Project 022 Evaluation of FAA Climate Tools: APMT

University of Illinois at Urbana-Champaign

Project Lead Investigator

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University Participants

University of Illinois at Urbana-Champaign

- PI: Dr. Donald Wuebbles
- Period of Performance: October 1, 2019 to September 30, 2020 (project started January 31, 2020)
- Tasks:
    1. Revisit High Speed Civil Transport and the potential effects on ozone and climate using the state-of-the-art Community Earth System Model (CESM) global chemistry-climate model.
    2. Conduct cruise altitude sensitivity study.

Project Funding Level

Support from the FAA over this time period was about $70,000 with an additional $70,000 in matching support, including about $70,000 from the University of Illinois at Urbana-Champaign.

Investigation Team

Dr. Donald Wuebbles: project oversight.
Jun Zhang (graduate student): conduct studies and perform analyses using the CESM Whole Atmosphere Community Climate Model (WACCM), a 3D atmospheric climate-chemistry model.

Task 1 – Revisiting HSCTs and Their Potential Effects on Ozone and Climate

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Objective(s)

This project has the primary objective of understanding how the understanding of atmospheric processes over the last few decades has affected analyses of the potential environmental effects on ozone and climate from assumed future fleets of supersonic aircraft. The aim here is to conduct a series of sensitivity global chemistry-climate modeling studies that revisit case studies run for High Speed Civil Transport (HSCT) emission scenarios for a mature fleet of aircraft. The emission scenarios analyzed in this study are developed from the NASA HSCT program from the late 1990s through the early 2000s and/or from the 1999 Intergovernmental Panel on Climate Change (IPCC) special assessment on aviation.

Research Approach

The study will use the Whole Atmosphere Community Climate Model (WACCM) of the Community Earth System Model (CESM), developed by the National Center for Atmospheric Research (NCAR). This model has 66 layers from the ground to the middle of the mesosphere and provides a comprehensive treatment of tropospheric and stratospheric chemical processes.

Results and Discussions

The calculated total column ozone percentage change from the HSCT emission scenarios are shown in Table 1 for different nitrogen oxides (NOx) emission indexes and fleet sizes in a 2015 background atmosphere. The results from the earlier 1999 NASA Atmospheric Effects of Aviation Project (AEAP) and IPCC aviation assessments (Kawa et al, 1999; Penner et al., 1999) using 2D and 3D models from that time period are shown here for comparison. The calculated percentage change in total column ozone from this study with WACCM is shown in the last row. All total column ozone changes are shown here for each emission scenario relative to the subsonic-only background atmosphere.

The results are more similar to the earlier results from the 2D models than the early-stage 3D models. For the baseline scenario Case A, this study determines a change in percentage ozone of -0.21% and -0.13% for the Northern Hemisphere (NH) and Southern Hemisphere (SH), respectively. This change falls into the range of +0.2 to -0.4% in the NH and +0.05 to -0.8 in the SH calculated from previous models shown in Table 1. For Cases B and C, with increasing NOx Emissions Index (EINOx) to either 10g or 15g NO_2/kg fuel, the WACCM derived ozone loss in the NH tends to be larger than that from most of the earlier models. Case D, for only NOx emissions with EINOx=15g NO_2/kg fuel, was not considered in the earlier assessments.

For the water vapor (H_2O)-only emissions scenario Case E, the WACCM results are lower than all of the earlier models in the NH. Doubling the fleet to 1000 HSCTs assumed to be in operation (Case F), the total column ozone percentage change calculated from WACCM is -0.45% and -0.27% in the NH and SH respectively, which is in the range of values calculated from previous models.

Figure 1 shows the sensitivity of ozone depletion in the NH as a function of NOx emission indices for a fleet of 500 supersonic aircraft calculated from WACCM and the comparison to earlier models. In general, WACCM derives a higher sensitivity in the NH between the levels of NOx emissions and the resulting ozone changes. As the EINOx goes from no NOx emission (the H_2O-only perturbation case) to 5g/kg fuel, WACCM has a higher sensitivity in ozone depletion than all of the earlier models. Increasing the EINOx from 5 to 15 g/kg fuel also shows WACCM having a stronger sensitivity compared to most of the earlier models, with one exception, the THINAIR 2D model.

Table 1. Percentage changes (%) in total column ozone for the WACCM results relative to the earlier NASA AEAP and IPCC aviation assessment results taken from Kawa et al. (1999) and Penner et al. (1999). The first and second value is for the Northern Hemisphere (NH) and Southern Hemisphere (SH) average percent change in total column ozone, respectively.

