

The impact of biogenic VOC emissions on tropospheric ozone formation in the Mid-Atlantic region of the United States

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Abstract

In many areas, natural sources contribute a substantial fraction of volatile organic compound (VOC) emissions, which are precursors to tropospheric ozone (O₃). To investigate the significance of biogenic VOC emissions on ozone formation, meteorological and air quality modelling were used to generate hourly ozone estimates for a case-study high ozone episode in the Mid-Atlantic region of the United States for three emissions scenarios: actual emissions; a 100% increase in biogenic VOCs; and an additional 100% increase in vehicular emissions of ozone precursors. The modelled concentrations reflect the total effect of changes from emissions, incorporating interactions between anthropogenic and biogenic emissions. Elevated biogenic emissions had a larger impact on ozone concentrations than did the comparable relative increase in vehicular emissions. For instance, the increased biogenics raised the max 1-h ozone level by 54 ppb, however the additional increase in vehicular emissions added only a further 17 ppb. The highest ozone levels and the largest increases in ozone typically were observed in urban areas for both increased emissions scenarios. Results indicate the importance of biogenic emissions for ozone formation in this region. This has implications for the design and implementation of ozone policies as these emissions are difficult to control, and for the impacts of climate change, which could raise biogenic VOCs levels through elevated temperature.

Keywords: ozone, air pollution, air quality modelling, volatile organic compounds, nitrogen oxides, biogenic emissions

1 Introduction

Tropospheric ozone (O_3) is formed through non-linear chemistry involving the precursors nitrogen oxides (NO_x) and volatile organic compounds (VOCs) in the presence of sunlight. While anthropogenic sources of ozone precursors, such as from power plants and motor vehicles, contribute to high levels of ozone, biogenic emissions also can be a significant source. In the Mid-Atlantic region of the United States, over three quarters of VOC emissions are biogenic [1].

This common urban air pollutant has been linked to a wide range of adverse human health effects, ranging from respiratory symptoms such as coughing and wheezing to premature mortality [2,3]. In 2003, over 100 million people in the United States resided in areas that do not meet the 8-hour National Ambient Air Quality Standard for ozone, and most of these areas are in the California, Mid-Atlantic, and Northeast regions [4].

An understanding of the role of biogenic precursors is thereby crucial to better management of ozone pollution. Biogenic emissions of ozone precursors are difficult to control, but could be affected through land-use and by global warming through elevated temperatures. In addition, there are some uncertainties in biogenic emissions inventories used in air quality modelling simulations. This research uses meteorological and air quality modelling to examine the relative importance of biogenic and motor vehicle emissions of ozone precursors for a case study episode.

2 Methods

2.1 Meteorological and air quality modelling

Hourly ozone concentrations were estimated using a meteorological and air quality modelling system for a high ozone episode of 27 June (h 00) to 30 June (h 00) GMT for the Mid-Atlantic region of the United States [5]. Meteorological simulations were performed with the Penn State/National Center for Atmospheric Research (NCAR) 5th generation Mesoscale Model (MM5) Version 3-4 [6]. Air quality modelling was conducted with the Models-3 framework, which includes separate processors for land-use, the interface of meteorology and chemistry, emissions processing, generation of initial and boundary conditions, estimation of photolysis rates, and chemistry and transport of pollutants [7-9]. The Community Multi-Scale Air Quality (CMAQ) Chemical Transport Model (CCTM), a 3-dimensional Eulerian model, was used for chemical and transport modelling.

The Models-3 Emissions Processing and Projection System (MEPPS) was used to model area, point, and mobile source emissions. MEPPS incorporates information on land-use, vegetation, meteorology, population, and road networks. Hourly emissions of biogenic VOCs from vegetation and NO_x from soils were estimated through the Biogenic Emissions Inventory System (BEIS2). Motor vehicle emissions were estimated through Mobile5.

One-way nesting with multiple domains were used for both the meteorological and air quality modelling simulations. The meteorological domains are provided in Figure 1. This research used results of Domain 3, which contains 2898 grid cells that are 12 km x 12 km in the horizontal. The case-study area consists of Virginia, Maryland, Delaware, West Virginia, Ohio, Pennsylvania, and the District of Columbia (Washington, DC), in the United States, which is an area with historically high ozone levels [4]. Model results provided ozone estimates for each grid cell for each hour of the simulation period. Evaluation of this modelling system using graphical and numerical measures found the ozone estimates to be satisfactory representations of measured values for this and other case studies. Additional information regarding the modelling system as well as model evaluation is provided in Bell and Ellis 2004 [5].

