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Impacts of transportation sector emissions on future U.S. air quality in a changing climate. Part I: Projected emissions, simulation design, and model evaluation[☆]

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ABSTRACT

Emissions from the transportation sector are rapidly changing worldwide; however, the interplay of such emission changes in the face of climate change are not as well understood. This two-part study examines the impact of projected emissions from the U.S. transportation sector (Part I) on ambient air quality in the face of climate change (Part II). In Part I of this study, we describe the methodology and results of a novel Technology Driver Model (see graphical abstract) that includes 1) transportation emission projections (including on-road vehicles, non-road engines, aircraft, rail, and ship) derived from a dynamic technology model that accounts for various technology and policy options under an IPCC emission scenario, and 2) the configuration/evaluation of a dynamically downscaled Weather Research and Forecasting/Community Multiscale Air Quality modeling system.

By 2046–2050, the annual domain-average transportation emissions of carbon monoxide (CO), nitrogen oxides (NO_x), volatile organic compounds (VOCs), ammonia (NH_3), and sulfur dioxide (SO_2) are projected to decrease over the continental U.S. The decreases in gaseous emissions are mainly due to reduced emissions from on-road vehicles and non-road engines, which exhibit spatial and seasonal variations across the U.S. Although particulate matter (PM) emissions widely decrease, some areas in the U.S. experience relatively large increases due to increases in ship emissions. The on-road vehicle emissions dominate the emission changes for CO, NO_x, VOC, and NH_3, while emissions from both the on-road and non-road modes have strong contributions to PM and SO_2 emission changes. The evaluation of the baseline 2005 WRF simulation indicates that annual biases are close to or within the acceptable criteria for meteorological performance in the literature, and there is an overall good agreement in the 2005 CMAQ simulations of chemical variables against both surface and satellite observations.

1. Introduction

Rapid population growth, global urbanization, and advanced technologies have led to significant fluctuations in transport, fuel consumption, and emissions of greenhouse gases (GHG) and air pollutants over different world regions. Since the advent of the Clean Air Act in 1970, there has been reduced pollution from transportation sources for many areas of the U.S., in large part due to cleaner cars, trucks, and fuels (https://www.epa.gov). Between 1970 and 2014, the emissions of air pollutants such as volatile organic compounds (VOCs), nitrogen oxides (NO_x), carbon monoxide (CO), and particulate matter with an aerodynamic diameter < 10 µm (PM_{10}) are down by 87%, 64%, 86%, and 37%, respectively (DOT, 2016). Transportation emissions of PM with an aerodynamic diameter <2.5 µm ($PM_{2.5}$) are also down by 48% over the U.S. since 1970. The reductions in transportation emissions of air pollutants are in part due to more stringent light-duty engine and fuel standards in the U.S. Additional complexities arise, however, when disaggregating the past changes in transport modes and the coincident GHGs and air pollutants emitted. Current levels in

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U.S. GHG emissions from passenger cars, light-duty trucks, medium/heavy-duty trucks, and buses have increased compared to 1990 by about 16%, 1%, 76%, and 127% respectively; however, other transport modes such as commercial aircraft, ships/boats, and rail have mixed GHG emission trends of about a 5% increase, 36% decrease, and 22% increase respectively (EPA, 2016a). The combined emissions from both on-road vehicles and non-road engines may contribute a large percentage (~up to 41%) of the total smog-forming anthropogenic NO_x emissions, and thus it is very important to continue to study their future trends in different world regions (Yan et al., 2014).

Correlating with an expanding global population, possibly beyond 9.6 billion by 2050 (EEA, 2015), it is projected that significant growth in the number of vehicles (>1 billion) in the global transportation sector is expected to continue through 2050 (IEA, 2014). The relationship of future transport fuel consumption to emission changes is not linear, however, and the emission projections depend on dynamic relationships between socioeconomic drivers and technological changes. Recent global emission scenarios that are driven by the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES) for the A1B scenario (Nakicenovic et al., 2000), predict a decline in transportation emissions of CO, NO_x, VOCs, and PM by 2030, but then an increase through 2040 due to the rapid increases in the number of on-road vehicles with minimal to no emission standards in Africa, as well as due to increasing emissions from non-road gasoline engines and shipping (Fig. 2 in Yan et al., 2014). Such global changes in emissions and air quality will affect the U.S., as both pollutants and precursors to pollutant formation can be transported to and from the U.S.

