Project 058 Improving Policy Analysis Tools to Evaluate Higher-Altitude Aircraft Operations

Massachusetts Institute of Technology

Project Lead Investigator

PI: Steven R. H. Barrett
Professor of Aeronautics and Astronautics
Director, Laboratory for Aviation and the Environment
Massachusetts Institute of Technology
77 Massachusetts Ave, Building 33-322, Cambridge, MA 02139
(617) 452-2550
sbarrett@mit.edu

Co-PI: Dr. Sebastian D. Eastham
Research Scientist
Laboratory for Aviation and the Environment
Massachusetts Institute of Technology
77 Massachusetts Ave, Building 33-322, Cambridge, MA 02139
seastham@mit.edu

University Participants

Massachusetts Institute of Technology

- P.I.: Prof. Steven R.H. Barrett
- FAA Award Number: 13-C-AJFE-MIT, Amendment Nos. 064 and 089
- Period of Performance: Feb. 5, 2020 to Aug. 31, 2022
- Reporting Period: Oct. 1, 2020 to Sep. 30, 2021
- Tasks (Note: Tasks not covered during this reporting period are listed as "*pending*" and are discussed further only in the context of tasks for the coming period of performance):
    1. Develop a set of emissions scenarios for high-altitude aviation.
    2. Extend and validate the Massachusetts Institute of Technology's (MIT) existing atmospheric simulation capabilities.
    3. Simulate atmospheric impacts of high-altitude emissions using updated capabilities.
    4. Convert estimated impacts into sensitivities.
    5. Develop and update operational tools capable of quantifying environmental impacts of aviation.
    6. Develop parameterization of contrails.
    7. Evaluate the evolution of aviation nitrogen oxides (NO_x) impacts on climate and air quality [*pending*].

Project Funding Level

$650,000 in FAA funding and $650,000 in matching funds. Sources of matching funds are approximately $132,000 from MIT, plus third-party in-kind contributions of $391,000 from NuFuels LLC, and $127,000 from Savion Aerospace Corp.

Investigation Team

Principal Investigator:	Prof. Steven Barrett (MIT) (all tasks)
Co-Principal Investigator:	Dr. Sebastian Eastham (MIT) (all tasks)
Postdoctoral Researcher:	Dr. Sadia Afrin (MIT) (all tasks)
Graduate Research Assistants:	Inés Sanz-Morère (MIT) (Tasks 1–4)
	Jeong Suk Oh (MIT) (Tasks 3-4)
	Joonhee Kim (MIT) (Tasks 5–6)

Project Overview

Companies are proposing, developing, and testing aircraft operating at higher altitudes, such as commercial supersonic aircraft and high-altitude, long-endurance (HALE) unmanned aerial vehicles. These aircraft offer the potential to enable new use cases and business models in the aviation sector. However, the combustion emissions of these vehicles will have atmospheric impacts that differ from those of conventional subsonic aviation due to the higher altitudes of emission. Emissions at higher altitudes are associated with a different chemical environment, longer emission lifetimes, and greater distances over which the emissions will be transported. Furthermore, new developments in emissions impact estimation have enabled a more nuanced view of the environmental consequences of conventional aircraft activity. This includes recognition that both their climate and air quality impacts vary depending on the prevailing conditions of the emission and the time horizon of the assessment.

In this project, we propose to quantify the environmental consequences of such high-altitude aviation emissions. For this purpose, we will perform high-fidelity atmospheric simulations by further developing and applying the GEOS-Chem UCX tropospheric-stratospheric chemistry-transport model and its adjoint. The results will be leveraged to (1) evaluate the climate (radiative forcing) effects of high-altitude aircraft emissions; and (2) estimate the sensitivity of the global ozone column and surface air quality to these emissions. As a result, the climate, air quality, and ozone impacts for a small number of different proposed supersonic aircraft designs and performance characteristics will be quantified. We will also perform a historical assessment of the impacts of aviation emissions, quantifying how factors such as changing emissions indices and an evolving chemical background have affected—and will affect—the total impacts. Using data from these simulations, a flexible, rapid approach for assessing the impacts of sub- and supersonic aircraft will be presented.

Task 1 - Develop a Set of Emissions Scenarios for High-Altitude Aviation

Massachusetts Institute of Technology

Objective

The objective of this task is to develop emissions inputs that cover scenarios relevant to near-future aviation, extending impact estimation to cover a range of altitudes exceeding those of current commercial airline activities. The specific focus of the work during this period was to develop global supersonic emissions inventories including variations in cruise altitude, Mach number, engine NO_x emissions index, and fuel sulfur content.