Models	Case A EINOx = 5 with H_2O	Case B EINOx = 10 with H_2O	Case C EINOx = 15 with H_2O	Case D EINOx = 15 without H_2O	Case E EINOx = 0 H_2O only	Case F EINOx = 5 with H_2O Fleet 1000
AER 2D	-0.3, -0.1	-0.3, -0.1	-0.3, -0.05	-	-0.6, -0.3	-0.7, -0.3
GSFC 2D	-0.4, -0.8	-0.6, -0.7	-0.8, -0.7	-	-0.4, -0.8	-0.9, -1.4,
LLNL 2D	-0.2, -0.2	-0.3, -0.1	-0.4, -0.01	-	-0.3, -0.3	-0.5, -0.3
CSIRO 2D	-0.2, -0.1	-0.3, -0.2	-0.5, -0.3	-	-0.2, -0.07	-0.5, -0.2
UNIVAQ 2D	-0.002, +0.02	+0.2, +0.1	+0.4, +0.2	-	-0.4, -0.2	-0.06, +0.005
SUNY 2D	-0.2, -0.1	-0.2, -0.06	-	-	-0.2, -0.1	-0.3, -0.2
THINAIR 2D	-0.2, -0.2	-0.5, -0.3	-0.9, -0.5	-	-	-0.4, -0.3
GMI 3D	+0.2, +0.05	-	-	-	-	-
LaRC 3D	-0.05, -0.1	+0.07, -0.03	-	-	-	-
SLIMCAT 3D	-0.4, -0.6	-0.5, -0.7	-	-	-0.6, -0.7	-
This study	**-0.21, -0.13**	**-0.38, -0.11**	**-0.66, -0.14**	**-0.62, -0.003**	**-0.13, -0.16**	**-0.45, -0.27**

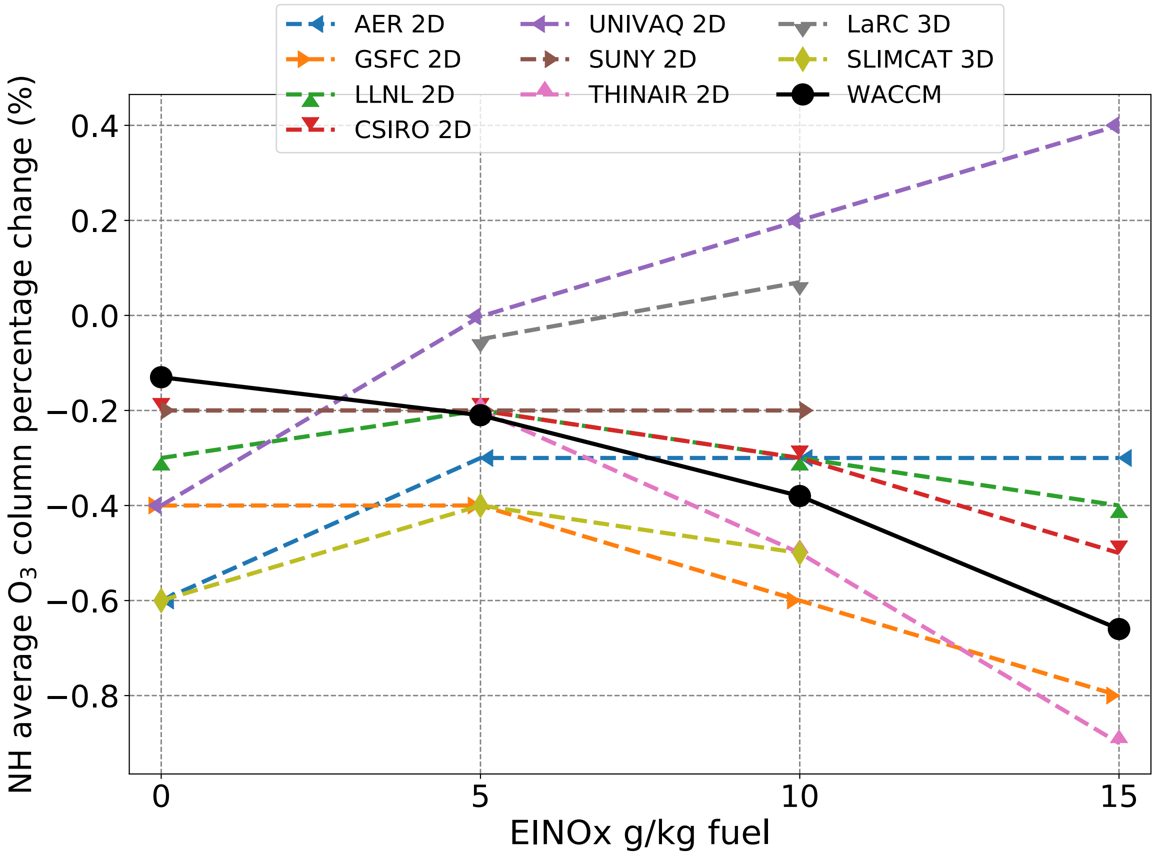

Figure 1. Northern Hemisphere (NH) total ozone column change (%) as a function of EINOx for a fleet size of 500 supersonic aircraft. Results from earlier models are shown in dashed lines while the WACCM results are shown in solid black line.