A technique to study such interconnections across the global-to-regional scale is through dynamically downscaling of global climate models (GCMs). Dynamical downscaling of GCMs is a technique that uses relatively coarse resolution initial and boundary conditions (ICONs/BCONs) from the GCM as driving fields to a regional numerical modeling system run at a spatially finer resolution. This technique has been well documented in the past (e.g., Leung et al., 2006), and is used to investigate current and future regional climate changes, as well as to infer the potential air quality responses over North America and the U.S. (Gao et al., 2012; Trail et al., 2013; Wang and Kotamarthi, 2015)

Downscaling GCMs using regional air quality models (AQMs) allows for novel investigations of the impacts of global changes on regional scale climate and air quality over the U.S., i.e., Regional Climate Models (RCMs), which has historically been used to investigate O_3 and $PM_{2.5}$ levels in current and future periods (Hogrefe et al., 2004; Tao et al., 2007; Nolte et al., 2008; Dawson et al., 2009; Weaver, 2009; Lam et al., 2011; Gao et al., 2013; Penrod et al., 2014; Gonzalez-Abraham et al., 2015), while other studies have expanded to looking at an extensive list of atmospheric pollutant changes and their aerosol-cloud-climate feedbacks (e.g., Yahya et al., 2017a; b). A past review of RCM studies show potential for future increases in summertime O_3 (1–10 ppb) over large regions of the U.S. (Jacob and Winner (2009) and references within); however, there are contrasts in the spatial variability of concentration change, as well as uncertainty in the direction of change across different simulations (Weaver, 2009). A recent study by Gonzalez-Abraham et al. (2015) used a downscaled RCM model driven with global and regional-scale changes of climate, biogenic emissions, land use, and anthropogenic emissions. They found that daily maximum 8-hr O_3 concentrations will increase between 2 and 12 ppb across most of the continental U.S. (CONUS) for an average future summer period of 2046–2054. Other work that has considered the impact of rigorously developed anthropogenic emission projections developed by groups at Massachusetts Institute of Technology, Northeast States for Coordinated Air Use Management, and the U.S. Environmental Protection Agency (EPA), have shown predominantly decreasing future primary pollutant levels over the U.S., which is largely due to decreases in precursor gases in the face of climate change (Fann et al., 2015; Garcia-Menendez et al., 2015; Rudokas et al., 2015).

RCM studies have also investigated the impacts of climate change on $PM_{2.5}$ concentrations and components (Avise et al., 2009; Pye et al., 2009; Lam et al., 2011), where the complexities of the secondary inorganic $PM_{2.5}$ components (e.g., sulfate (SO_4^{2-}), nitrate (NO_3^-), and ammonium (NH_4^+)) and organic carbon (OC) response to changes in meteorological drivers lead to additional uncertainties in $PM_{2.5}$ predictions (± 0.1–$1\ \mu g\ m^{-3}$) that are further discussed in Jacob and Winner (2009) and Tai et al. (2010). Gonzalez-Abraham et al. (2015), however, found that $PM_{2.5}$ levels may increase by between 4 and $10\ \mu g\ m^{-3}$ in the Northeast, Southeast, Midwest, and South regions of the U.S. Much of the variability between different RCM studies comes from the uncertainties in the models' approximations of physical and chemical processes in the atmosphere; however, further model error stems from uncertainty in RCM inputs that include the meteorological and chemical ICONs/BCONs, and quite importantly the emissions and their projection methods.

In a study on near-future (2026–2030) U.S. air quality, Penrod et al. (2014) used an offline Weather Research and Forecasting (WRF; Skamarock and Klemp, 2008; Skamarock et al., 2008) model and Community Multiscale Air Quality (CMAQ; Byun and Schere, 2006) modeling system (hereafter WRF/CMAQ) that was driven by ICONs/BCONs from the National Center for Atmospheric Research (NCAR) Community Climate System Model (CCSM). The WRF model has been used extensively in dynamically downscaled regional climate simulations, where its applicability and limitation were well summarized in Leung et al. (2006). The Penrod et al. (2014) simulations incorporated domain-uniform/lumped growth factors (GFs) for future anthropogenic emissions (all sources/sectors), which were developed by Argonne National Laboratory (ANL), and based on the IPCC A1B scenario. Results showed that future U.S. air quality is characterized by mainly decreases in O_3 due to decreasing NO_x emissions, except in the eastern U.S., where increased temperature leads to increased O_3. Future concentrations of $PM_{2.5}$ and many of its components are projected to decrease, due to decreases in emissions of primary pollutants (which lead to decreased concentrations of primary and secondary anthropogenic pollutants), as well as increased precipitation in the winter. Considering that the emission projections in Penrod et al. (2014) and Gonzalez-Abraham et al. (2015) are domain-uniform and U.S.-uniform, respectively, the state-level spatial variability in the projected emissions across the U.S. is not accounted for. Ran et al. (2015) developed a robust region-to-county GF disaggregation and county-to-grid allocation (i.e., updating spatial surrogates) approach for non-power sector emission projections, and showed that it can represent future population density and land use changes in more detail, thus impacting future spatial variability in emissions and important air quality variables. The emission projections in the aforementioned studies, however, neglected considerable detail regarding the technology stock and explicit relationships that exist between socioeconomic drivers and technological changes in the transportation sector. In fact, due the effects of stringent emission standards (i.e., technology) offsetting the impending growth in fuel consumption, Yan et al. (2014) projected global transportation emissions to initially decrease in the near-future, 2026–2030, but then to increase in some scenarios by 2046–2050.

Part I of this sequence of papers first describes the methodology of a novel Technology Driver Model (TDM; see graphical abstract),