Environment International 108 (2017) 41–50

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

The impact of climate change and emissions control on future ozone levels: Implications for human health

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ARTICLE INFO

Keywords:
Ozone
Climate change
Predictive modeling
Emissions
Pollution
Public health
Mortality

ABSTRACT

Overwhelming evidence has shown that, from the Industrial Revolution to the present, human activities influence ground-level ozone (O_3) concentrations. Past studies demonstrate links between O_3 exposure and health. However, knowledge gaps remain in our understanding concerning the impacts of climate change mitigation policies on O_3 concentrations and health. Using a hybrid downscaling approach, we evaluated the separate impact of climate change and emission control policies on O_3 levels and associated excess mortality in the US in the 2050s under two Representative Concentration Pathways (RCPs). We show that, by the 2050s, under RCP4.5, increased O_3 levels due to combined climate change and emission control policies, could contribute to an increase of approximately 50 premature deaths annually nationwide in the US. The biggest impact, however, is seen under RCP8.5, where rises in O_3 concentrations are expected to result in over 2,200 additional premature deaths annually. The largest increases in O_3 are seen in RCP8.5 in the Northeast, the Southeast, the Central, and the West regions of the US. Additionally, when O_3 increases are examined by climate change and emissions contributions separately, the benefits of emissions mitigation efforts may significantly outweigh the effects of climate change mitigation policies on O_3-related mortality.

1. Introduction

Since the Clean Air Act of 1970, atmospheric ozone (O_3) concentrations have declined in the US. Nevertheless, the American Lung Association reported that, as of 2013, over 138 million people in the US (~44%) continue to live in areas where O_3 levels exceed regulatory standards (ALA, 2015). Among common air pollutants that impact public health, O_3 is one of the most detrimental. Risk of O_3-related adverse outcomes is a public health concern due to widespread O_3 exposure, which is ubiquitous in industrialized regions. Research has consistently linked O_3 exposure to a variety of adverse health outcomes including increased emergency room (ER) visits and hospitalizations, asthma exacerbation, cardiovascular stress, impaired lung function, and premature death (Bell et al., 2005; Bell et al., 2007; Bell et al., 2004; Bernard et al., 2001; Jackson et al., 2010; Post et al., 2012; Tagaris et al., 2009; Levy et al., 2005; Gryparis et al., 2004; Stieb et al., 2009; Jerrett et al., 2009). Multiple studies have demonstrated the connections between climate change to O_3 concentrations and these potential health outcomes. For example, Tagaris et al. found the highest climate-induced O_3 increases coincided with the most densely populated areas in the US and increases in national premature mortality of approximately 300 additional deaths annually (Tagaris et al., 2009). Bell et al. also showed that climate change-induced O_3 increases are associated with significant increases in premature mortality and ER/hospital admissions (Bell et al., 2007; Bell et al., 2004). Additionally, by comparing future O_3 concentrations and associated adverse health outcomes from seven published studies, Post et al. showed substantial heterogeneity in the projections when different models and methods were considered (Post et al., 2012). One such example found in this comparison of studies demonstrated a large discrepancy in O_3-related excess mortality due to climate change among the studies examined (ranging from −600 deaths to over 2500 deaths annually).

Abbreviations: O_3, ozone; RCPs, Representative Concentration Pathways; NMVOC, non-methane volatile organic carbon; NOx, nitrogen oxides; GCMs, global climate models; SRES, Special Report on Emissions Scenarios; GHGs, greenhouse gases; CESM, Community Earth System Model; NCAR, National Center for Atmospheric Research; WRF, Weather Research and Forecasting model; CMAQ, Community Multi-scale Air Quality model; CAM-Chem, Community Atmosphere Model w/ chemistry; MDA8 O_3, maximum daily average eight-hour ozone; ICLUS, Integrated Climate and Land-Use Scenarios

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http://dx.doi.org/10.1016/j.envint.2017.08.001
Received 30 December 2016; Received in revised form 1 August 2017; Accepted 1 August 2017
Available online 08 August 2017
0160-4120/

The primary drivers of ground-level O_3 generation are precursor emissions (nitrogen oxides (NO_x) and volatile organic compounds (VOCs)), presence of methane, and favorable meteorological conditions (Dawson et al., 2007; Jacob and Winner, 2009; Nolte et al., 2008). Because both emissions and meteorology vary in space, O_3 concentrations can be spatially heterogeneous at the scale of a few kilometers to tens of kilometers (Diem, 2003). Therefore, spatially-resolved estimates of O_3 levels are important when evaluating its potential impact on air quality and human health as well as developing applicable mitigation and adaptation policies. However, as Post et al. reported, the coarse spatial resolution of global climate models (GCMs) cannot resolve the fine-scale features in future O_3 levels (Post et al., 2012).

Both dynamical and statistical downscaling approaches have been developed to address this resolution incongruence. Dynamical downscaling involves executing high-resolution regional climate models (RCMs) and air quality models using GCM outputs as boundary conditions. This method integrates atmospheric chemistry composition, allowing for extrapolation of future atmospheric conditions (Nolte et al., 2008). However, the high computational demand (due to high-resolution, full-chemistry simulations) limits the application to multiple GCM outputs and reduces the availability of these methods (Gao et al., 2013; Gao et al., 2012; Murphy, 2000). Previous studies have used dynamical downscaling methods to study the impact of climate change on future O_3 and air quality. At 36 km resolution, Nolte et al. used dynamical downscaling methods to show significant increases in summer O_3 and a lengthening of the O_3 season under a high emissions scenario as well as substantial decreases during the summer season under a lower emissions scenario (Nolte et al., 2008).

