Project 022 Evaluation of FAA Climate Tools: Aviation Portfolio Management Tool (APMT)

University of Illinois at Urbana-Champaign

Project Lead Investigator

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University Participants

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- P.I.: Dr. Donald Wuebbles (FAA Award 13-C-AJFE-UI-029)
- Period of Performance: October 1, 2021 to September 30, 2022 (project started February 5, 2020)
- Tasks:
    1. Examine potential environmental effects of possible fleets of supersonic aircraft, particularly on ozone and climate
    2. Support and perform analyses for the International Civil Aviation Organization (ICAO) Impact Sciences Group (ISG)

Project Funding Level

Support from the FAA over this time period was approximately $70,000. An additional approximately $70,000 in matching support was provided by the University of Illinois at Urbana-Champaign.

Investigation Team

Dr. Donald Wuebbles: oversee project

Dr. Jun Zhang (graduate student; graduated in the fall of 2021): conduct studies and perform analyses using the Community Earth System Model (CESM) Whole Atmosphere Community Climate Model (WACCM), a three-dimensional atmospheric-climate-chemistry model.

Dr. Dharmendra Singh (postdoctoral associate): conduct studies and perform analyses using the CESM WACCM.

Project Overview

This project uses state-of-the-art modeling and technical knowledge to analyze the potential global environmental effects of aircraft and to conduct analyses that underpin the development of analytical tools for assessing costs-and benefits, to inform decision-making regarding technology development. The studies rely on state-of-the-art models of the Earth system that can provide useful scientific input for consideration by decision-makers. The analyses in the project will aid in decision-making by translating complex models into simpler tools for use in cost–benefit analyses. Specific project goals include (a) evaluation of potential environmental effects of assumed fleets of supersonic commercial and business jet aircraft, to compare their benefits in terms of decreased air-travel time; (b) when needed, science-based evaluation of analytical tools used by the FAA; (c) development of ideas and concepts for the next-generation treatment of aviation effects on the Earth system; and (d) updated evaluation and analyses of the science of aviation effects on atmospheric composition. The accomplishments for this year fit within these overall objectives.

Task 1 - High-Speed Civil Transport Aircraft and Their Potential Effects on Ozone and Climate

University of Illinois at Urbana-Champaign

Objective

To quantify the costs and benefits of using advanced aircraft and engine technologies, the FAA uses tools that are underpinned by state-of-the-art technical knowledge. These tools are used to inform decision-making by providing the benefits and costs of various options that could enable technology development. The overall objective of this project is to enhance understanding of the relationships between subsonic or proposed supersonic aircraft and the atmospheric state, and the development and evaluation of the capabilities, limitations, and uncertainties of metrics and simple models (e.g., the Aviation Portfolio Management Tool), to assist decision-makers. Interest in developing commercial supersonic transport aircraft has been renewed because of the increased overall demand by the public for air travel, aspirations for more intercontinental travel, and the desire for shorter flight times. Various companies and academic institutions have been actively considering the designs of such supersonic aircraft. As these new designs are developed, the environmental impacts of these realistic fleets on ozone and climate have required exploration. This study examines one such proposed supersonic fleet developed by scientists and engineers at the Georgia Institute of Technology (Georgia Tech) that is projected to fly at Mach 2.2, corresponding to cruise altitudes of 17–20 km, which would burn 122.32 Tg of fuel each year and emit 1.78 Tg of nitrogen oxides (NO_x) annually.

Research Approach

The CESM2/WACCM6 model was used to conduct the numerical experiments. This state-of-the-art coupled chemistry–climate model includes comprehensive troposphere–stratosphere–mesosphere–lower thermosphere chemistry from the Earth's surface to approximately 140 km. We also used the PORT (Parallel Offline Radiation Tool) model, a configuration of the Community Atmosphere Model in the CESM, which runs the radiative transfer code offline for derivations of the radiative forcing on climate.