Research Approach

To achieve the goals outlined above, a mathematical model is needed that can produce an estimate of emissions of key chemical species (NO_x, sulfur oxides [SO_x], water vapor, soot, etc.) resulting from a single flight. The team incorporated work from the ASCENT Project 47 engine model into a simplified supersonic civil aircraft performance model to estimate the distribution of emissions along a supersonic aircraft flight path. This was combined with a market model to produce a set of reasonable global emissions inventories for supersonic aircraft, including different assumptions regarding cruise altitude and engine NO_x emissions index. This inventory will be used as a central case for evaluation of supersonic aircraft emissions environmental impacts using the updated APMT model. An ongoing, second objective is to generate a second inventory using the ASCENT Project 10 aircraft design data, enabling comparison of impacts resulting from different assumptions (and therefore different inventories).

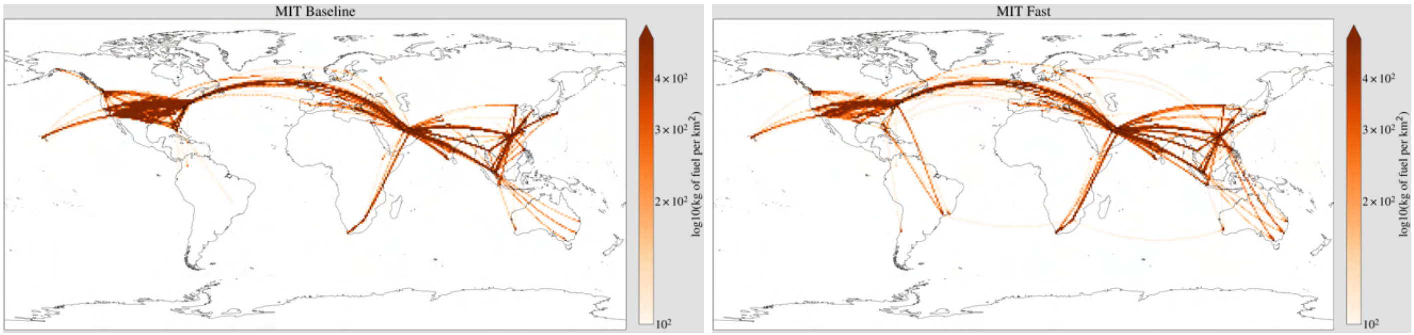

Figure 1. Emissions maps for representative supersonic aircraft developed at Massachusetts Institute of Technology for a baseline (left) and "fast" (right) case.

Milestones

- Multiple emissions datasets were generated from the supersonic aircraft engine design developed by ASCENT Project 47, as well as the emissions inventory developed by the ASCENT Project 10 supersonic fleet results.
- Emissions maps for representative supersonic aircraft were generated (Figure 1).

Major Accomplishments

- A supersonic aircraft performance and design model capable of producing global emissions inventories was finalized.
- Emissions inventories for several different representative supersonic aircraft have been estimated.
- Emissions inventories were provided to ASCENT Project 22 to enable comparison of estimated impacts using multiple different models.

Publications

None.

Outreach Efforts

Progress on all tasks was communicated during biweekly briefing calls with the FAA and reported in quarterly progress reports.

Awards

None.

Student Involvement

During the reporting period of academic year (AY) 2020/21, the MIT graduate student involved in this task was Inés Sanz-Morère.

Plans for Next Period

Task 1 was largely completed in AY 2020/21. The team will continue testing, refining, and comparing the global emissions datasets in AY 2021/22.

References

Not applicable.

Task 2 - Extend and Validate MIT's Existing Atmospheric Simulation Capabilities

Massachusetts Institute of Technology

Objective

The objective of Task 2 is to extend and validate MIT's existing atmospheric simulation capabilities, with the specific goal of ensuring that impacts on critical metrics of air quality and climate can be accurately represented. During AY 2020/21, the team developed and tested a higher-resolution version of the GEOS-Chem UCX tropospheric-stratospheric global chemistry-transport model to capture localized effects.

