Atmospheric Environment 173 (2018) 96–107

Contents lists available at ScienceDirect

Atmospheric Environment

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

Evaluating commercial marine emissions and their role in air quality policy using observations and the CMAQ model

Allison M. Ring[a,*], Timothy P. Canty[a], Daniel C. Anderson[a,1], Timothy P. Vinciguerra[b], Hao He[a], Daniel L. Goldberg[c], Sheryl H. Ehrman[b], Russell R. Dickerson[a,d,e], Ross J. Salawitch[a,d,e]

[a] Department of Atmospheric and Oceanic Science, University of Maryland, College Park, MD 20742, USA
[b] Department of Chemical and Biomolecular Engineering, University of Maryland, College Park, MD 20742, USA
[c] Energy Systems Division, Argonne National Laboratory, Argonne, IL 60439, USA
[d] Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD 20742, USA
[e] Department of Chemistry and Biochemistry, University of Maryland, College Park, MD 20742, USA

ARTICLE INFO

Keywords:
Surface ozone
OMI satellite
Commercial marine vessel
Air quality
Emissions inventory
Community Multiscale Air Quality (CMAQ) model

ABSTRACT

We investigate the representation of emissions from the largest (Class 3) commercial marine vessels (c3 Marine) within the Community Multiscale Air Quality (CMAQ) model. In present emissions inventories developed by the United States Environmental Protection Agency (EPA), c3 Marine emissions are divided into off-shore and near-shore files. Off-shore c3 Marine emissions are vertically distributed within the atmospheric column, reflecting stack-height and plume rise. Near-shore c3 Marine emissions, located close to the US shoreline, are erroneously assumed to occur only at the surface. We adjust the near-shore c3 Marine emissions inventory by vertically distributing these emissions to be consistent with the off-shore c3 Marine inventory. Additionally, we remove near-shore c3 Marine emissions that overlap with off-shore c3 Marine emissions within the EPA files.

The CMAQ model generally overestimates surface ozone (O_3) compared to Air Quality System (AQS) site observations, with the largest discrepancies occurring near coastal waterways. We compare modeled O_3 from two CMAQ simulations for June, July, and August (JJA) 2011 to surface O_3 observations from AQS sites to examine the efficacy of the c3 Marine emissions improvements. Model results at AQS sites show average maximum 8-hr surface O_3 decreases up to ~6.5 ppb along the Chesapeake Bay, and increases ~3–4 ppb around Long Island Sound, when the adjusted c3 Marine emissions are used.

Along with the c3 Marine emissions adjustments, we reduce on-road mobile NO_X emissions by 50%, motivated by work from Anderson et al. 2014, and reduce the lifetime of the alkyl nitrate species group from ~10 days to ~1 day based on work by Canty et al. 2015, to develop the "c3 Science" model scenario. Simulations with these adjustments further improve model representation of the atmosphere. We calculate the ratio of column formaldehyde (HCHO) and tropospheric column nitrogen dioxide (NO_2) using observations from the Ozone Monitoring Instrument and CMAQ model output to investigate the photochemical O_3 production regime (VOC or NO_X-limited) of the observed and modeled atmosphere. Compared to the baseline, the c3 Science model scenario more closely simulates the HCHO/NO_2 ratio calculated from OMI data.

Model simulations for JJA 2018 using the c3 Science scenario show a reduction of surface O_3 by as much as ~13 ppb for areas around the Chesapeake Bay and ~2–3 ppb at locations in NY and CT downwind of New York City. These reductions are larger in 2018 than in 2011 due to a change in the photochemical O_3 production regime in the Long Island Sound region and the projected decline of other (non-c3 Marine) sources of O_3 precursors, highlighting the importance of proper representation of c3 Marine emissions in future modeling scenarios.

