Project 091(B) Environmental Impacts of High-altitude and Space Vehicle Emissions

University of Illinois at Urbana-Champaign

Project Lead Investigator

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- P.I.: Dr. Donald Wuebbles
- FAA Award Number: 13-C-AJFE-UI-048
- Period of Performance: January 1, 2024, to September 30, 2025 (partial year; project started January 1, 2023)
- Tasks:
  1. Examine the environmental impacts of technologies related to scenarios for extensive potential use of high-altitude vehicles, including rockets, and their associated emissions by mid-century
  2. Coordinate with Massachusetts Institute of Technology (MIT) and Aerospace Corporation in these studies

Project Funding Level

Project funding support from the Federal Aviation Administration (FAA) over this time period was approximately $175,000; an additional $175,000 of in-kind matching support was provided by the University of Illinois.

Investigation Team

Dr. Donald Wuebbles (P.I.), project oversight

Swarnali Sanyal and Rachana Pradhan (postdoctoral associates), conducting studies and performing analyses with the Community Earth System Model Whole Atmosphere Community Climate Model (WACCM), a three-dimensional atmospheric climate-chemistry model including the whole atmosphere.

Project Overview

This project uses state-of-the-art modeling capabilities for atmospheric physics and chemistry processes in association with expert analysis to develop an assessment of the potential impacts of rockets (i.e., high-altitude and space vehicle emissions) on the global environment, specifically the compositions of gases and particles in the global atmosphere (troposphere, stratosphere, mesosphere, and above) and the resultant potential impacts on the Earth's climate. These analyses are useful for policymakers to understand the potential effects of projected rocket emissions on the environment.

Task 1 – Revisiting High-Speed Civil Transports and Their Potential Effects on Ozone and Climate

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Objectives

Numerical models of the Earth's physics and chemistry system that fully represent atmospheric processes from the ground to the top of the mesosphere (and above), to further improve understanding and evaluation of the environmental impacts of technologies related to scenarios for extensive potential use of high-altitude vehicles, including rockets, and their associated emissions by mid-century (approximately the year 2050). The aim, in coordination with the FAA, Aerospace Corporation (which will develop the rocket emission scenarios), and Massachusetts Institute of Technology (MIT) (which will also use its global modeling capabilities) is to further assess the state of understanding of potential high-altitude and space vehicle emissions on the global environment, and to publish these analyses in major science journals.

Research Approach

The study uses the state-of-the-art WACCM model that is part of the range of models within the Community Earth System Model (CESM), developed through community-coordinated efforts by the National Center for Atmospheric Research (NCAR). The version of the WACCM model used here has 66 layers from the ground to above the mesosphere and provides a comprehensive treatment of tropospheric and stratospheric (and above) chemical processes. WACCM is one of the most advanced models worldwide for studying atmospheric processes and one of the few with a complete representation of stratospheric and mesospheric processes and higher; for example, it is one of very few models to represent the quasi-biennial oscillation that is important to stratospheric ozone. It has a comprehensive treatment of gas phase, particle based and heterogeneous chemistry. This model extends higher in the atmosphere than any other atmospheric model in existence except for another version of this model that goes even higher (to be considered for later studies, but it is computationally very expensive). Therefore, the model used here is ideal for studying the environmental impacts from rockets.

Results and Discussion

Emissions from rockets and their effects on stratospheric ozone have been a subject of research since the 1970s (e.g., Prather et al., 1990; Harris & Wuebbles, 2014; Dallas et al., 2020). However, research in this area has comprised largely incomplete evaluations and has relied on poorly understood emission assumptions. A major need exists for assessment of the state of the science for understanding the environmental impacts according to the most up-to-date understanding of the potential future annual rocket emissions over the coming decades. Below, the existing research is summarized relating to such emissions.

More satellites have been launched into low Earth orbit during the past few years than during the previous 60 years, as a result of a combination of larger rockets and higher launch rates. Most of this growth has come from kerosene-fueled rockets, from which black carbon (BC) emissions have doubled in the past four years (Miraux, 2022). Emissions from solid fuel rockets have increased only slightly. Hydrazine-fueled rocket launches have decreased during this period, because of propellant toxicity concerns. Hydrogen-fueled launches have been constant but have represented only a small fraction of all launches. Methane-fueled rockets in advance testing are expected to play a major role in the future, although the rate at which methane would replace existing rocket fuel is uncertain.