Research Approach

The team is using the GEOS-Chem UCX tropospheric-stratospheric global chemistry-transport model as the central tool to quantify climate, air quality, and ozone impacts resulting from high-altitude aviation (Eastham et al., 2014). It is therefore necessary to evaluate the capabilities of this model for these purposes and to extend those capabilities where necessary. Two major subtasks have been identified: Task 2a, increasing the resolution of the model to capture localized impacts at a global resolution of 2°×2.5° or equivalent; and Task 2b, implementing a technique to estimate stratospherically adjusted radiative forcing (RF), rather than instantaneous RF. Task 2b was largely completed in AY 2019/20, whereas Task 2a work was completed in AY 2020/21.

The team modified GEOS-Chem v11 (UCX) to ensure that simulations could be successfully completed at the increased resolution. Although GEOS-Chem has previously been used at these resolutions, the focus has been on surface quantities (e.g., air quality); it was for this reason that the increased horizontal resolution was desired. Model viability and capability with regards to stratospheric chemistry had not been evaluated at the higher resolution. Figure 2 compares performance of the GEOS-Chem model at the increased resolution in terms of comparison to satellite observations of total ozone column, a diagnostic of the model's ability to simulate stratospheric composition. Compared to the results at the coarser 4°×5° resolution (Figure 3), the 2°×2.5° simulation is again able to simulate the key features of the stratospheric ozone cycle. Although a general positive bias remains, we find that the higher-resolution simulations also produce a more accurate (deeper) ozone hole in the Antarctic spring.

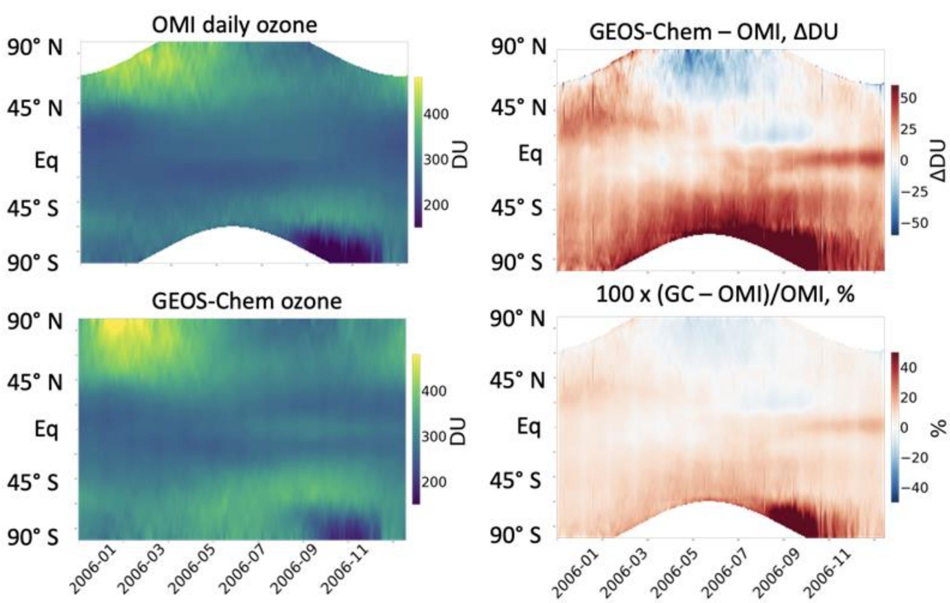

Figure 2. Global total ozone column for each day in 2006 and at each latitude. Top left: observations from the Ozone Mapping Instrument (OMI). Bottom left: simulated totals from a simulation performed at a resolution of 2°×2.5° using GEOS-Chem. Top right: absolute differences between simulations and observations. Bottom right: relative differences between simulations and observations. DU = Dobson units.