Results and Discussion

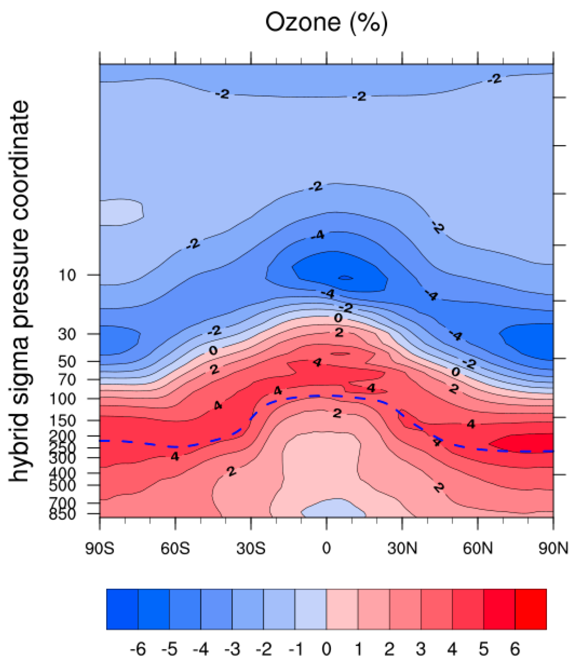
With the Georgia Tech emission scenario for a new proposed fleet of supersonic aircraft, our study investigated the potential atmospheric impacts of this realistic near-term supersonic design. We used the state-of-the-art whole-atmospheric-chemistry climate model WACCM with the latest specified dynamics scheme to assess the impacts on atmospheric ozone and non-CO_2 and non-contrail climate forcing of this near-future supersonic aircraft fleet, whose target entry into service is in approximately 2030–2035. This new proposed supersonic fleet is projected to fly at Mach 2.2 and 17–20 km altitude, to burn 122.32 Tg of fuel each year, and to emit 1.78 Tg NO_x. The aircraft designs and emission scenarios proposed in this study are quite different from those in a study by Eastham et al. (2022) for a different supersonic fleet. Eastham et al. proposed a fleet of supersonic aircraft flying at Mach 1.6 and 15–17 km altitude, burning 19 Tg of fuel each year, and emitting 170 Gg NO_x. The fuel burn and NO_x emissions projected in our study are approximately 6 and 10 times larger than the projections in Eastham et al. (2022), respectively.

As shown in Figure 1, we found that the proposed fleet of supersonic aircraft is predicted to cause a 0.74% decrease in global column ozone, which is approximately 2 Dobson units of global ozone depletion, equivalent to as much as 20% of the total impact of chlorofluorocarbon emissions at their peak. This ozone depletion is attributable primarily to the large amounts of NO_x released into the atmosphere from supersonic aircraft, whereas the impacts of water vapor and SO_2 on the ozone column are relatively smaller. The maximum ozone loss occurs in the northern hemisphere tropics in the fall season, with an approximately 1.4% regional decrease in the total column ozone. The ozone decrease calculated in our study is more than 10 times higher than the estimate from Eastham et al. (2022), who calculated a decrease of 0.046% in global column ozone. This number is consistent with the NO_x emissions used in our study and by Eastham et al. (2022).

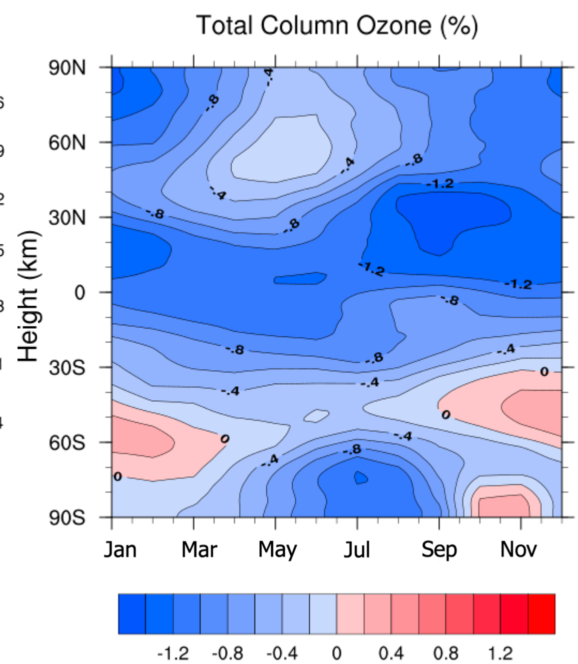
We assessed the ozone increase in the upper troposphere and lower stratosphere, and the ozone decrease in the middle to the upper stratosphere. The mechanisms of ozone change at different latitudes have been explored. In the tropics, the ozone increase is attributed to smog chemistry production and total odd-oxygen production; at the middle latitude, the combination of smog chemistry production, total odd-oxygen production, and decreased ozone loss from the HO_x–O_x cycle are responsible for the ozone increase. In the polar region, the decreased HO_x–O_x loss rate plays a relatively more important role.