Milestones

- Journal paper completed to examine effects of historical projected fleets of supersonic aircraft on stratospheric ozone and climate. Paper under review with the *Journal of Geophysical Research*. This paper provides a historical context for further studies of supersonic aircraft effects on ozone and climate.
- NOx and H_2O emissions from fleets of HSCTs can potentially affect stratospheric ozone and climate.
- New analyses on ozone change from HSCTs are similar to results from the 1999 NASA and IPCC aviation assessments, although with a greater sensitivity to NOx emissions.
- Ozone effects from an HSCT fleet depends on the amount of NOx and H_2O emissions and resulting chemical interactions through ozone destroying catalytic cycles.
- These studies provide important context for the studies of actual projected fleets that we will be examining next in our studies.

Task 2 – Conducting Sensitivity Studies on Cruise Altitude

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Objectives

This study is intended to show how the stratosphere responds to different cruise altitudes. The potential effects from hypothetical fleets of stratospheric-flying aircraft will be evaluated by conducting a series of sensitivity studies in a projected realistic 2050 background atmosphere.

Research Approach

Here we use a state-of-the-art 3D chemistry-transport model to evaluate the sensitivity of the atmosphere, especially the stratosphere, to different cruise altitudes from a possible supersonic aircraft fleet. A parametric approach is applied in which the fleet fuel use, NOx emission index as well as the geographical distribution of the emissions are all treated constant while the emission altitude varies systematically at a 2 km cruise range. The cruise emissions are assumed to be uniformly distributed vertically over a 2 km band ranging from 13 to 23 km, with a total of eight emission scenarios.

Results and Discussions

This study has evaluated the sensitivity of the potential environmental effects at different cruise altitudes of supersonic transport on atmospheric ozone and radiative forcing. A series of sensitivity studies of possible future cruise altitudes were conducted to evaluate the relative atmospheric response from NOx and H_2O emissions for a fleet of supersonic aircraft assumed to fully operational by 2050. For these calculations, a fixed fleet fuel use and geographical distribution is assumed.

For a range of cruise altitudes from 13 to 23 km evaluated in this study, the resulting ozone impacts depending on the altitude and can be either positive or negative if examining the annual and global averaging total ozone column change (Figure 2). For emissions in the upper troposphere and lower stratosphere, such as the cases for cruise altitude between 13 and 17 km, total column ozone indicates a slight increase. At these altitudes, the ozone chemistry is affected by the coupling of HOx/NOx/ClOx/BrOx chemistry and the resulting ozone impact is less significant and much less dependent on the altitude of the aircraft emissions. At higher cruise altitudes from 17 to 23 km, where the ozone chemistry is dominated by NOx and the stratospheric lifetimes are longer, stratospheric ozone is reduced, primarily as a result of the NOx-Ox catalytic cycles, and the magnitude of the ozone destruction increases with higher cruise altitude. The resulting changes in total column ozone at these altitudes is highly dependent on the cruise altitude. A cruise altitude from 16 to 18 km shows a minimal total column ozone change resulting from the offsetting effects of ozone production and reduction at different heights. The inflection point is at around 17 km, where the effect from supersonic emission on ozone transitions from ozone production to ozone depletion. The maximum total column ozone loss occurs in the NH high latitudes in the fall to winter season. With higher cruise altitudes, more ozone depletion is found in the SH as more emitted NOx and H_2O are lifted upward and transported southward across the equator.

This study looked at a range of cruise altitudes that encompass the range of the concepts currently being discussed by the industry for supersonic business jets and smaller supersonic airliners. The sensitivity study is based on an assumed Mach-2.4, 300-passenger conceptual supersonic airliner and a projected network based on its 5000 nautical mile range that was developed in the 1990s. As a consequence, the fleet fuel use in these studies is likely larger than any of the much smaller business jets being considered. Likewise, their range, projected markets, utilization, and fleet sizes could be much different, which would result in changes to the geographical patterns of the emissions. If developers are successful at developing designs with low sonic boom, then the geographical distributions could also be quite different because of flights occurring over land. When viewed as impact scaled by fleet fuel use, this study provides insights on the potential impacts on ozone relative to cruise altitudes (Figure 2). As such, this study suggests that developing low NOx combustors could be important if large fleets of supersonic aircraft flying at the highest altitudes ever become viable. In future studies, the environmental effects of other design and operation parameters need to be evaluated thoroughly to facilitate technological development in order to make widespread supersonic travel more environmentally feasible.