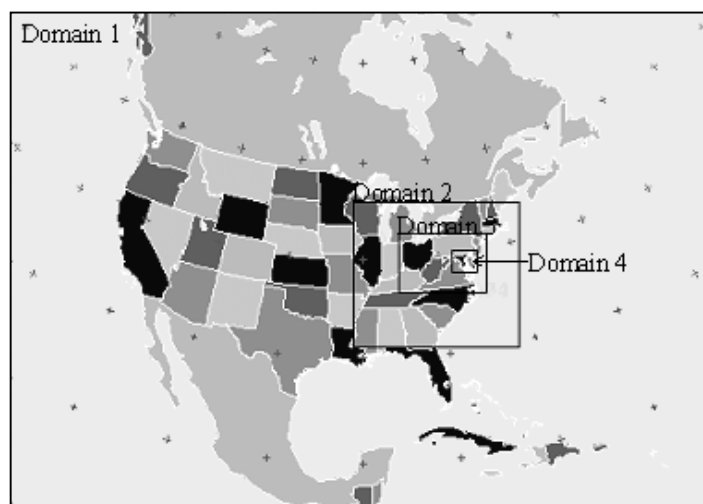


Figure 1: Spatial domains used in modelling simulations

2.2 Emissions scenarios

Three emissions scenarios were considered: (A) a baseline scenario with actual emissions; (B) a 100% increase in biogenic emissions of VOCs; (C) a 100% increase in vehicular emissions of ozone precursors, VOCs and NO_x , in addition to a 100% increase in biogenic VOC emissions. Modelled ozone concentrations for each scenario were compared using several metrics, incorporating various spatial and temporal averaging structures. Each scenario reflects the interaction of both biogenic and anthropogenic compounds and therefore represents the total biogenic contribution, rather than the pure biogenic contribution as defined by Tao et al. 2003 [10].

3 Results

3.1 Comparison of ozone concentrations under various emissions scenarios

Model estimates from both elevated emissions scenarios were compared with those from the baseline (Scenario A). A sample of these comparisons is shown in Table 1. The fraction of the domain with 1-h maximums larger than 124 ppb, the 1-h United States regulatory standard, was also calculated. Although this standard is being replaced by an 8-h requirement, the calculations still provide insight into regulatory compliance. Ozone estimates were highest for Scenario C, corresponding to the higher overall emissions of precursors, however the difference between Scenarios A and B was larger than between Scenarios B and C, reflecting the significance of biogenic VOC emissions. In other words, the initial impact of elevated biogenic VOCs had a larger effect than the incremental increase in vehicular emissions of ozone precursors.

Table 1: Modelled ozone concentrations for various emissions scenarios

	Scenarios B - A	Scenarios C - A	Scenarios C - B
Max 1-h avg	54 ppb	70.7 ppb	16.7 ppb
Simulation-wide avg	3.1 ppb	6.3 ppb	3.2 ppb
% of domain > 124 ppb	11.9 %	27.7 %	15.8 %

Figure 2 shows the largest change in ozone levels for each elevated emissions scenario, in comparison the baseline, Scenario A, throughout the simulation time periods. This reflects the largest increase or decrease for a single 12 km by 12 km grid cell. The increase in biogenic VOCs had a larger resulting increase in ozone than did the same percent (100%) increase in vehicular emissions of ozone precursors. Both adjusted emissions scenarios showed decreases in ozone concentrations for some grid cells due to the non-linear nature of ozone formation, however these decreases were typically small.

