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A statistical modeling framework for projecting future ambient ozone and its health impact due to climate change

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HIGHLIGHTS

- A statistical framework to estimate future ozone level is developed.
- Ozone projections based on outputs of 8 climate model simulations are examined.
- Calibrated model outputs can reduce projection variation across climate models.
- Higher ozone level and asthma emergency department visit are projected in Atlanta.

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ABSTRACT

The adverse health effects of ambient ozone are well established. Given the high sensitivity of ambient ozone concentrations to meteorological conditions, the impacts of future climate change on ozone concentrations and its associated health effects are of concern. We describe a statistical modeling framework for projecting future ozone levels and its health impacts under a changing climate. This is motivated by the continual effort to evaluate projection uncertainties to inform public health risk assessment. The proposed approach was applied to the 20-county Atlanta metropolitan area using regional climate model (RCM) simulations from the North American Regional Climate Change Assessment Program. Future ozone levels and ozone-related excesses in asthma emergency department (ED) visits were examined for the period 2041–2070. The computationally efficient approach allowed us to consider 8 sets of climate model outputs based on different combinations of 4 RCMs and 4 general circulation models. Compared to the historical period of 1999–2004, we found consistent projections across climate models of an average 11.5% higher ozone levels (range: 4.8%, 16.2%), and an average 8.3% (range: −7%–24%) higher number of ozone exceedance days. Assuming no change in the at-risk population, this corresponds to excess ozone-related ED visits ranging from 267 to 466 visits per year. Health impact projection uncertainty was driven predominantly by uncertainty in the health effect association and climate model variability. Calibrating climate simulations with historical observations reduced differences in projections across climate models.

1. Introduction

Tropospheric ozone is an ambient air pollutant regulated worldwide due to its adverse effects on human health (Anenberg et al., 2010) and vegetation (van Dingenen et al., 2009). As a secondary pollutant, ozone is produced through photochemical oxidation of carbon monoxide and volatile organic compounds in the presence of nitrogen oxides and sunlight. Consequently, ozone concentrations are highly sensitive to meteorological conditions and emissions pathways that affect the availability of precursors. Empirical studies have demonstrated associations between observed ozone levels and (1) precursor levels (Nail et al., 2011; Blanchard et al., 2012), and (2) meteorological variables including temperature, air stagnation, wind speed, and cloud cover at various spatial and temporal scales (Jacob and Winner, 2009).

Coherent evidence from climate model simulations suggests that the growing anthropogenic greenhouse gas emissions will likely result in higher surface temperatures and more frequent extreme weather events in the future (Intergovernmental Panel on Climate Change (IPCC) 2012). These environmental changes have

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the potential to increase future ambient ozone concentrations, which may have important public health implications including increased mortality and morbidity (Murazaki and Hess, 2006). Timely knowledge on the health impacts of climate change can play an important role in supporting regulatory policies that protect public health and maintain environmental sustainability (Menne and Ebi, 2005; Frumkin et al., 2008). While numerous studies have examined projections of future heat-related health outcomes (Huang et al., 2011; Peng et al., 2011), the number of studies on future air pollution-related outcomes is more limited (Sujaritpong et al., 2013).

Previous studies on future ozone projections have predominantly utilized chemical transport models (CTM) driven by climate model outputs (Hogrefe et al., 2004; Knowlton et al., 2004; Bell et al., 2007; Tao et al., 2007; Tagaris et al., 2009; Lei et al., 2012; Orru et al., 2013). These studies have consistently reported global and regional increases in future ozone levels. CTMs are 3-dimensional numerical models that use emissions inventory and meteorological data to simulate the complex atmospheric chemistry and physics involved in ozone formation. While CTMs provide large spatial coverage and incorporate current scientific knowledge on environmental processes, one limitation is that their outputs are deterministic and thus provide only a single projection for a given scenario with no associated measure of uncertainty. Therefore uncertainty quantification on health impact projections based on CTMs has mainly focused on the sensitivity of outputs in response to different emission scenarios and inter-model comparisons (Post et al., 2012).

In this paper we describe a statistical framework for projecting future ozone levels and corresponding emergency department (ED) visit health impacts. In contrast to CTMs, our statistical approach is motivated by its ability to provide measures of uncertainty (in terms of standard errors) for projections under a given scenario. Our approach is also motivated by the increasing interest in evaluating air pollution projection uncertainties that can be used in public health risk assessment (Mastrandrea et al., 2010).

