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

Massachusetts Institute of Technology

Project Lead Investigator

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University Participants

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- PI: Steven R. H. Barrett
- FAA Award Number: 13-C-AJFE-MIT, Amendment No. 064
- Period of Performance: Feb. 5, 2020 to Feb. 4, 2022
- Reporting Period: Feb. 5, 2020 to Sep. 30, 2020
- 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 [*pending*].
    4. Conversion of estimated impacts into sensitivities [*pending*].
    5. Develop and update operational tools capable of quantifying environmental impacts of aviation.

Project Funding Level

$500,000 funding from FAA and $500,000 matching funds. Sources of match are approximately $109,000 from MIT, plus third-party in-kind contributions of $391,000 from NuFuels LLC.

Investigation Team

Principal Investigator:	Prof. Steven Barrett (MIT) (all Tasks)
Co-Principal Investigator:	Dr. Sebastian Eastham (MIT) (all Tasks)
Graduate Research Assistants:	Inés Sanz-Morère (MIT) (Tasks 1–3, Task 5)
	Joonhee Kim (MIT) (Task 3– 5)

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 become enablers for new use cases and business models in the aviation sector. However, the combustion emissions of these vehicles will have atmospheric impacts which differ from 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. 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) to 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 and a rapid assessment approach for assessing the impacts of supersonic aircraft will be presented.

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

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Objective

The overall objective of this task is to develop emissions inputs which 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 physics-based parameterization which could be used to generate emissions maps resulting from a given supersonic aviation scenario.

Research Approach

In order to achieve the goals outlined above, a mathematical model is necessary which can produce an estimate of emissions of key chemical species (nitrogen oxides (NO_x), sulfur oxides (SO_x), water vapor, soot, etc.) resulting from a single flight. This requires a physics-based approach. During the reporting period, the team has developed a prototype iterative model which can estimate the distribution of emissions along a supersonic aircraft flight path. This will support estimation of impacts resulting from aircraft design data provided from ASCENT Project 10, in addition to enabling perturbation analysis for plausible design and mission deviations. This prototype also incorporates engine modeling data developed under ASCENT Project 47.

Milestones

- This Task was initiated during this project year. Bi-weekly project discussions with the FAA are now underway.
- The first prototype of this model has been completed and is now undergoing refinement and testing using representative aircraft designs.
- Regular meetings between members of the ASCENT Project 58 and ASCENT Project 47 teams have been established.

Major Accomplishments

- The first prototype of a model to estimate fuel burn and emissions for a given mission under realistic constraints has been completed.

Publications

None

Outreach Efforts

Progress on all tasks was communicated during bi-weekly briefing calls with the FAA.

Awards

None

Student Involvement

During the reporting period of AY 2019/20, the MIT graduate student involved in this task was Inés Sanz-Morère.

Plans for Next Period

In the coming year, the MIT ASCENT Project 58 team will complete the prototype code described above, including integration of engine model information from ASCENT Project 47 and adaptation to incorporate the supersonic fleet results from ASCENT Project 10, as processed by the Volpe Forecasting and Economics Support Group. This is expected to result in a set of emissions maps for representative supersonic aircraft designs, covering a range of possible scenarios.

References

N/A

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 they can accurately represent impacts on critical metrics of air quality and climate. During AY 2019/20, the team conceptualized and implemented an approach to estimate stratospherically adjusted radiative forcing using the GEOS-Chem UCX chemistry transport model.

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. 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, implementation of a technique to estimate stratospherically adjusted radiative forcing (RF), rather than instantaneous RF. Work in the AY 2019/2020 period has been on Task 2b.

As implemented in GEOS-Chem by Heald et al. (2014), the standard radiative transfer code in GEOS-Chem (RRTMG) calculates only the instantaneous RF and not the stratospherically adjusted RF which has been recommended for calculations of climate-relevant forcing (Maycock et al, 2011; IPCC 2007). Stratospheric adjustment has been shown to change the net RF attributable to changes in stratospheric water vapor by around 50%, and may therefore be important to accurate calculation of the impacts of high-altitude aviation (Solomon et al 2010).

We have now implemented a scheme in GEOS-Chem which can calculate the stratospheric adjustment using the Fixed Dynamical Heating approximation (Fels, 1980). For this purpose, we use a time-marching method. We assume a quasi-steady state such that, in a given baseline scenario, stratospheric heating is in equilibrium. Following Maycock et al (2011), this can be expressed as

$$\frac{\mathrm{d}T}{\mathrm{d}t} = Q_{\mathrm{DYN}} + (Q_{\mathrm{LW}}(T,\chi) + Q_{\mathrm{SW}}(\chi)) = 0$$

where Q_{LW}, Q_{SW}, and Q_{DYN} are the longwave radiative, shortwave radiative, and dynamical heating rates, respectively, each with units of K day^{-1}. Here we assume that dynamical heating is fixed, that shortwave heating changes as a function of species concentrations χ only, and that longwave heating changes as a function of both species concentration and temperature, T.