To determine the climate impact of this proposed fleet of supersonic aircraft, we estimated the stratospheric-adjusted radiative forcing (Figure 2) from changes in atmospheric concentrations of ozone (59.5 mW/m^2), water vapor (10.1 mW/m^2), black carbon (−3.9 mW/m^2), and sulfate aerosols (−20.3 mW/m^2), thus resulting in a net non-CO_2, non-contrail forcing of 45.4 mW/m^2, indicating an overall warming effect. In contrast, Eastham et al. (2022) estimated a net radiative forcing from non-CO_2, non-contrail forcing of −3.5 mW/m^2, varying from −3.0 to −3.9 mW/m^2 year to year, thereby indicating an overall cooling effect.

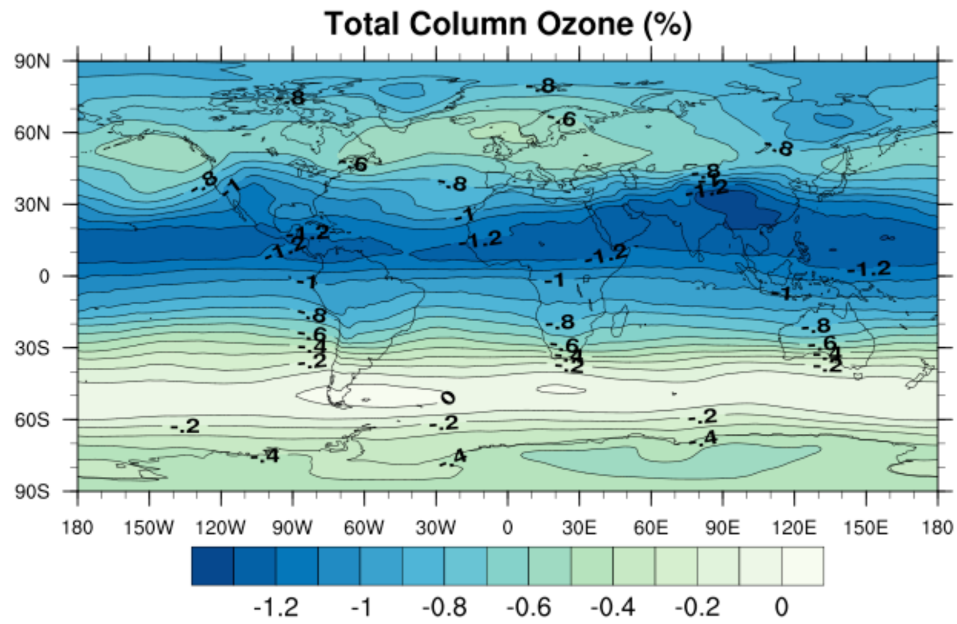
The atmospheric impacts of any proposed fleet of supersonic aircraft must be fully examined and understood before these aircraft are placed into operation. Some assumptions made in this study might contribute to uncertainties in the resultant effects on ozone and climate. For example, the background atmosphere was assumed to be under volcanic clean conditions in the 2035 time period. Ozone depletion might be more substantially affected if emissions were to occur on a background of a major volcanic eruption and the background atmosphere influence on heterogeneous chemistry. We did not consider plume chemistry in this study, which may be important in the initial plume if compared with the well-mixed case in short time intervals. The dynamic effects due to local heating by black carbon and ozone changes are also not included but may substantially influence ozone and climate for supersonic aviation.



(a)



(b)



(c)

Figure 1. For the assumed supersonic aircraft fleet emissions, (a) the simulated annual and zonal mean perturbations (%) in atmospheric ozone concentration at steady state, (b) seasonal dependence of the calculated change in the total column ozone (%), and (c) annual average change in the total column ozone distribution (%).