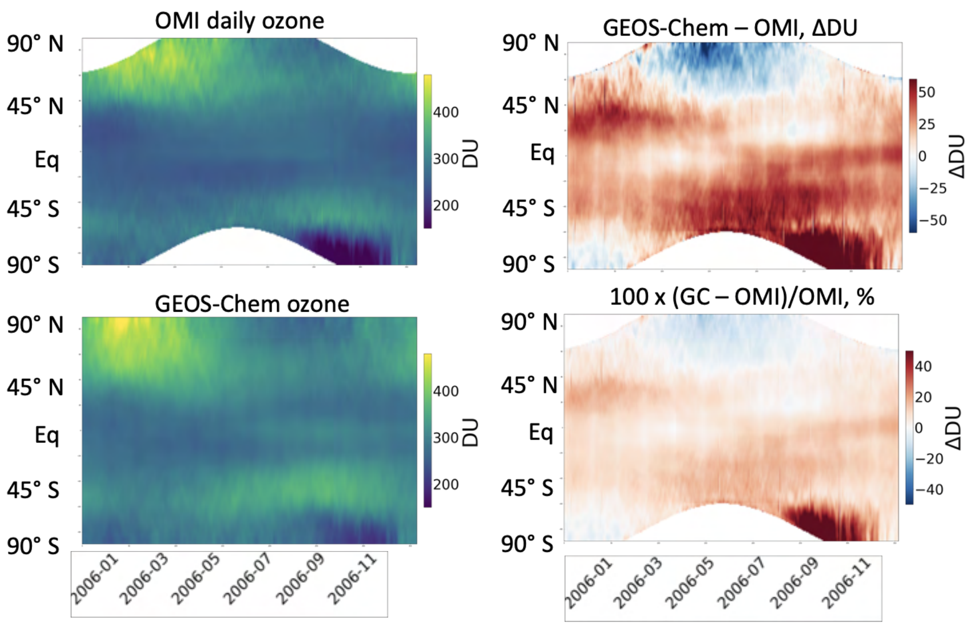

Figure 3. Global total ozone column for each day in 2006 and at each latitude. Top left: observations from the Ozone Mapping Instrument (OMI). Bottom left: simulated totals from a simulation performed at a horizontal resolution of 4˚×5˚ using GEOS-Chem. Top right: absolute differences between simulations and observations. Bottom right: relative differences between simulations and observations. DU = Dobson units.

Milestones

- GEOS-Chem simulation resolution was increased from 4˚×5˚ to 2˚×2.5˚ globally (Task 2a).
- GEOS-Chem simulation results at both resolutions were compared with observational data (Task 2a).

Major Accomplishments

A manuscript was submitted for review that used the new stratospherically adjusted radiative forcing calculations to evaluate the impacts of supersonic civil aviation on the environment.

Publications

Eastham, S. D., Fritz, T., Sanz-Morère, I., Prashanth, P., Allroggen, F., Prinn, R. G., Speth, R. L., & Barrett, S. R. H. (2021). *Atmospheric impacts of a near-future supersonic aircraft fleet: An evaluation of climate forcing resulting from a near-future supersonic aircraft fleet* [Manuscript submitted for publication].

Outreach Efforts

Progress on all tasks was communicated during biweekly briefing calls with the FAA and reported in quarterly progress reports.

Awards

None.

Student Involvement

During the reporting period of AY 2020/21, the MIT graduate students involved in this task were Inés Sanz-Morère and Jeong Suk Oh.

Plans for Next Period

Task 2 was completed in AY 2020/21.

References

Eastham, S. D., Weisenstein, D. K., & Barrett, S. R. H. (2014). Development and evaluation of the unified tropospheric–stratospheric chemistry extension (UCX) for the global chemistry-transport model GEOS-Chem. Atmospheric Environment, *89*, 52–63.

Task 3 - Simulate Atmospheric Impacts of High-Altitude Emissions Using Updated Capabilities

Massachusetts Institute of Technology

Objective

The objective of this task is to estimate the atmospheric response to the representative near-future aviation scenarios described in Task 1, and to convert the raw model outputs to impacts. These simulations will calibrate the simulated impacts and performance of the new version of the Aviation environmental Portfolio Management Tool – Impacts (APMT-I).

Research Approach

Specific outcomes to be investigated for each scenario are changes to the global ozone column; changes to the global average and Northern Hemispheric ozone layer; effects on polar ozone depletion; changes in surface air quality, including ozone and fine particulate matter ($PM_{2.5}$); changes in UV-B radiation reaching the surface; and total induced radiative forcing. This will extend to limited-scale health impact evaluation, quantifying the human and economic impact of changes in radiative forcing and surface air quality. These outcomes will be estimated by performing simulations with the GEOS-Chem UCX model at the enhanced global resolution of $2^{\circ}\times2.5^{\circ}$. Comparing the simulated impacts of different supersonic emissions scenarios will enable us to deduce the sensitivity of environmental impacts to changes in supersonic fleet parameters.

Milestone

With the inputs and modeling capabilities now ready, simulations for evaluating the atmospheric response from supersonic emissions scenarios have begun.

Major Accomplishments

GEOS-Chem simulations using the supersonic emissions inventory developed by MIT and informed by the ASCENT Project 47 engine design have started. The emissions inventory developed by the ASCENT 10 supersonic aircraft design team have also begun processing for simulation with GEOS-Chem.

