as the length, intensity and frequency, which is helpful to evaluate the severity and impact of air pollution events from wildfires. Prior use of the smoke wave term in epidemiological studies can be found in Liu *et al* [9]. The primary definition of a smoke wave is at least two consecutive days with wildfire-specific

$PM_{2.5}$ higher than the 98th quantile of all wildfire-specific $PM_{2.5}$ across all days in all 561 counties at the present day. Smoke wave days with this definition are denoted as SW_{98}. Each day in each county is categorized as a smoke wave day or a non-smoke-wave day. Relatively more intense smoke wave days with wildfire-specific $PM_{2.5} > 99.5$th quantile wildfire-specific $PM_{2.5}$ levels were denoted as $SW_{99.5}$. The $SW_{99.5}$ days are a subset of SW_{98} days. The modeled wildfire-specific $PM_{2.5}$ value of the 98th-quantile threshold is $5.65\ \mu g\ m^{-3}$ and the value for 99.5th quantile is $15.57\ \mu g\ m^{-3}$. Future smoke waves under a changing climate are defined with the same smoke wave definitions (i.e., the same $PM_{2.5}$ threshold values to define SW_{98} and $SW_{99.5}$) to consistently compare changes in the number of smoke wave days and smoke wave intensity (average wildfire-specific $PM_{2.5}$ levels in each smoke wave). We computed the number of primary (SW_{98}) and relatively more intense ($SW_{99.5}$) smoke wave days at the present-day and future.

Liu *et al* [9] found that the risks of respiratory hospital admissions for the Medicare population (⩾65 years) in the Western US were 2.28% (95% confidence interval (CI): −2.21%, 6.97%) higher on a SW_{98} day compared to a non-smoke-wave day, whereas admissions were 7.2% (95% CI: 0.25%, 14.63%) higher on a $SW_{99.5}$ day compared to a non-smoke-wave day. We did not find an association with certainty for cardiovascular diseases. As the relative risk of respiratory admission is more certain for $SW_{99.5}$, we chose to focus on investigating the health burden of $SW_{99.5}$ days in the future under climate change, using these risk-response relationships estimated for the present day. The health burden of SW_{98} is reported in supplementary results I.

Future population projection

We estimated future health burden under two population scenarios: (1) county-level elderly populations stay the same in the future (i.e., no population growth); and (2) county-level elderly population changes based on projected population growth trends. The first population scenario is not intended to represent a realistic scenario as population is indeed anticipated to increase; however, this method is used to isolate the impact of climate change, whereas the second case includes both the influences of climate change and of anticipated population growth.

For the second case, to estimate the number of elderly persons residing in each county in the future, we first calculated the percentage of elderly population in 2050 based on the population estimates in each age group from the US Census National Population Projections (2014) [18], and then multiplied the percentage with the projected total population in each county.

We calculated the projected number of elderly persons (⩾65 y) for county c in 2050 (E^c) as:

$$E^c = D^c * (P^c * F/P), \tag{1}$$

where:

c is a given county that experienced ⩾1 smoke wave either during 2004–2009 or 2046–2051.

D^c is the total population including all ages for county c in 2050. We obtained the projected county-level total population in 2050 estimated from Integrated Climate and Land Use Scenarios (ICLUS v1.3) Population Projections [19].

P^c is the percentage of the population that is ⩾65 years in county c at the present day (from US Census 2010) [20].

F is the projected percentage of the US population that is ⩾65 years in 2050.

P is the average percentage of the population that is ⩾65 years for the present day (2010) in the 561 counties [18].

Change in number of respiratory admissions

We estimated the change in number of respiratory admissions (ΔH) from the present day (2004–2009) to the future (2046–2051) under a changing climate due to changes in the number of $SW_{99.5}$ days. We first calculated the change in the number of additional smoke wave days in the future by county and the resulting respiratory admissions during these days by county, and then calculated the difference of respiratory admissions if these smoke wave days were non-smoke-wave days. The formula can be expressed as:

$$\Delta H = \sum_{c=1}^{n} (\Delta N_{99.5}^{c} * B^c * R_{99.5} * S^c - \Delta N_{99.5}^{c} * B^c * S^c), \tag{2}$$

where:

n is the total number of counties that experienced at least 1 $SW_{99.5}$.

$\Delta N_{99.5}^{c}$ is the difference between the numbers of $SW_{99.5}$ days in the future and the numbers of $SW_{99.5}$ days at the present day in county c.

B^c is the baseline rate of respiratory hospital admissions in county c, i.e. the admission rate during non-smoke-wave days at the present day.

$R_{99.5}$ is the overall estimated relative risk in respiratory admission rate during $SW_{99.5}$ days compared to non-smoke-wave days (relative risk = 1.072).