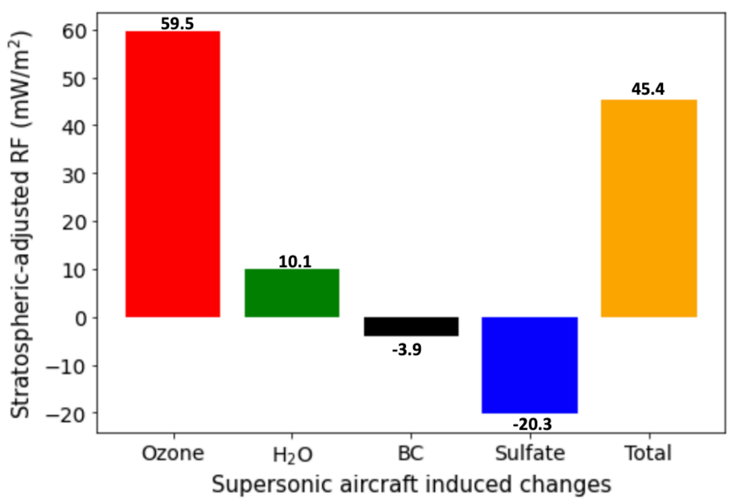


Figure 2. Annual and global average changes in stratospheric-adjusted radiative forcing (mW/m^2) at the tropopause for supersonic aircraft induced changes in ozone, H_2O, black carbon, and sulfate.

We also have received emissions for two different supersonic commercial aircraft designs and associated mature fleets from the Massachusetts Institute of Technology (MIT). We are currently translating these emissions onto our model grid and including those emissions in the climate-chemistry WACCM model, and we will be running the scenarios in separate studies for the two aircraft designs. The aim of this task is to compare our analyses with those from the MIT model and to develop a joint journal manuscript. Runs for these analyses are expected to start soon.

Milestones

- A journal manuscript has been submitted to the journal *Earth's Future*, on the basis of the Georgia Tech proposed supersonic transport (SST) commercial aircraft.
- An article on the future of travel and tourism, including a discussion of aviation and possible development of supersonic aircraft, has been published.
- Emissions received from MIT for its proposed fleet of SSTs are being translated onto our model grid as a prelude to the model runs for these scenarios.

Publications

Wuebbles, D. J. (2022). The future of travel and tourism in the changing climate. *International Affairs Forum, 14(1*), 18–13.

Zhang, J., Wuebbles, D., Kinnison, D., Pfaender, J. H., Tilmes, S., & Davis, N. (2022). Potential impacts on ozone and climate from a proposed fleet of supersonic aircraft. [Manuscript submitted for publication.] *Earth's Future.*

Task 2 - Support and Analyses for the International Civil Aviation Organization Impact Sciences Group

University of Illinois at Urbana-Champaign

Objectives

A series of analyses conducted last year resulted in reports for ICAO relating to the environmental impacts of aviation.

Research Approach

The University of Illinois at Urbana-Champaign, particularly through Dr. Wuebbles, has contributed to three of the reports for ICAO, one of which was led by Dr. Wuebbles.

Results and Discussion

The three reports for ICAO to which the University of Illinois at Urbana-Champaign contributed are described below.

1. Assessment of the Impact of Airport Emissions on Local Levels of NO_x and Human Health; Impacts of Cruise Emissions of NO_x on Human Health; Impacts of Cruise NO_x on Climate

Dr. Wuebbles was a contributing author to this report.

According to the current view, aviation NO_x emissions over the 1940–2018 period have contributed to a net warming of the climate system. However, the uncertainty associated with the estimates of the net climate forcing remains high. A recent study has suggested that the net climate impact of aviation NO_x might switch to net cooling, depending on future background atmospheric composition, future aircraft emissions, or the consideration of new processes or refined parameterizations. The estimated impacts of NO_x emissions on the climate system relative to other forcing agents are dependent on the choice of the climate metric and the time horizon considered. In response to the important challenges due to climate change, several studies have focused on how to reduce the climate impact of aviation through changing flight operations. In the case of NO_x, lowered flight altitudes may provide a possible mitigation option for reducing the NO_x climate impact at the cost of increased CO_2.

Aircraft ground operations and the landing and takeoff cycle emit various gaseous and particulate pollutants or their precursors, thus affecting human health. Aircraft landing and takeoff emissions contribute to premature mortality around major airports. At the local scale, NO_2 health impacts have been shown to outweigh $PM_{2.5}$ health impacts. Most NO_x emissions from aviation do not occur near the ground, and more than 90% occur above 3,000 ft. Those emissions still contribute to the background levels of O_3 and thus to the O_3 at ground level. Similarly, cruise emissions could potentially be an important source of surface-level particulate matter globally and an important cause of aviation-related premature mortality.

The options for controlling aviation NO_x are limited, and are countered by the international growth in commercial aviation and by the mandate to increase engine energy efficiency by increasing engine core temperatures. Historically, continued reductions in NO_x have tended to increase fuel burn and the resulting emissions of CO_2—the primary gas of concern regarding climate change. Thus, a trade-off arises between reducing impacts on climate, due primarily to CO_2, and reducing the impacts on air quality from NO_x.