Publications

None.

Outreach Efforts

Progress on all tasks was communicated during biweekly briefing calls with the FAA and reported in quarterly progress reports.

Awards

None.

Student Involvement

During the reporting period of AY 2020/21, the MIT graduate students involved in this task were Inés Sanz-Morère and Jeong Suk Oh.

Plans for Next Period

During the next project period, the project team will generate and refine the outputs of atmospheric responses to representative supersonic aircraft emissions and use the results to test APMT-IC. These estimates will also calibrate the climate, air quality, and ozone impacts sensitivities developed in Task 4 using GEOS-Chem simulations.

References

Not applicable.

Task 4 - Convert Estimated Impacts into Sensitivities

Massachusetts Institute of Technology

Objective

The objective of this task is to convert the impacts calculated under Task 3 for each scenario into sensitivities of environmental impacts with regards to key parameters. This will then support the operationalization of emissions impacts estimation in Task 5.

Research Approach

Two approaches are being taken in this task. First, a number of different supersonic aircraft emissions scenarios are to be simulated using the updated GEOS-Chem model, covering different assumptions regarding the aircraft fleet (e.g., NO_x emissions index, cruise Mach number). Differences in outcomes from these simulations will provide an estimate of the sensitivity of environmental impacts with respect to variations in these parameters.

Second, we will investigate the use of a gridded sensitivity approach consistent with that used in prior iterations of APMT. This will require a set of GEOS-Chem simulations in which representative perturbations of a species are included over a predefined region, with these regions defined based on a literature review. Changes in model output (i.e., air quality, ozone column, radiative forcing etc.) will be taken as the sensitivity of that output to an emission anywhere within the source region. By covering the full range of target altitudes, a gridded sensitivity map can be reconstructed where changes in gridded outputs can be evaluated through element-wise multiplication of the sensitivities with a gridded aircraft emissions distribution.

Consistency between the two approaches will be evaluated by calculating impacts for each of the MIT inventories using both methods and quantifying differences. Where necessary, additional simulations will be performed to refine the regions for which sensitivities are calculated.

Milestones

- A preliminary set of target regions for perturbations was identified.
- Simulations in GEOS-Chem to evaluate the atmospheric responses to representative perturbations in each region for each key species have begun.

Major Accomplishments

- Emissions files required to generate sensitivity matrices from GEOS-Chem simulations were generated.
- Perturbation emissions files have been prepared and initialized. This will generate the preliminary climate and air quality sensitivity arrays which will quickly evaluate impacts from emissions in varying altitudes and regions.

Publications

None.

Outreach Efforts

Progress on all tasks was communicated during biweekly briefing calls with the FAA and reported in quarterly progress reports.

Awards

None.

Student Involvement

For the AY 2020/21reporting period, graduate students Inés Sanz-Morère and Jeong Suk Oh were involved with this task.

Plans for Next Period

During the next project period, the project team will generate both scenario-specific and gridded sensitivity data to account for variations in altitude, latitude, and season. The team will also estimate uncertainty bounds for these sensitivities.

References

Not applicable.

Task 5 - Develop and Update Operational Tools Capable of Quantifying Environmental Impacts of Aviation

Massachusetts Institute of Technology

Objective

The objective of this task is to operationalize the results of Tasks 1 to 4. The eventual outcome will be a re-engineered version of APMT for climate and air quality impacts, calibrated based on updated sensitivity data and upgraded to provide monetized impacts that consider the possibility of different cruise altitudes (among other characteristics).

Research Approach

This task aims to produce a more broadly capable operational tool. During AY 2020/21, the existing version of APMT-IC in MATLAB was updated to incorporate new information on the impacts of aviation from the Lee et al. (2020) assessment as APMT-IC v24c. This included estimating the effective radiative forcing (ERF) for contrail-cirrus with updated uncertainty distributions.

The team also began re-engineering APMT-IC in the programming language Julia. The new version of the model will evaluate climate, air quality, and ozone impacts from gridded emissions using the sensitivity-based approach described in Task 4. Air quality impacts will be regionalized to show impacts by country.