Rocket propulsion systems typically combine the exhausts from several of the four primary propellant types (by fuel: kerosene, ammonium perchlorate, hydrazine, and hydrogen). Mixed rocket emissions into the stratosphere are mostly (>90% of approximately 8 Gg/yr) a combination of carbon dioxide (CO_2), carbon monoxide (CO), H_2O, and hydroxide (OH); the exact amounts vary, depending on propellant and altitude. None of these major emission components significantly affect stratospheric ozone, even at implausibly higher launch rates (Larson et al., 2017). Nitrogen oxide emissions (<1%) from some rocket types can affect ozone (Ross et al., 2004), although to a lesser degree than solid fuel chlorine emissions.

Direct ozone loss caused by chlorine emissions (0.2 Gg/yr) from solid fuel rockets is well understood. Models agree on the amount and distribution (Voigt et al., 2013). Alumina emissions from solid fueled rockets (0.4 Gg/yr) cause ozone loss through heterogeneous chlorine-involving Cl_y activation reactions; the importance of these reactions are less well bounded because of uncertainties in the alumina surface area density, the extent of sulfate coating, and reaction coefficients (Danilin et al., 2003). In situ plume data suggest that ozone loss from alumina might be larger than that from chlorine (Danilin et al., 2001).

Indirect ozone loss caused by the absorption and scattering of solar radiation by rocket BC and alumina particles in the stratosphere has not yet been investigated. General principles of stratospheric processes suggest that rocket BC and alumina increase heating rates and temperatures in the stratosphere, and cause ozone loss (Lee et al., 2021). Linear scaling of solid aerosol climate mitigation models and models of rocket BC emissions (Maloney, 2022) suggest that the ozone loss from rocket BC and alumina stratospheric heating is comparable to that from chlorine emissions (Weisenstein et al., 2015).

Hydrogen-fueled projected space travel has been estimated to enhance stratospheric water by as much as 9%, thus leading to a potential 20% increase in polar stratospheric clouds in both hemispheres (Larson et al., 2017). An even larger effect of hydrogen-based space travel may arise from the expected increases in stratospheric nitrogen oxides, which, combined with hydrogen oxide (HO_x) cycle perturbations, leads to a 0.5% loss of the globally averaged ozone column, with column losses in the polar regions exceeding 2%.

New space technologies, such as large low Earth orbit constellations and active removal of space debris, dispose of derelict spacecraft into the middle atmosphere. The effects of stratospheric aerosols generated by destruction of space debris during reentry is a new area of research (Boley & Byers, 2021). Reentry vaporization and lower mesosphere particle production and sedimentation are a source of stratospheric particles likely to exceed present-day launches by 2030 (Boley & Byers, 2021). Very little is known regarding the composition, sizes, and steady-state distribution of reentry particles, or their possible impact on stratospheric ozone.

Three scenarios have been developed through our coordination with ASCENT Project 091A at MIT. These scenarios for 4,000 launches per year projected to occur annually by 2050 were evaluated with the WACCM model. These scenarios correspond to assuming the use of (1) fossil fuel, (2) methane fuel, and (3) hydrogen fuel. A series of meetings has been jointly held with MIT and Aerospace Corporation over the past project year towards not only developing the scenarios, but also to coordinate the modeling studies done with WACCM and with the MIT model. Our team is coordinating with MIT to evaluate the results from the model calculations and to complete a joint journal paper.

Milestones

- Completed analyses for the modeling studies for the three scenarios. The University of Illinois runs are fine and will be the basis of a journal paper. The MIT runs were shown to have an error in the upper boundary conditions that affected interpretation of their findings.
- Completed a journal paper currently being reviewed by the authors – being submitted to the journal

These studies will provide important context for further studies of rocket use projections, which our team will be examining next.

Publications

Kulkarni, R., Sanyal, S., Ma, C. Z., McDonald, H., Speth, R. L., Ross, M., & Wuebbles, D. J. (2025). Effects of Potential Future Emissions from Different Rocket Fuel Types on Climate and Stratospheric Ozone. *AGU Advances*, submitted.

Outreach Efforts

- Presented at ASCENT Meetings in October 2024 and May 2025.
- Presented at the FAA Aviation Emissions Characterization (AEC) Roadmap meeting in October 2024 and May 2025.
- Participated in biweekly meetings with the project manager.
- Participated in monthly International Civil Aviation Organization (ICAO) Impacts and Science Group (ISG) meetings (Dr. Wuebbles).

Student Involvement

Two postdoctoral associates, Swarnali Sanyal and Rachana Pradhan, were responsible for the analyses and modeling studies within the project, and for leading the preparation of the journal article.

Plans for Next Period

- Revise paper based on reviewer comments and complete journal publication of the paper.
- Complete development of additional scenarios to examine potential rocket launch issues and key questions to enhance understanding of the envelope (range) of potential impacts on ozone and climate from such vehicles. Complete modeling studies for these new scenarios.

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