Our framework involves the following steps. First, using historical observations for the period 1999–2004, we develop a statistical *prediction model* of daily ozone concentrations as a function of meteorological variables and important ozone precursors: non-methane volatile organic compounds (VOC), and nitrogen oxides (NO_x). Our prediction model builds upon the extensive literature on statistical models for ambient ozone (Thompson et al., 2001; Cheng et al., 2007; Camalier et al., 2007; Chang et al., 2010). Findings from these models have been used for obtaining air quality forecasts, as well as providing insights on factors that influence ozone concentrations. Second, future ozone concentrations for the period 2041–2070 are then projected using future meteorology from climate model simulations and projected precursor levels as predictors. Finally, using a locally-derived concentration-response function, health impact projections due to climate- and precursor-related changes in future ozone levels are made. Uncertainties in the modeled ozone-meteorology/precursor relationship are propagated through the projection stages and quantified. The approach is applied to the 20-county Atlanta metropolitan area, a region currently with ozone levels exceeding the US National Ambient Air Quality Standards.

An additional important advantage of projecting ozone concentrations using a statistical model is that it requires considerably less computational effort compared to CTMs. Variation in climate simulations by different models is a well-recognized source of uncertainty (Jun et al., 2008; Knutti, 2010). Due to the effort required for running CTMs, previous analyses using these models have typically only examined outputs from one general circulation model (GCM) or one regional climate model (RCM), which makes synthesizing findings across studies difficult. In this analysis using our statistical approach, we made ozone projections based on simulations from multiple climate models. Climate model outputs were obtained from the North American Regional Climate Change Assessment Program (NARCCAP) (Mearns et al., 2009), which is an international collaboration examining projection variability due to the choice of GCM and RCM. In this study 8 different GCM-RCM combinations were examined.

2. Materials and methods

2.1. Data collection

We acquired individual records of ED visits to acute care hospitals in the 20-county Atlanta metropolitan area for 1999–2004. The ED database is part of the larger Study of Particles and Health in Atlanta (SOPHIA) (Strickland et al., 2010). Using International Classification of Diseases 9th Revision (ICD-9) diagnosis codes, total ED visits due to asthma and wheeze (ICD-9 codes 493 and 786.07) were aggregated on each day. We restricted the study period to the warm months of March to October.

Daily 8-h maximum ozone, 24-h average VOC, and 24-h average NO_x concentrations for 1999–2004 were obtained from the Jefferson St. site, a centrally-located monitor in the SouthEastern Aerosol Research and Characterization (SEARCH) network. Daily meteorological conditions for 1999–2004, including minimum, maximum and average temperature, dew-point temperature, total precipitation, and total solar radiation (global horizontal irradiance), were obtained from the National Climatic Data Center and the National Solar Radiation Data Base for monitors located at the Hartsfield-Jackson Atlanta International Airport.

Climate model outputs of daily maximum surface temperature, 3-h precipitation and 3-h solar radiation were obtained from NARCCAP for the historical period of 1999–2000 and for the future period of 2041–2070. NARCCAP is a public database of RCM simulations available as 50 km by 50 km gridded output. All NARCCAP simulations were conducted under the IPCC Special Report on Emissions Scenarios (SRES) A2 emissions scenario (Nakicenovic, 2000). The A2 scenario represents the higher end of IPCC emission scenarios and entails large population increases, high carbon dioxide emissions, and weak environmental concerns.

To assess uncertainties in RCM projections, we examined NARCCAP simulations from 8 combinations of different RCMs driven by boundary conditions of different GCMs, as available at the time of this analysis. The RCMs include: the Canadian Regional Climate Model (CRCM, http://www.cccma.ec.gc.ca/data/crcm.shtml), the Handley Regional Model 3 (HRM3, http://www.metoffice.gov.uk/precis/), the Regional Climate Model version 3 (RCM3, users.ictp.it/~pubregcm/RegCM3), and the Weather Research & Forecasting model (WRFG, http://www.wrf-model.org/index.php). The GCMs include: the Community Climate model version 3 (CCSM3), the Canadian Global Climate Model version 3 (CGCM3), the Geophysical Fluid Dynamics Laboratory (GFDL) Climate Model version 2.1, and the United Kingdom Hadley Centre Climate Model version 3 (HadCM3). Detailed descriptions on the RCM and GCM characteristics are summarized by NARCCAP online (http://www.narccap.ucar.edu/). The following 8 RCM-GCM combinations were conducted by NARCCAP and examined in this study: CRCM-CCSM, CRCM-CGCM3, HRM3-GFDL, HRM3-HadCM3, RCM3-CGCM3, RCM3-GFDL, WRFG-CCSM, and WRFG-CGCM3. For each combination, we extracted data for the one grid cell that contained the airport monitoring station, as calibrations were not improved when considering data from all grid cells. The 3-h data were processed to obtain daily total precipitation and total solar radiation for the historical and future periods.