Figure 4 describes, at a high level, how the updated APMT will function. The main inputs will include parameters such as the number of Monte Carlo (MC) simulations, time horizon, lens or RCP scenario, and emissions. Based on the chosen RCP lens, the model will determine which distributions of predefined parameters to sample from for the MC runs. Emissions inputs will be specified either as (1) gridded emissions, gridded flight distances, and years or (2) default settings from predefined emissions inventories. The model will use the emissions inputs and sensitivity matrices embedded in APMT to obtain the global radiative forcing, change in surface ozone and $PM_{2.5}$ concentrations, and Dobson units for each key emissions species.

After the model parameters are defined and emissions are specified, the model will loop over the same set of calculations for every MC run (e.g., emissions to RF to temperature change to damages, or emissions to change in air quality to health impacts). This is shown in the central black box of Figure 4. All the inputs fed into this section are deterministic, as the model provides one set of parameters *N* times (where *N* is the specified number of MC simulations). Similarly, the model obtains one set of results for every MC run so that it can calculate a distribution of results for the variables of interest.

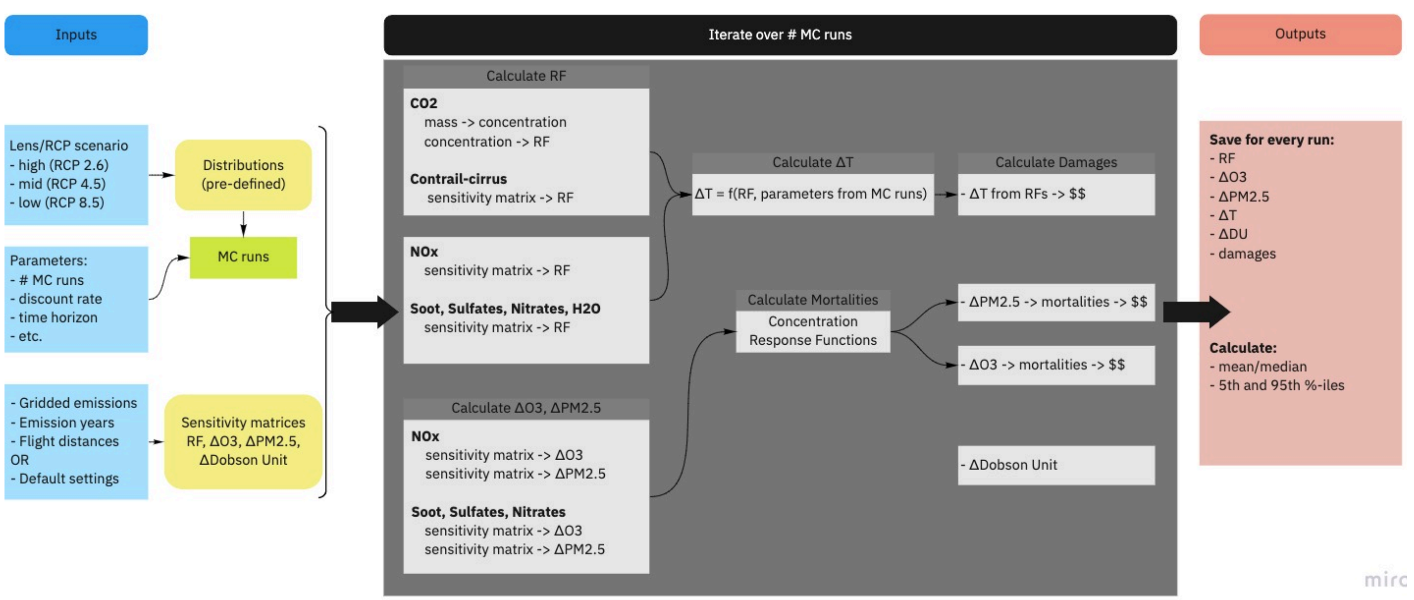

Figure 4. Flowchart of the new internal structure of Aviation Environmental Portfolio Management Tool (APMT).

Milestones
The current version of APMT-IC was updated to match Lee et al. (2020)'s estimates for stratospherically adjusted radiative forcing and the impact metrics listed in Grobler et al. (2019) accordingly. The team briefed FAA on the architectural changes required to restructure APMT and incorporate sub- and supersonic aviation in a single evaluation tool.

Major Accomplishments
The current version of APMT-IC (v24c) now includes the latest estimates of the impacts of current-day aviation NO_x, in addition to the effects of contrails on a per unit of fuel burn basis. Updates to the existing version of APMT were documented in an updated APMT-IC Design Document (v24c). A demonstration of the in-development APMT in Julia showed the new structure of gridded inputs and outputs of climate, air quality, and ozone impacts from both subsonic and supersonic emissions.