1. Introduction

Tropospheric ozone (O_3) is a harmful secondary pollutant regulated by the United States Environmental Protection Agency (EPA). The Clean Air Act (CAA) passed in 1970, and subsequent amendments, have led to continued reductions of atmospheric pollutants and improved air

* Corresponding author.
E-mail address: aring1@umd.edu (A.M. Ring).
[1] Now at: Department of Chemistry, Drexel University, Philadelphia, PA 19104, USA.

https://doi.org/10.1016/j.atmosenv.2017.10.037
Received 13 June 2017; Received in revised form 6 October 2017; Accepted 14 October 2017
Available online 20 October 2017
1352-2310/

quality across the US [EPA, 1970; 1990]. One mandate of the CAA required establishment of the National Ambient Air Quality Standards (NAAQS), which provides states with clear attainment requirements for six "criteria pollutants" harmful to public health. States with areas designated as non-attainment, meaning concentrations of regulated pollutants are above the federal standard, are required to submit a State Implementation Plan (SIP) to the EPA. These plans outline how state environmental agencies, through regulatory efforts, policy enforcement, and proposed emissions limitations from upwind sources, intend to meet the required attainment standard. SIPs rely on data and modeling simulations to support proposed regulatory strategies [Cohan and Chen, 2014; Digar et al., 2011].

Nitrogen dioxide (NO_2) and O_3 are criteria pollutants, with attainment standards of 100 ppb 1-hr average [EPA, 2010] and 70 ppb 8-hr average, respectively [EPA, 2015c]. These compounds have long been a primary focus of state and federal agencies when developing air quality attainment strategies for the SIP process. Based on the most recent national emissions inventory, the largest contributor to the total anthropogenic NO_X ($NO + NO_2$) budget in the US is the transportation sector (~56%) which includes on-road vehicles, off-road vehicles, aircraft, commercial marine vessels, and locomotives. Electrical generating units contribute ~25% to the total NO_X budget and consist of commercial fuel combustion, industrial boilers, and residential heating. Industrial processes like cement and chemical manufacturing, mining, oil and gas production, etc. account for ~11% of anthropogenic NO_X, and the remainder comes from biomass burning, gas stations and waste disposal activities (~8%) [EPA, 2016]. Due to the anthropogenic contribution, air quality attainment strategies usually focus on the largest NO_X emitters like electrical generating units (EGUs) and mobile (on-road and off-road) sources.

Many studies have shown elevated pollution levels around waterways [Cooper, 2003; Goldberg et al., 2014; Lawrence and Crutzen, 1999; Murphy et al., 2009; Pirjola et al., 2014; Williams et al., 2009], an important consideration for states with coastlines. Higher levels of criteria pollutants are observed at Air Quality System (AQS) monitoring sites near the coasts along heavily trafficked marine water ways [Gégo et al., 2007; Mazzuca et al., 2016; Stauffer et al., 2015; Yu et al., 2006]. It is estimated that approximately 80% of goods traded globally are transported via commercial marine vessels (CMVs) [Pirjola et al., 2014], and that emissions from CMVs contribute approximately 15–30% to the global anthropogenic NO_X budget [Corbett et al., 2007; Eyring et al., 2005; Williams et al., 2009]. Due to the immense number and international identity of CMVs, NO_X regulation and enforcement are difficult, even when ships are operating in near-shore shipping lanes and port environments [Eyring et al., 2005; Pirjola et al., 2014].

To manage emissions from CMVs, the International Maritime Organization (IMO) has instituted controls for diesel engine vessels in specified Emission Control Areas (ECA); zones that extend 200 nautical miles off the coast of participating countries [EPA, 2008]. The US petitioned the IMO to include the North American continent in the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI, an international agreement that regulates air pollution from large ocean-going vessels, allowing the US and Canada to regulate CMV emissions within ECAs [EPA, 2008; 2009b]. The US was successfully added to the list of IMO participating countries in 2008, requiring all class 3 commercial marine vessels (c3 Marine) operating within US coastal waters to comply with IMO regulations [EPA, 2008]. As of 2015, ~50% of the c3 Marine global fleet is 20+ years old, ~20% is between 10 and 20 years, and ~30% is less than 10 years old [UN, 2015]. This means ships younger than 20 years old (~50% of the global fleet) are required to meet the Tier I IMO emissions regulations (17 g/kWh of NO_X at idle) passed in 2000 [IMO, 2014]. As more of the global fleet is retired, new vessels must meet the more stringent global Tier II regulations (14.4 g/kWh of NO_X at idle) and Tier III regulations (3.4 g/kWh of NO_X at idle) if operating within ECAs [IMO, 2014].