2. Allowed Emission of Carbon Dioxide for Limiting Global Mean Temperature Increases to 1.5 or 2 °C

Dr. Wuebbles wrote major sections of this report. The ICAO Committee on Aviation Environmental Projection Long Term Aspirational Goal Task Group (LTAG-TG), during the process of developing the scenarios for aviation CO_2, requested the following from the ISG:

> "ISG should examine the literature and summarize the amount of carbon dioxide (a.k.a. carbon budget) that can be released into the atmosphere while limiting the increase in global mean temperature to 1.5 and 2 degrees Celsius. These carbon budgets can then be compared against the aviation CO_2 scenarios being developed by LTAG-TG. The ISG should also capture the latest information on the impacts of non-CO_2 aviation emissions such that decision-makers understand the relative impact of aviation CO_2 emissions and the non-CO_2 emissions on the climate."

This report addresses the above request from the LTAG-TG.

The aim of this report is to examine and summarize the understanding of the amount of CO_2, in terms of the number of gigatons of CO_2 ($GtCO_2$) that could still be emitted into the atmosphere by human activities if the amount of climate change, in terms of the global mean surface temperature increase, is to be limited to either 1.5 or 2 °C over pre-industrial levels. The Paris Agreement sets a long-term temperature goal of: "holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change" (Article 2.1 (a)) (as discussed later, this statement is often interpreted as starting with the period from 1850 to 1900, when adequate global temperature records became available). Although CO_2 is the main driver of human-induced long-term climate change, approximately one third of the current changes in climate relate to non-CO_2 emissions of other gases and particles emitted by human activities (Smith et al., 2020). We will start by considering these allowed emissions only in terms of CO_2 and will include assumptions regarding the contributions of non-CO_2 effects.

The amount of allowable remaining carbon emissions—the "remaining carbon budget"—to limit global warming to 1.5 or 2 °C over pre-industrial levels from all anthropogenic sources is provided in this report, according to the Intergovernmental Panel on Climate Change (2021). The remaining amounts of carbon emissions from January 1, 2020 are estimated to be 500 and 1,350 $GtCO_2$ for 1.5 and 2 °C limits, respectively, for a 50% probability, and 400 and 1,150 $GtCO_2$ limits, respectively, for a 67% probability of limiting temperature increases to 1.5 and 2 °C. The assumptions underlying these estimates are described, along with updates on the current level of global warming. Non-CO_2 effects (e.g., largely from methane, nitrous oxide, and fluorinated gases) are included in the above estimates and introduce an uncertainty in the allowed CO_2 emissions for a given temperature limit, and the probability of staying at or below this limit. The total aviation forcing effect was approximately 3.5% of the total anthropogenic climate forcing in 2011. Aviation non-CO_2 climate effects are currently estimated to be approximately two thirds of the total aviation forcing, according to historical data, although future projections are uncertain.

3. Understanding the Potential Environmental Impacts from Supersonic Aircraft: An Update

Dr. Wuebbles led the team writing this report and wrote major sections of the report.

Increasing demand for air travel, the aspiration for more intercontinental travel, and the desire for shorter flight times have all contributed to renewed interest in the potential development of civil aircraft that fly at supersonic speeds. Consequently, various governments and companies worldwide have been reconsidering the development of supersonic aircraft for the business jet and commercial airline markets. Fleets of hundreds to thousands of these supersonic business jets and/or SST aircraft would probably be necessary to make their development economically feasible. This report is aimed at providing an update on the understanding of the noise and the environmental concerns relating to emissions, and the resulting impacts on climate and ozone, associated with the substantial use of such aircraft. A short summary of the history of these environmental concerns is described below.