Publications
None.

Outreach Efforts
Progress on all tasks was communicated during biweekly briefing calls with the FAA and reported in quarterly progress reports.

Awards
None.

Student Involvement
During the reporting period of AY 2020/21, the MIT graduate student involved in this task was Joonhee Kim.

Plans for Next Period
The project team will integrate the Task 4 sensitivities from GEOS-Chem into the new version of APMT and calibrate the results using the outputs of atmospheric impacts from Task 3. After integration and calibration, the team aims to provide another demonstration of the re-engineered APMT and updated outputs. The tool will also include an option to run APMT using the original, subsonic-only data (v24c) as described in the design document. The team also plans to generate a development plan of changes required in APMT to update the CO_2 background concentration from RCP to SSP scenarios based on the latest IPCC Working Group I Sixth Assessment Report.

References
Grobler, C, Wolfe, PJ, Dasadhikari, K, Dedoussi, IC, Allroggen, F, Speth, RL, Eastham, SD, Agarwal, A, Staples, MD, Sabnis, JS, Barrett, SRH: Marginal climate and air quality costs of aviation emissions, Environ. Res. Let. 14 114031, 2019.

Lee, DS, Fahey, DW, Skowron, A, Allen, MR, Burkhardt, U, Chen, Q, Doherty, SJ, Freeman, S, Forster, PM, Fuglestvedt, J, Gettelman, A, De León, RR, Lim, LL, Lund, MT, Millar, RJ, Owen, B, Penner, JE, Pitari, G, Prather, MJ, Sausen, R and Wilcox, LJ: The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018, Atmos. Environ., 117834, 2020.

Task 6 – Develop Parameterization of Contrails
Massachusetts Institute of Technology

Objective
This task aims to parameterize contrails, linking distance flown in a given region to the expected radiative forcing. In the existing version of APMT-IC (v24c), the total impacts of emissions are quantified per unit of additional fuel burned for the current subsonic fleet. Lee et al. (2020)'s review of aviation's impacts from 2000 to 2018 highlighted the need for a more sophisticated representation of the relationship between the number and distribution of flights and their contrail impacts.

Research Approach
Parameterization of contrail production which are based only on quantity of fuel burned, or even total global cruise flight distance, do not consider the localized nature of the likelihood of contrail formation as a function of region or the climate impact resulting from a persistent contrail. Recent work from Agarwal et al. (in preparation) demonstrates the spatial and temporal variations of contrail impacts for current cruise altitudes between 9 km and 12 km (Figure 5). The climate impacts

of contrails will be incorporated into the in-development version of AMPT-IC as an "RF by location," with a similar sensitivities-based approach as described in Task 5.

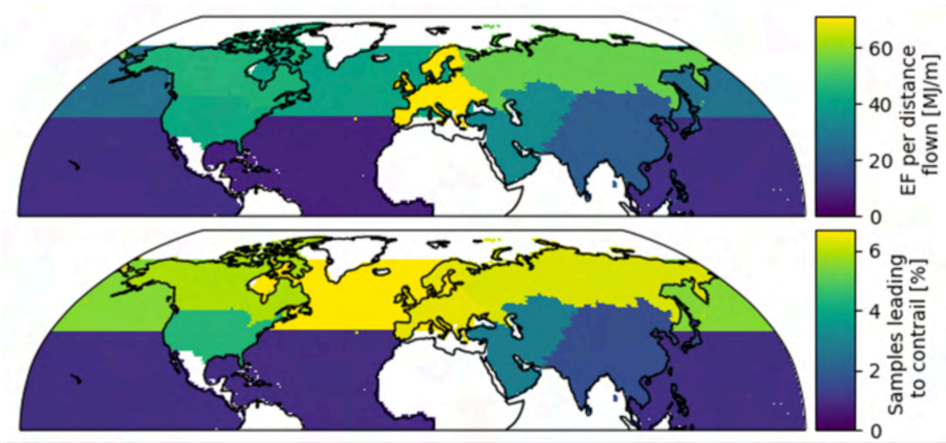

Figure 5. Spatial distribution of mean contrail energy forcing (EF) per distance flown (upper panel) and proportion of samples leading to a contrail (lower panel) in the Northern Hemisphere (Agarwal et al. [in preparation]).

Milestones

The in-development APMT-IC in Julia has been updated to accept gridded flight distances. Coarsely defined regions and the expected, average contrail forcing resulting from 1 km of flight in those regions have been estimated based on Agarwal et al (in preparation).