S^c is the future elderly populations in county c (either 1) estimated as the same as those of the

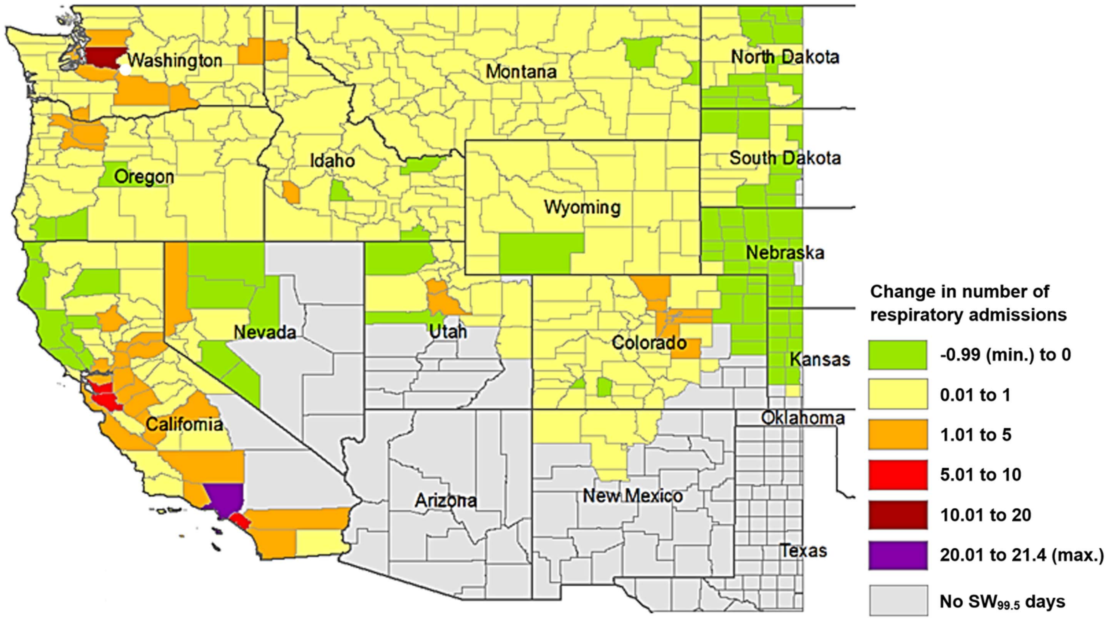

Figure 1. Change in number of respiratory admissions due to changes in the relatively more intense category of smoke waves ($SW_{99.5}$) accounting for population change during 2046–2051 compared with 2004–2009.

present-day, or 2) estimated to increase as projected (E^c)).

Confidence intervals are calculated based on the estimated statistical uncertainty of $R_{99.5}$.

Results

Change in number of smoke wave days and intensity under climate change

Climate change is anticipated to lead to more smoke wave days in the Western US [10]. In earlier work we studied exposure of SW_{98}, and this study added exposure of $SW_{99.5}$ as we previously found significant health effects during relatively more intense smoke waves [9]. We estimate that 440 counties will be exposed to at least one SW_{98} in 2046–2051. In total we estimate 4990 more SW_{98} county-days (summed across all counties), among which 2600 are also $SW_{99.5}$ county-days, during 2046–2051 compared with the estimated smoke wave county-days in 2004–2009.

Health burden from wildfire-specific $PM_{2.5}$ in the future under climate change

During the study period there were about five million Medicare fee-for-service enrollees in the study area of the Western US. The mean number of county-level daily respiratory admissions is 0.4 admissions day^{-1}. The county with the highest average daily number of respiratory admissions is Los Angeles County (31 admissions day^{-1}). There were in total 245 926 respiratory admissions in all Western US counties during 2004–2009.

First, we calculated the change in hospital admissions under the scenario that the future elderly population in each county remains the same as that of the present day thereby isolating the impact of climate change. Based on the smoke-wave-health association for $SW_{99.5}$ estimated previously [9], the change in number of $SW_{99.5}$ days is estimated to lead to 61.5 (95% CI: 2.14, 125) more respiratory admissions in the Western US across 6 years.

Accounting for future population changes in each county, $SW_{99.5}$ are estimated to impose 178 (95% CI: 6.17, 361) additional respiratory admissions. Summary statistics of the change in respiratory admissions by county in the future compared to the present day are shown in supplementary table A.2. These results combine spatial patterns for each county's change in wildfire-specific $PM_{2.5}$ that affects whether a day is a $SW_{99.5}$ day or non-smoke-wave day; baseline health response; baseline population; and for some estimates the anticipated population growth.

Spatial pattern of health burden from wildfire $PM_{2.5}$ under climate change

Populated counties such as central to southern California and northwestern Washington are anticipated to have the highest increase in number of respiratory admissions due to increased number of $SW_{99.5}$ days under the scenario of non-population growth, which isolates the impact of climate change. When incorporating population change as well as climate change in the future, the number of respiratory admissions in areas such as greater Denver and Salt Lake City are also estimated to increase, in addition to central California and western Washington (figure 1). Respiratory admission counts from wildfires are estimated to decrease in coastal northern California in the future due to fewer $SW_{99.5}$ days. Although counties in the northern Rocky Mountain area are likely to experience more smoke wave days in the future compared to the present day [10], these counties are anticipated to experience smaller increases in the number of respiratory admissions than some other areas (figure 1), possibly due to their small populations and low baseline respiratory admission rates.