The main engines of most commercial marine vessels are run solely for propulsion while auxiliary engines are run continuously to meet all other energy demands for ship operation. NO_X emissions rates from these two engine types are highly dependent upon fuel composition and engine temperatures. The slower the ships are moving, the longer and hotter these engines are running, resulting in higher NO_X emissions [Cooper, 2003]. Commercial marine vessels are also a significant source of large particles called giant cloud condensation nuclei (GCCN), contributing to enhanced boundary layer cloud formation [Sorooshian et al., 2015] as well as particulate matter with a diameter < 2.5 μm ($PM_{2.5}$), a criteria pollutant that contributes to hundreds of thousands of premature deaths globally [Cohan and Chen, 2014; Cohen et al., 2005; Corbett and Koehler, 2003; Pope et al., 2002].

Elevated levels of tropospheric O_3 over CMV traveled bodies of water have been measured by both *in situ* and remote techniques [Cleary et al., 2015; Goldberg et al., 2014]. Advection of this polluted air over coastal land and cities may contribute to the elevated pollution over these regions [Loughner et al., 2011; Loughner et al., 2014; Stauffer et al., 2015] and at coastal AQS monitoring sites. For major metropolitan cities near heavily trafficked CMV areas like Baltimore, MD, Philadelphia, PA, and New York, NY, the development of attainment strategies addressing CMV emissions will become increasingly important as global shipping activity is projected to increase in the future [EPA, 2009b; McDill et al., 2015].

In this paper, we investigate the role of CMV emissions on regional air quality, and the representation of this pollution source within a regulatory air quality model. We adjust the vertical distribution of emissions from the largest (class 3) commercial marine vessels, and examine the effect of this adjustment on surface O_3 production for various model simulations conducted for years 2011 and 2018. Comparisons of modeled surface O_3 to AQS data, and modeled column formaldehyde (HCHO) and NO_2 to satellite measurements, are used to evaluate model performance for 2011. We also quantify the effect of an improved model framework for a 2018 SIP attainment strategy developed by the Maryland Department of the Environment (MDE).

2. Model description

2.1. The CMAQ platform

We use the Community Multiscale Air Quality (CMAQ) model version 5.0.2 [Byun and Schere, 2006], an EPA approved regulatory air quality model used by state and federal agencies to develop surface O_3 attainment strategies. CMAQ v5.0.2 uses the 2005 Carbon Bond (CB05) chemical mechanism consisting of 156 chemical reactions with 51 species representing the photochemistry of the troposphere [Yarwood et al., 2005]. An updated version of CB05 called the Carbon Bond Mechanism version 6 (CB6) was released in 2010 [Yarwood et al., 2010], however it is not publically available for use with CMAQ at the time of paper submission. All CMAQ simulations have 12 km × 12 km horizontal resolution, with the model domain covering the eastern half of the United States.

Meteorological input was generated by the EPA using the Weather Research Forecasting (WRF) version 3.4 model [Skamarock et al., 2008] for the year 2011 and processed with Meteorological Chemistry Interface Processor (MCIP) version 4.2 [Otte and Pleim, 2010] to reformat WRF output for use in CMAQ [EPA, 2014]. For biogenic emissions, we use the Biogenic Emission Inventory System (BEIS) version 3.61, which incorporates improved vegetation data, land use cover data, and canopy model formulation [Bash et al., 2016].

All anthropogenic emissions used for this study are the Alpha 2 version, developed by the Mid Atlantic Regional Air Management Association (MARAMA) [McDill et al., 2015] and based on the EPA 2011 National Emissions Inventory (2011 NEI) version 2 data [EPA, 2015a]. Emissions inventories for year 2018 are generated by applying growth factors for all inventory sectors to the 2011 base case emissions