Major Accomplishments

Inputs of gridded flight distance to calculate the impacts of contrails per distance flown have been successfully implemented in APMT-IC.

Publications

None.

Outreach Efforts

Progress on all tasks was communicated during biweekly briefing calls with the FAA and reported in quarterly progress reports.

Awards

None.

Student Involvement

During the reporting period of AY 2020/21, the MIT graduate student involved in this task was Joonhee Kim.

Plans for Next Period

The project team will integrate "RF by location" sensitivities in APMT in the next reporting period by extending the embedded dataset to include alternative estimates of contrail impact per unit distance and validating and calibrating the results with a comparison to literature estimates. This will result in the first reduced-order, flexible tool for rapid evaluation of aviation's contrail-related climate impacts.

References

Agarwal, A., Fritz, T. M., Sabnis, J. S., Eastham, D. S., Speth, R. L., & Barrett, S. R. H. (2021). *Global contrail radiative forcing inferred using an intermediate fidelity contrail model* [Manuscript in preparation].

Lee, D. S., Fahey, D. W., Skowron, A., Allen, M. R., Burkhardt, U., Chen, Q., Doherty, S. J., Freeman, S., Forster, P. M., Fuglestvedt, J., Gettelman, A., De León, R. R., Lim, L. L., Lund, M. T., Millar, R. J., Owen, B., Penner, J. E., Pitari, G., Prather, M. J., Sausen, R., & Wilcox, L. J. (2020). The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmospheric Environment, 117834.

Task 7 - Evaluate the Evolution of Aviation NO_x Impacts on Climate and Air Quality

Massachusetts Institute of Technology

Objective

This task aims to quantify how climate and air quality impacts of aviation emissions have changed over time, and the degree to which these changes are due to the evolution of background—rather than aviation—emissions. Continuous growth in aviation emissions has resulted in near-term impacts having greater significance relative to the expected impacts based on a "steady-state emissions" model. This has been partially explored in recent work in the context of aviation NO_x and its climate impacts only (Lee et al., 2020), suggesting that its impacts are small and uncertain relative to those of aviation CO_2 (Skowron et al., 2021). However, these analyses have neglected the air quality impacts of aviation NO_x, which previous studies have found to be substantial (Barrett et al., 2010; Cameron et al., 2017; Eastham & Barrett, 2016; Yim et al., 2015), and for which monetized damages may be of a similar order of magnitude to aviation's net climate impacts (Grobler et al., 2019). The objective of this task is to estimate quantitatively the impacts of aviation NO_x on both climate and air quality in the context of a changing atmosphere, including the latest scientific understanding of the mechanisms underlying these impacts. This is a future task of the project and will begin in the coming project year.

Research Approach

The project team will process schedule data from OAG covering the period from 1980 onward, and identify which aircraft and engine types are needed from the Base of Aircraft Data (BADA) and ICAO Aircraft Engine Emissions Databank (EEDB). Flights for each schedule year will be simulated to produce gridded estimates of fuel burn, distance flown, and aircraft emissions. Estimated fuel burn totals will be validated, and emissions for years in which schedule data are not available will be estimated by linear interpolation. Pending future funding, the team will perform a retrospective analysis to quantify how the climate and air quality impacts of aviation NO_x have evolved over time, and the degree to which this has been due to factors within, or outside of, the aviation industry's control.

Milestone

This task is planned to begin in 2022.

Major Accomplishments

None.

Publications

None.

Outreach Efforts

None.

Awards

None.

Student Involvement

None.

Plans for Next Period

During the next project period, the project team will acquire the OAG schedule data and identify surrogates for aircraft and engine types where information is not available. The feasibility of using the Aviation Environmental Design Tool (AEDT) to generate aviation emissions for each year will be evaluated. The team will also generate initial estimates for daily, gridded aircraft emissions based on schedule years.

References

Barrett, S. R. H., Britter, R. E., & Waitz, I. A. (2010). Global mortality attributable to aircraft cruise emissions. Environmental Science & Technology, *44*(19), 7736–7742. https://doi.org/10.1021/es101325r

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Skowron, A., Lee, D. S., De León, R. R., Lim, L. L., & Owen, B. (2021). Greater fuel efficiency is potentially preferable to reducing NOx emissions for aviation's climate impacts. Nature Communications, *12*(1). https://doi.org/10.1038/s41467-020-20771-3

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