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Impacts of transportation sector emissions on future U.S. air quality in a changing climate. Part II: Air quality projections and the interplay between emissions and climate change[☆]

Patrick Campbell [a, 1], Yang Zhang [a, *], Fang Yan [b, c, 2], Zifeng Lu [b, c], David Streets [b, c]

[a] Department of Marine, Earth, and Atmospheric Sciences, NCSU, Raleigh, NC 27695, USA
[b] Computation Institute, University of Chicago, Chicago, IL 60637, USA
[c] Energy Systems Division, Argonne National Laboratory, Argonne, IL 60439, USA

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ABSTRACT

In Part II of this work we present the results of the downscaled offline Weather Research and Forecasting/Community Multiscale Air Quality (WRF/CMAQ) model, included in the "Technology Driver Model" (TDM) approach to future U.S. air quality projections (2046–2050) compared to a current-year period (2001–2005), and the interplay between future emission and climate changes. By 2046–2050, there are widespread decreases in future concentrations of carbon monoxide (CO), nitrogen oxides ($NO_x = NO + NO_2$), volatile organic compounds (VOCs), ammonia (NH_3), sulfur dioxide (SO_2), and particulate matter with an aerodynamic diameter $\leq 2.5\ \mu m$ ($PM_{2.5}$) due mainly to decreasing on-road vehicle (ORV) emissions near urban centers as well as decreases in other transportation modes that include non-road engines (NRE). However, there are widespread increases in daily maximum 8-hr ozone (O_3) across the U.S., which are due to enhanced greenhouse gases (GHG) including methane (CH_4) and carbon dioxide (CO_2) under the Intergovernmental Panel on Climate Change (IPCC) A1B scenario, and isolated areas of larger reduction in transportation emissions of NO_x compared to that of VOCs over regions with VOC-limited O_3 chemistry. Other notable future changes are reduced haze and improved visibility, increased primary organic to elemental carbon ratio, decreases in $PM_{2.5}$ and its species, decreases and increases in dry deposition of SO_2 and O_3, respectively, and decreases in total nitrogen (TN) deposition. There is a tendency for transportation emission and CH_4 changes to dominate the increases in O_3, while climate change may either enhance or mitigate these increases in the west or east U.S., respectively. Climate change also decreases $PM_{2.5}$ in the future. Other variable changes exhibit stronger susceptibility to either emission (e.g., CO, NO_x, and TN deposition) or climate changes (e.g., VOC, NH_3, SO_2, and total sulfate deposition), which also have a strong dependence on season and specific U.S. regions.

1. Introduction

Rapidly changing transportation sector emissions influence atmospheric chemistry and climate, and the impacts of the emissions on air quality vary for different countries and their dominating transportation modes (Eyring et al., 2010; Lee et al., 2010; Uherek et al., 2010). Many studies have investigated the past and projected changes in the transportation sector and their emissions in developed and developing countries (e.g., Arora et al., 2011; EEA, 2012; IEA, 2014; Yan et al., 2014). Recently many retrospective studies have probed into the impacts of the transportation sector on air quality and health across the world. Bickford (2012) showed that diesel freight transport via trucks and trains contribute about 20% and 3% of all U.S. emissions of nitrogen oxides ($NO_x = NO + NO_2$) and particulate matter (PM) with an aerodynamic diameter $\leq 2.5\ \mu m$ ($PM_{2.5}$), respectively, and that incorporation of biodiesel and truck-to-rail modal shifts can help reduce

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[*] Corresponding author. Department of MEAS, Campus Box 8208, Raleigh, NC 27695-8208, USA.

E-mail address: yzhang9@ncsu.edu (Y. Zhang).

[1] Currently at Computational Exposure Division, National Exposure Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, NC, 27709, USA.

[2] Currently at Mobile Source Control Division, California Air Resources Board, Sacramento, CA 95814.

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emissions and improve air quality in some regions. Viana et al. (2014) showed that shipping emissions in coastal regions of Europe contribute significantly to PM and nitrogen dioxide (NO_2) levels, as well as enhance new particle formation in urban areas. Other studies show that the mobile source sector is a major anthropogenic source (~21–24%) of high ozone (O_3) pollution in the summer in the Yangtze River Delta region of China (Li et al., 2015), and there are elevated $PM_{2.5}$ concentrations in near-roadway regions of southern California that contributes to a large burden of coronary heart disease mortality (Ghosh et al., 2016).

There is considerable interest in studying transportation emission changes in the future that are influenced by policy, socioeconomic, and technological drivers, and the consequences of the resulting emission changes on future regional air quality. In a review paper by Colvile et al. (2001), they summarized the impacts of air pollution from three different transportation modes (road, aircraft, and ships), discussed the immense global potential for growth of the transport sector in the future, and demonstrated the continued importance of road transportation research that has and will continue to be subjected to demand management to meet environmental objectives. Since this review, significant research has been dedicated to modeling transportation emission projections to investigate the impacts on air quality and health, and the implications for future air pollution control and policy. Through integrated transportation-land use projection modeling, McDonald-Buller et al. (2010) showed that the emissions of O_3 precursors over the large city of Austin, TX decrease dramatically by 2030 due to implementation of more stringent federal motor vehicle control programs, while the O_3 concentrations and impacts on population exposure varied in response to different policy scenarios. Implementation of Euro 3 vehicle emission standards over China may reduce emissions by more than 50% (compared to no-policy changes) of O_3 precursor gases and black (BC) and organic carbon (OC) particles, while mitigating surface O_3 and $PM_{2.5}$ concentrations by more than 10 ppb and $10\ \mu g\ m^{-3}$ in 2020 respectively (Saikawa et al., 2011). Transitioning from Tier 1 to Tier 2 emission standards for on-road gasoline-fueled light duty vehicles (both cars and trucks) in the eastern U.S. shows large benefits in reducing the absolute (relative) daily maximum 8-hr O_3 and maximum daily $PM_{2.5}$ concentrations by 16 ppb (14%) and $4.5\ \mu g\ m^{-3}$ (9%) in 2022 respectively (Vijayaraghavan et al., 2012).