Statistical downscaling methods use efficient statistical methods based on historical atmospheric patterns to relate coarse-resolution GCM simulations to finer grid results, which is much less computationally demanding (Gao et al., 2013). Previous studies have investigated the relationship between O_3 and changes in meteorological conditions using statistical models. For example, Cox and Chu examined 100 meteorological variables for potential effects on ambient O_3, and found that maximum surface temperature, wind speed, relative humidity, mixing layer, and cloud cover were significant. Both Dawson et al. and Camalier et al. found similar statistically significant results showing that daily maximum temperature, relative and absolute humidity, wind speeds, and mixing height greatly affect O_3 concentration (Dawson et al., 2007; Cox and Chu, 1996; Camalier et al., 2007). The limitations of statistical downscaling are mainly due to the assumption that the statistical association between O_3 levels and meteorological conditions will remain the same in the future, which may not be realistic given potential future variations in atmospheric chemistry and emissions (Mahmud et al., 2008).

In addition to air pollution levels estimated at fine spatial scales, the impacts on future O_3 levels due to climate change and future emissions need to be assessed separately for effective mitigation measures. Above all, the impact of air pollution emissions control can have a more immediate effect on air quality and subsequent human health than the effects from slowing down climate change (Fiore et al., 2015). Previously utilized emission scenarios, however, do not allow for such separation of O_3 levels due to climate change and emissions. The latest Representative Concentration Pathways (RCPs) differ from previous emission scenarios such as the Special Report on Emissions Scenarios (SRES) by integrating current and planned environmental policies (IIASA, 2013; Moss et al., 2010; van Vuuren et al., 2011). As a result, RCP-based climate model simulations reflect the combined impact of both climate change and planned emission control on air pollutant levels (IIASA, 2013). This integrated combination provides a platform to develop methods to examine the separate contributions of climate change and emissions. There are multiple RCP scenarios with underlying population growth, economic, and emissions assumptions. RCP2.6, 4.5 and 6.0 all represent some form of improvement upon our current trajectory of growth and environmental policy. RCP8.5, however, represents a “business-as-usual” scenario in which nations choose to retain current economic, environmental, and social tracks. For example, RCP4.5 represents a future scenario with medium to low greenhouse gas emissions, medium-level air pollution, less crop land, and low population growth. RCP8.5, on the other hand, is characterized by high population growth, low to medium crop land use, increasing trends for methane and nitrous oxide, and higher concentrations of almost all air pollutants (van Vuuren et al., 2011).

The objective of this study is to estimate the contribution of climate change and emissions control to future O_3 levels separately at high spatial resolution in the Continental US. We present a hybrid dynamical-statistical downscaling approach to project and separate the impacts of climate change and air pollution emissions control on future O_3 levels under both RCP4.5 and 8.5. Additionally, we expand our analysis and estimate county-level excess mortality due to projected O_3 exposure in the 2050s and evaluate the spatial and temporal patterns of associated estimated health risks. The 2050s were selected for the future projected years based on the IPCC common use of 2050 as a threshold for major global temperature divergence (i.e. potential to rise above 2 °C) (IPCC, 2013).

2. Data and methods

Our four-step hybrid health impact projection approach is shown in Fig. 1. Step 1 involves a dynamical downscaling framework following two RCPs respectively. This framework is composed of a GCM, a RCM, and an atmospheric chemistry model, which estimates county-level O_3 concentrations in the 2050s due to the combined effects of climate change and environmental policies as described in RCPs. Step 2 develops a statistical downscaling model to estimate future changes in O_3 concentrations from climate change, which uses both real-world historical climate conditions and high-resolution future climate conditions simulated by the RCM in Step 1. Step 3 estimates the future change in O_3 concentrations due to emissions only by subtracting the statistical downscaling results (Step 2) from the dynamical results (Step 1). Finally, in Step 4, the results from Steps 1–3 are placed in a human health context by estimating the future excess mortality due to projected changes in O_3 concentrations.

2.1. Step 1: dynamical downscaling for O_3 change due to changes in climate and air pollution emissions

The Community Earth System Model version 1.0 (CESM 1.0) is a state-of-the-art global climate model developed by the National Center for Atmospheric Research (NCAR) (Gent et al., 2011). As a fully coupled earth system model, there is a total of four components in CESM(Neale et al., 2010): 1) the land surface component - Community Land Model (CLM4) (Oleson et al., 2010); 2) the ocean model and sea ice component - Parallel Ocean Program version 2 (POP2) (Smith et al., 2010) and Los Alamos National Laboratory Sea Ice Model, version 4 (CICE4) (Hunke and Lipscomb, 2008); 3) the atmospheric chemistry module - adapted from the Model for Ozone And Related chemical Tracers version 4 (MOZART-4) (Emmons et al., 2010); and 4) the bulk aerosol model (coupled to the atmospheric component Community Atmosphere Model, CAM4), referred to as CAM-Chem (Emmons et al., 2010; Lamarque et al., 2005). More details regarding the configurations of CAM-Chem have been described in previous studies (Gao et al., 2013; Lamarque et al., 2012). CESM/CAM-Chem was continuously run from 2001 to 2059 under both RCP4.5 and RCP8.5 with spatial resolution of 0.9° by 1.25°.

The dynamical downscaling framework was developed to conduct high resolution simulations (12 km) at two time slices from 2001 to 2004 for the baseline historical period and 2055 to 2059 for future scenarios under RCP 4.5 and RCP 8.5 (Gao et al., 2013; Gao et al., 2012). The Weather Research and Forecasting (WRF, version 3.2.1) and the Community Multi-scale Air Quality Model (CMAQ, version 5.0)