Interest in the potential development of commercial and civil aircraft that fly at supersonic speeds has been renewed. Noise and emissions impacts were first extensively studied in the 1970s, then again in the 1990s and early 2000s. Consequently, a need exists to update understanding of the potential impacts of noise and the environmental concerns relating to emissions, particularly the resulting affects ozone and climate. SST fleets of differently sized aircraft using conventional fuels are being considered, extending from business jets to larger aircraft that can transport hundreds of passengers. Scientists are now undertaking new studies using state-of-the-art models of global atmospheric chemistry and physics to understand the potential effects on stratospheric ozone and the radiative forcing of climate associated with SST fleets. These studies set the stage for the next generation of analyses of potential environmental effects from supersonic aircraft that are under consideration for development. Along with the emissions of long-lived CO_2, the radiative forcing of climate in turn depends on the spatial changes in concentrations of water vapor, O_3, CH_4 (primarily because of feedback from the emissions of NO_x and water vapor), and particles (both inorganic and organic aerosols). The emissions from the fleet of aircraft particularly depend on the fleet size, flight characteristics, Mach speed, cruise altitude, fleet fuel use at cruise, NO_x emission index, and assumptions regarding sulfur in the fuel and soot emissions. For projections of the number and type of aircraft currently under evaluation for SST fleets, a 1% change in globally averaged total ozone over the next two to three decades is likely, and whether the change is positive or negative will depend on specific fleet parameters. The climate effects are also likely to be small, resulting in generally much less than a 0.03 °C change in globally averaged surface temperature (the total effect will also depend on whether sustainable aviation fuels are used). Substantial progress has been made in modeling and mitigating the effects of sonic booms from supersonic flight. Ongoing research to assess the impact on the public has indicated that future low-boom supersonic aircraft designs will create quieter sonic "thumps" that are much less irritating than conventional sonic booms. Nonetheless, further studies are necessary to fully evaluate the noise effects for specific aircraft.

Major Accomplishments

- Three reports were well received by the ICAO.
- Dr. Wuebbles gave a major presentation to the ICAO during the summer of 2022 about the potential environmental effects of supersonic commercial aircraft.

Milestones

Analyses have been completed, and reports have been published.

Publications

Hauglustaine, D. R., Miake-Lye, C., Arunachalam, S., Barrett, S. R. H., Fahey, D. W., Fuglestvedt, J. S., Madden, P., Skowron, A., van Velthoven, P., & Wuebbles, D. J. (2022). *Assessment of the impact of airport emissions on local levels of NO_x and human health; impacts of cruise emissions of NO_x on human health; impacts of cruise NO_x on climate*. International Civil Aviation Organization (ICAO). The United Nations, Montreal.

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Additional Information and Future Efforts

Outreach Efforts

Presentations at ASCENT meetings
Presentations to ICAO
Presentations at the SPARC (Stratosphere-troposphere Processes And their Role in Climate) conference and at the AGU (American Geophysical Union) annual meeting

Biweekly meetings with project manager
ICAO ISG meetings (monthly) for Dr. Wuebbles

Student Involvement

Former graduate student Jun Zhang (now a postdoctoral associate at the National Center for Atmospheric Research (NCAR) was primarily responsible for the analyses and modeling studies within the project, and for leading the initial preparation of the project reports. A new postdoctoral associate, Dr. Dharmendra Singh, is currently performing the newest studies. He is working with another team member, postdoctoral associate Dr. Swarnali Sanyal, as he learns to perform the modeling runs required.

Plans for Next Period

- Complete studies based on the emission inventories developed by ASCENT Project 10 to consider specific designs of SSTs from MIT, and compare those results to model analyses performed by MIT for the same scenario plus their similar analyses of the Georgia Tech SST fleet. Publish journal article.
- Use the results from this study to inform the development of the Aviation Portfolio Management Tool–Impacts Climate (APMT-IC) for supersonic impacts (ASCENT Project 58).
- Initiate new projects for the ICAO ISG (new meetings expected to start after January 1, 2023).

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Eastham, S. D., Fritz, T., Sanz-Morère, I., Prashanth, P., Allroggen, F., Prinn, R. G., ... Barrett, S. R. (2022). Impacts of a near-future supersonic aircraft fleet on atmospheric composition and climate. *Environmental Science: Atmospheres.* https://doi.10.1039/D1EA00081K

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Smith C. J., Kramer R. J., Myhre G., Alterskjær K., Collins W., Sima A., Boucher O., Dufresne J.-L., Nabat P., Michou M., Yukimoto S., Cole J., Paynter D., Shiogama H., O'Connor F. M., Robertson E., Wiltshire A., Andrews T., Hannay C., Miller R.L., Nazarenko L., Kirkevåg A., Olivié D., Fiedler S., Pincus R and P. M. (2020) Effective radiative forcing and adjustments in CMIP6 models. *Atmos. Chem. Phys.* 20, no. 16, 9591-9618, doi:10.5194/acp-20-9591-2020.

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Zhang, J., Wuebbles, D., Kinnison, D., Pfaender, J. H., Tilmes, S., & Davis, N. (2022). Potential impacts on ozone and climate from a proposed fleet of supersonic aircraft. [Manuscript submitted for publication.] *Earth's Future.*