To better probe the interactions between future human activities, climate change, air quality, human health, and ecosystems, the Intergovernmental Panel on Climate Change (IPCC) research community has developed two popular sets of scenarios that are based on expert judgments of plausible future emissions considering socioeconomic, environmental, and technological trends. These include 1) the Special Report on Emissions Scenarios (SRES; Nakicenovic et al., 2000), and 2) the Representative Concentration Pathways (RCP; Moss et al., 2010). Both the IPCC SRES and RCP scenarios have their own uncertainties in the projections, and there are both similarities and differences between the scenario families (Rogelj et al., 2012). Using RCP4.5 and 8.5 scenarios, Baklanov et al. (2010) assessed the effects of future climate change on air quality, as well as climate change impacts on the policy measures designed for reducing the health impacts of transportation sector emissions. They showed that the direct impacts of climate change on air quality near major cities in Europe include enhancements in strong winds in mid-latitude high and low pressure systems, in conjunction with suppressed mixing will lead to strong long-range, near-surface export of pollutants. Baklanov et al. (2010) also indicated that the RCP8.5-predicted increases in temperature and photolysis are expected to increase near-surface O_3 levels in the future, but that the increases will be outweighed by the expected decline in the emissions of O_3 precursor gases due to transportation in Europe. Penrod et al. (2014) used dynamically downscaled climate model output and regional all-sector emission changes over the U.S. based on the SRES A1B family scenario, and showed that increased temperatures lead to increases of up to 5 ppb in maximum 8-hr average O_3 in the winter over the U.S., and the large reductions in NO_x emissions drive decreases in O_3 over most of the U.S. during summer. Also, Penrod et al. (2014) showed that significant emission reductions dominate the climate change impacts on future $PM_{2.5}$ concentrations over the U.S.

The emission projections in previous work did not account for explicit relationships between socioeconomic factors and technology changes (Yan et al., 2014), and also simply assumed that the emission projections are the same across the entire domain used in the air quality modeling system. It is essential to more accurately differentiate emitters by their emission characteristics that are continually influenced by dynamic changes in technology (i.e., economic development, policy changes, and emission control strategies), while determining the emission factors using explicit relationships rather than by expert judgments (Yan et al., 2014). It is also beneficial to combine the emission changes in short-lived species from the transportation sector, with simultaneous increases in the long-lived greenhouse gases (GHGs) such as methane (CH_4) and carbon dioxide (CO_2), as these gases also have direct and indirect effects on air pollutant concentrations, and thus more appropriately represent possible future scenarios. The spatial, temporal, and socioeconomic-technological relationship variabilities in future emission projections can have important impacts on the predicted air quality changes in the future, especially when combined with variability in regional climate change impacts.

Over the past 30 years there are increasing trends in total U.S. population, vehicles miles traveled, energy and fuel consumption, and gross domestic product; however, air pollutant emissions and concentrations have shown decreasing trends due to implementation of dynamic technological changes in the transportation sector (Yan et al., 2014). In the future, the impacts of changing transportation emissions involve a complex interplay between socioeconomic-technological-driven changes and the global and regional influences of climate change in the U.S., both of which may include spatial and seasonal variability across different regions. In Part I of this work (Campbell et al., 2018), we provided an overview of the advanced Technology Driver Model (TDM) approach (see graphical abstract in Part I), explained the dynamically downscaled air quality modeling system configuration and design summary, detailed and quantified the dynamic transportation sector emission changes from the Speciated Pollutant Emission Wizard-Trend (SPEW-Trend) model over the U.S., and comprehensively evaluated the model system. In this Part II, we use the transportation emission projections from Part I and quantify their impacts on future U.S. air quality in the face of future climate and GHG changes (Section 2), and then summarize the important results (Section 3).

2. Projected air quality changes over the U.S. by 2046–2050

This section presents the projected U.S. air quality changes due to transportation sector emissions (Part I) and the interplay among emission, GHG, and climate changes. To do this, a 5-year current (2001–2005) and future (2046–2050) period from a Community Climate System Model (CCSM) simulation is dynamically downscaled and provides the initial (ICONs) and boundary conditions (BCONs) for the IPCC A1B scenario to the Weather Research and Forecast version 3.6.1, which then drives the offline Community Multiscale Air Quality model version 5.0.2 (WRF_CCSM/CMAQ) model (see Part I, Section 2 for more details). Table 1 summarizes the six WRF_CCSM/CMAQ sensitivity simulation sets.

These consist of 1) a current-year 2001–2005 period (CURR),