In each of the non-baseline scenarios, the species concentrations will change from those in the baseline scenario, but the temperatures remain the same. This means that the net heating rate can become non-zero such that

$$\frac{\mathrm{d}T}{\mathrm{d}t} = Q'_{\mathrm{DYN}} + (Q'_{\mathrm{LW}}(T,\chi') + Q'_{\mathrm{SW}}(\chi')) \neq 0$$

resulting in a change in temperature over time. Under the fixed dynamical heating assumption, we assume that the dynamical heating is the same with and without the perturbation such that $Q'_{DYN} = Q_{DYN}$. We can then estimate the temperature tendency as

$$\frac{\mathrm{d}T}{\mathrm{d}t} = -\left(Q_{LW}(T,\chi) + Q_{SW}(\chi)\right) + \left(Q'_{\mathrm{LW}}(T,\chi') + Q'_{\mathrm{SW}}(\chi')\right)$$

using the longwave and shortwave heating rates from the baseline simulation.

In each perturbation simulation, we calculate the temperature tendency and then integrate forwards in time using the Runge-Kutta 4th order method with a time step of 12 hours. Only stratospheric grid cells are considered. For each calculation we allow only T to vary, and therefore only Q'_{LW} needs to be recalculated. The integration is performed independently for each model column to find the net temperature adjustment ΔT in each grid cell. Integration is stopped once the maximum temperature tendency anywhere in the stratospheric column is less than 1 mK per day, or if the integration time exceeds 150 simulation days.

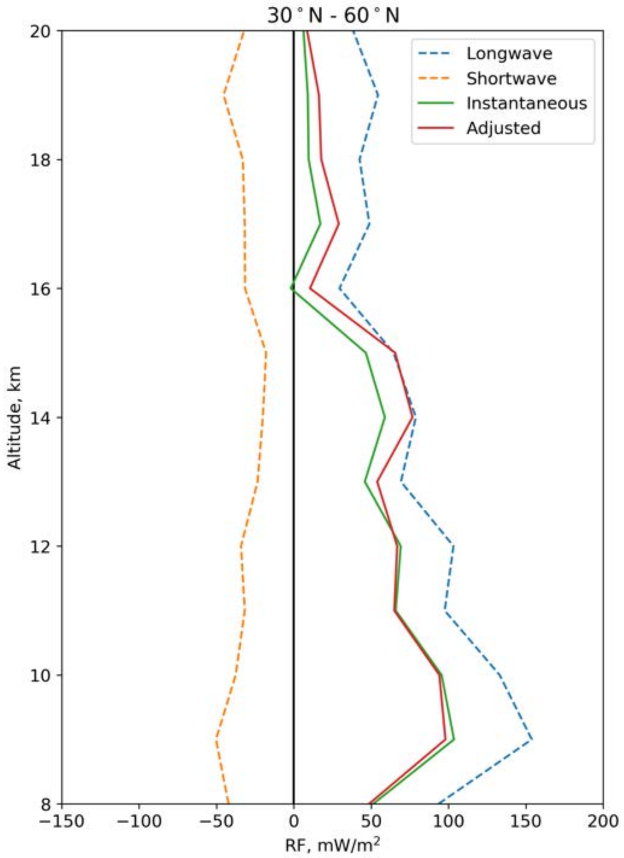

Figure 1. A comparison of the instantaneous RF components (dash), the instantaneous net RF (solid, green), and the stratospherically adjusted net RF (red) for a hypothetical contrail layer forming at a range of different altitudes.

The temperature adjustment is calculated using radiative transfer calculations including all constituents. The RF due to each constituent in a single simulation is then calculated by repeating the longwave and shortwave radiative transfer calculations with that constituent excluded. For these “excluded-constituent” calculations, the temperature adjustment is not recalculated; instead, the same temperature adjustment as was calculated for the “all-constituent” calculation is used.

Using this model, an initial assessment of the impacts of stratospheric water vapor emissions as a function of altitude has been carried out, comparing to the results from Solomon et al. (2010). We find that our results agree qualitatively with those shown in the reference paper. We also calculated the expected radiative impacts of a hypothetical contrail layer, with and without the adjustment (Figure 1).

These calculations demonstrate the importance of including stratospheric adjustment in RF calculations of higher-altitude aviation and will be used to perform all subsequent GEOS-Chem based RF calculations for ASCENT Project 58.

Milestones

- Work has begun on familiarization of the graduate student team with the core modeling tool GEOS-Chem.
- A strategy to estimate stratospherically adjusted RF was identified, implemented, and tested.

Major Accomplishments

- Stratospherically adjusted radiative forcing has been successfully implemented into the GEOS-Chem model.

Publications

None

Outreach Efforts

Progress on all tasks was communicated during bi-weekly briefing calls with the FAA.