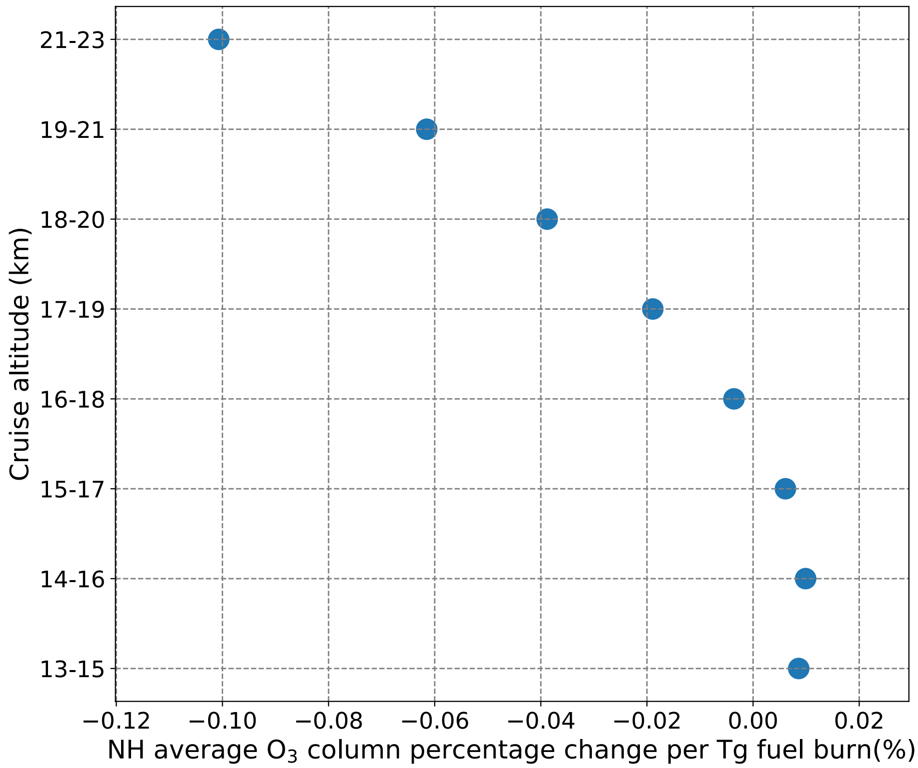

Figure 2. Northern Hemisphere total column ozone change (%) per Tg of fuel burn as a function of cruise altitudes.

Milestones

- Journal paper completed and submitted to the *Journal of Geophysical Research* examining the sensitivity of fleets of supersonic aircraft on stratospheric ozone and climate. This study provides further context for future studies of the environmental effects from future fleets of supersonic aircraft.
- Stratospheric ozone response of supersonic aircraft emissions depends on cruise altitudes and the sensitivity of ozone to emissions was found to increase with altitudes.
- The calculated ozone impact is small for cruise altitudes below 17 km and the ozone depletion increase sharply as the cruise altitudes increase above 17 km.
- Low NOx combustors may be important to consider for fleets of potential future supersonic aircraft with cruise altitudes above 17 km.
- These studies provide important context for the studies of actual projected fleets that we will be examining next in our studies.

Major Accomplishments

The model performs well and the results establish a new paradigm for studies of the impacts from fleets of supersonic aircraft, while also being consistent with earlier studies.

Completed the sensitivity studies. Submitted the journal paper.

Publications

Zhang, J., Wuebbles, D. J., Kinnison, D. E., & Baughcum, S. L. Potential Impacts of Supersonic Aircraft Emissions on Ozone and Resulting Forcing on Climate. Volumes 1 and 2. Both papers are submitted to the *Journal of Geophysical Research*, September 2020.

Outreach Efforts
ASCENT Advisory Committee Meeting, September 2020 (Presentation).
Bi-weekly meeting with project manager.
ICAO Impacts and Science Group (ISG) meetings (monthly) for Dr. Wuebbles.

Student Involvement
Graduate Student Jun Zhang is responsible for the analyses and modeling studies within the project and leading the initial preparation of the project reports.

Plans for Next Period
- Begin studies based on the emission inventories developed by ASCENT Project 10 to consider specific designs of supersonic transports (SSTs).
- Use the results from this study to inform the development of Aviation Portfolio Management Tool – Impacts Climate (APMT-IC) for supersonic impacts (ASCENT Project 58).

References:
Kawa, S. R., Anderson, J. G., Baughcum, S. L., Brock, C. A., Brune, W. H., Cohen, R. C., ... & Waugh, D. (1999). Assessment of the effects of high-speed aircraft in the stratosphere: 1998. National Aeronautics and Space Administration report. NASA/TMM1999-209237.

Penner, J. E., Lister, D. H., Griggs, D. J., Dokken, D. J., & McFarland, M. (Eds). (1999). Aviation and the global atmosphere (pp. 1–373). Cambridge, UK: Cambridge University Press.