Discussion

This study provides scientific evidence on how the risk of respiratory hospital admissions for the elderly will be affected by future wildfire-induced air pollution under a changing climate in the Western US. The results suggest that communities in California, central Colorado, and Washington are anticipated to have an increase in respiratory admissions in the future due to the growing wildfire treat and population increase. Despite that the differences in future respiratory admissions are modest, hospital admission is a serious event and should therefore happen rarely. Our findings can inform decision makers in establishing or modifying public health programs regarding wildfires in severely affected communities to reduce health consequences from future wildfire-specific air pollution, as well as adjusting the capacity of health care facilities. The results can also raise the awareness among the general public of potential health consequence of climate change.

The growing aging population in the US affects the impact of the health burden from wildfire-inducted air pollution under climate change, as a larger population can be at risk. The percentage of the elderly population in the Western US is estimated to increase from 15.7% at the present day to 20.9% in 2050 [18]. An additional 5.7 million elderly persons are estimated to be exposed to SW_{98} in the Western US [10]. The potential health impact due to growing threat of wildfires is a function not only of the changes in forest fires and associated exposure to wildfire-related air pollution, but also the rate of population growth and the aging of the population.

Some previous studies have suggested that future increase in air pollution from wildfire activity due to climate change is anticipated to pose health risks in affected populations [21, 22]. A previous study also quantified national-level increase in premature death, acute respiratory and cardiovascular hospital admissions due to wildfire smoke in the near future for the year 2016 [23], but did not estimate the change in admissions under climate change.

There are three main strengths of our study. The study is the first to predict future respiratory admission increase due to wildfire-specific $PM_{2.5}$ under climate change. This interdisciplinary study combined the state-of-art wildfire pollution model, the GEOS-Chem model, with results from the latest research on wildfire-specific $PM_{2.5}$ and respiratory health [9]. Second, the present study addressed a key challenge of identifying days affected by smoke from all wildfires, rather than from a single wildfire. As smoke exposure can come from multiple wildfires across large areas, we defined smoke days based on the levels of wildfire-specific $PM_{2.5}$ levels instead of using start and end days of a particular fire, as have earlier studies. Third, our county-specific results are highly policy relevant, providing information on the spatial patterns of results. This study covered all counties in the Western US, including rural counties, and generated maps that can inform both policy-makers and the general public in every county about future health effects.

This study is also subject to assumptions and limitations. Our findings assumed future baseline respiratory admission rate to be the same as that of the present day. Future change in medical technology and improvement of population health are largely unknown. It is also possible that the baseline respiratory admissions rate might increase (or decrease) as the population ages. Future studies could address temporal changes in the baseline health response. The study could also be updated as the wildfire modeling and climate change scenarios improve, such as incorporation of the possibility that fire suppression in the western US might lead to an unnatural accumulation of forests, thereby providing fuel that may increase the probability of large fires [24, 25]. The GEOS-Chem model did not include changes in vegetation due to climate change or to CO_2 fertilization, which may result in faster growth of vegetation [26]. Future studies could also explore adaptation to wildfire events, variation in the wildfire smoke-health association, more health endpoints, and additional climate scenarios to develop a more comprehensive understanding of community health risks due to future wildfire smoke.

The significant increase in hospital admissions provides suggestive evidence that other types of outcomes for respiratory ailments may increase in the future due to wildfires, and further research on this topic is warranted. $PM_{2.5}$, measured as total mass from all sources, is associated with a wide range of health effects, such as cardiovascular diseases, respiratory diseases, cancer, and mortality [27–29]. We investigated only respiratory admissions, which were shown to be associated with wildfire smoke in the present day in this study region [9]. Our research framework could provide the basis for such work. This interdisciplinary study linked atmospheric science, global climate modeling, wildfire schemes, and epidemiology. We incorporated county-specific information on baseline health rates, present day and future exposure to wildfires, and population growth. Future studies can further investigate the health consequences of wildfires and other natural disasters using our framework of methods with potentially improved availability of source-specific pollutant data.

The estimated increase in respiratory admissions due to future wildfire smoke highlights one of the potential of human health impacts from a changing climate. Our results indicated that under climate change, increased threat of wildfire will generate smoke that can affect populations living far from wildfire centers. In addition to increasing fire suppression resources and evacuation efforts in areas directly affected by future wildfires, policy-makers should also consider improving the capacity of emergency care facilities to meet the needs of communities affected by wildfire smoke. These results, summed with other health outcomes from climate change impacts such as cardiovascular diseases, infectious diseases, heat stress, and death [22, 30, 31], contribute to our overall understanding of the public health burden of climate change. Climate change policies can be informed by scientific evidence on the health risks from natural disasters such as wildfires as well as other health impacts.

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