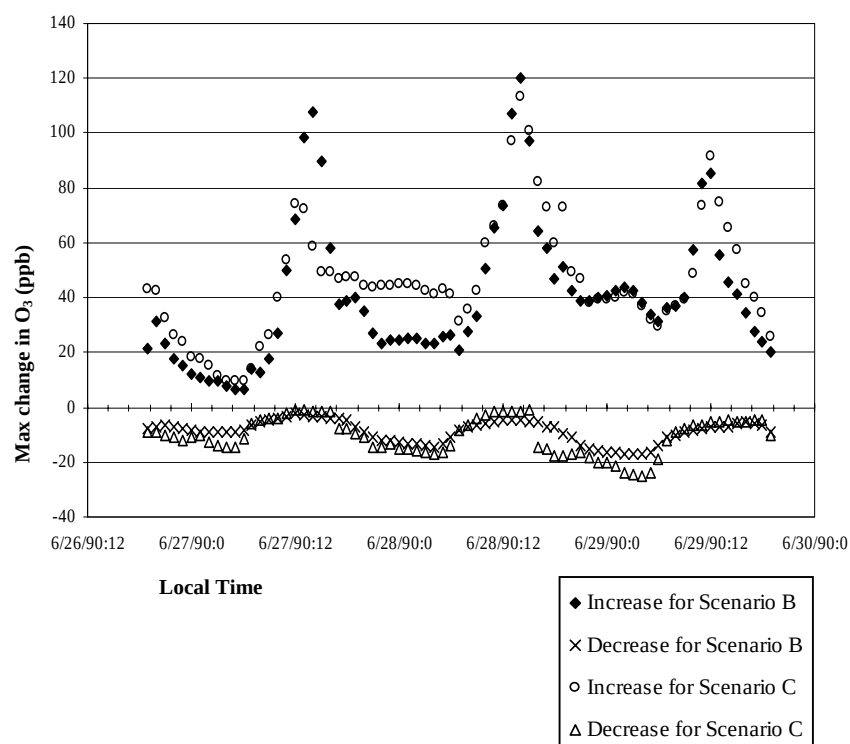


Figure 2: Maximum increases and decreases in estimated 1-h ozone across all grid cells, comparing adjusted emissions scenarios to the baseline, Scenario A

Figure 3 shows the percent increase in the domain-wide ozone level for each adjusted emissions scenario, in comparison to the baseline scenario. This demonstrates that the largest increase in ozone levels occurred in areas and time periods with existing high concentrations. Further, a comparison of urban and rural areas was performed using the highest 10% population density as urban and the lowest 10% population density as rural, based on U.S. census data. This comparison found higher increases in ozone levels under both elevated emissions scenarios in urban areas as opposed to rural areas, which corresponds to the higher ozone concentrations under the baseline, Scenario A.

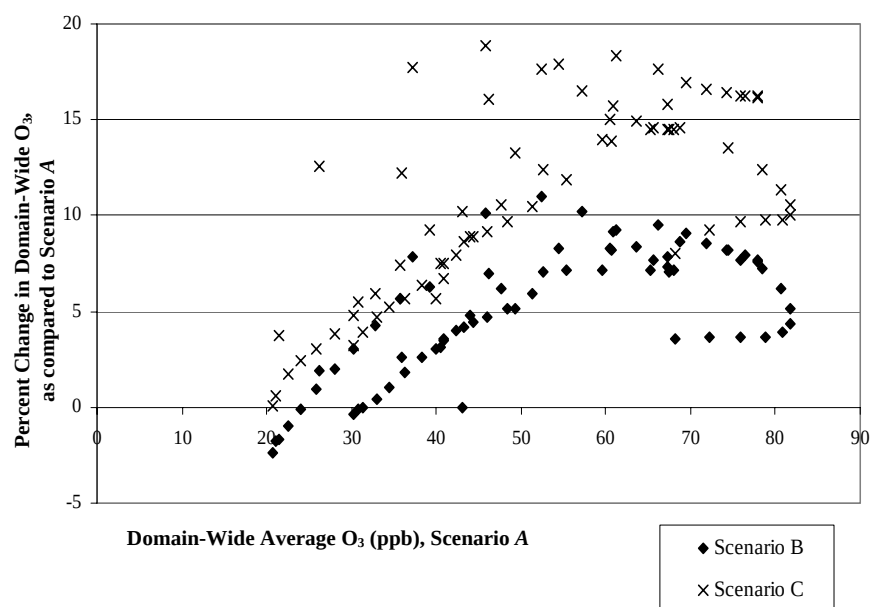


Figure 3: Percent change in the domain-wide ozone concentration for each hourly time step, comparing each adjusted emissions scenario to the baseline, Scenario A

4 Discussion

These results indicate that biogenic emissions of VOCs in the Mid-Atlantic region play a larger role than the relative same percent increase (100%) in motor vehicle emissions of ozone precursors for this representative high-ozone case study. While ozone concentrations were higher under both elevated emissions scenarios, as compared with the baseline, the incremental impact of vehicular emissions was less than the initial increase in biogenic VOCs.

While a 100% increase in biogenic emissions is quite high, such emissions do vary in response to land-use patterns and temperature. Elevated temperatures from climate change could affect ozone air quality in several ways, including more emissions of biogenic VOCs from vegetation and faster chemical reaction rates for the formation of ozone. The higher temperature and modified weather patterns from climate change could raise biogenic VOCs by 25 to 82% [11-14].

This work demonstrates the crucial role of biogenic VOCs on ozone in this region. Findings consider total effects, including potential interaction between biogenic and anthropogenic emissions. Without additional simulations, the independent effects from the biogenic and anthropogenic components cannot be separated. However the synergism between these various emissions sources is likely to be high in cases where emissions of both source types are high [10]. Therefore, although biogenic precursors contribute significantly to high ozone

levels, reductions in the emissions of anthropogenic precursors could lower ozone levels and thereby reduce the subsequent health and other impacts.

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