Awards

None

Student Involvement

During the reporting period of AY 2019/20, the MIT graduate student involved in this task was Inés Sanz-Morère.

Plans for Next Period

The team will feed the new RF scheme back to the GEOS-Chem community to maximize the impact of ASCENT Project 58's work. It will also perform an evaluation of the effect of stratospheric adjustment on aviation-attributable RF, verifying its results against literature estimates. Finally, the team will begin work on Task 2a, developing and validating a high-resolution version of the GEOS-Chem UCX model.

References

Fels, S. B., Mahlman, J. D., Schwarzkopf, M. D. and Sinclair, R. W.: Stratospheric Sensitivity to Perturbations in Ozone and Carbon Dioxide: Radiative and Dynamical Response, J. Atmos. Sci., 37(10), 2265–2297, 1980.

Heald, C. L., Ridley, D. a., Kroll, J. H., Barrett, S. R. H., Cady-Pereira, K. E., Alvarado, M. J. and Holmes, C. D.: Contrasting the direct radiative effect and direct radiative forcing of aerosols, Atmos. Chem. Phys., 14(11), 5513–5527, 2014.

IPCC: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, 2007.

Maycock, a. C., Shine, K. P. and Joshi, M. M.: The temperature response to stratospheric water vapour changes, Quart. J. Roy. Meteor. Soc., 137(657), 1070–1082, 2011.

Solomon, S., Rosenlof, K. H., Portmann, R. W., Daniel, J. S., Davis, S. M., Sanford, T. J. and Plattner, G.-K.: Contributions of stratospheric water vapor to decadal changes in the rate of global warming, Science, 327(5970), 1219–1223, 2010.

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 each of the scenarios described in Task 1. This is a future task of the project and will begin in the coming project year.

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 surface air quality and exposure to UV-B. These outcomes will be estimated by performing simulations with the GEOS-Chem UCX model at the enhanced global resolution of $2^{\circ} \times 2.5^{\circ}$. The outcomes will be calculated for each emissions scenario and in each case including different assumptions regarding cruise altitude, Mach number, engine NO_x emissions index, and fuel sulfur content.

Milestones

This task is planned for a later stage in the project and has not yet begun.

Major Accomplishments

This task is planned for a later stage in the project and has not yet begun.

Publications

None

Outreach Efforts

This task is planned for a later stage in the project and has not yet begun.

Awards

None

Student Involvement

N/A

Plans for Next Period

During the next project period, the project team will perform a baseline evaluation of subsonic aviation using the updated GEOS-Chem model to enable calibration of the future results to be used with the Aviation environmental Portfolio Management Tool – Impacts Climate (APMT-IC). It will also identify (and initiate) an experimental design which enables sensitivities of climate, air quality, and ozone to be evaluated using GEOS-Chem simulations.

References

N/A

Task 4 – Conversion of 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 these results in Task 5. This is a future task of the project and will begin in the coming project year.

Research Approach

Sensitivities of each outcome will be calculated with respect to variables such as cruise altitude, Mach number, engine NO_x emissions index, and fuel sulfur content. In addition, we will determine uncertainty distributions for each sensitivity. Due to the lack of recent literature on impacts from high-altitude aviation, there is not yet a scientific consensus from which uncertainties can be derived. The methods applied for past APMT-IC calculations are subsequently not applicable. Instead, impacts calculated from GEOS-Chem for high altitude scenarios will be compared to prior NASA studies to establish the appropriate shape and bounds for each outcome sensitivity.

Milestones

This task is planned for a later stage in the project and has not yet begun.

Major Accomplishments

This task is planned for a later stage in the project and has not yet begun.

Publications

None

Outreach Efforts

This task is planned for a later stage in the project and has not yet begun.

Awards

None

Student Involvement

N/A

Plans for Next Period

During the next project period, the project team will survey the literature to establish the appropriate shape and bounds for the target set of outcome sensitivities. This will enable rapid adoption of the results generated by Task 3 into the APMT model, pending developments in Task 5.

References

N/A

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

Massachusetts Institute of Technology

Objective

This task aims to operationalize the results of Tasks 1–4. 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 which take into account the possibility of different cruise altitudes (among other characteristics).

Research Approach

This task aims to produce a more broadly capable operational tool. The broad goal of incorporating new and updated sensitivity information must first be supported by an assessment of capabilities and requirements. This task is also expected to support updates of the tool to incorporate new information on impacts of existing aviation. During AY 2019/2020, this was accomplished through two subtasks.

First, an exercise was conducted to establish the extent of modifications required for APMT-IC and APMT-AQ (an air quality version) to account for higher-altitude aviation, including the effect of perturbations to the target altitude. Second, the existing version of APMT-IC was compared to the recent Lee et al. (2020) assessment of climate impacts of aviation. A summary of this comparison is shown in Figure 2.

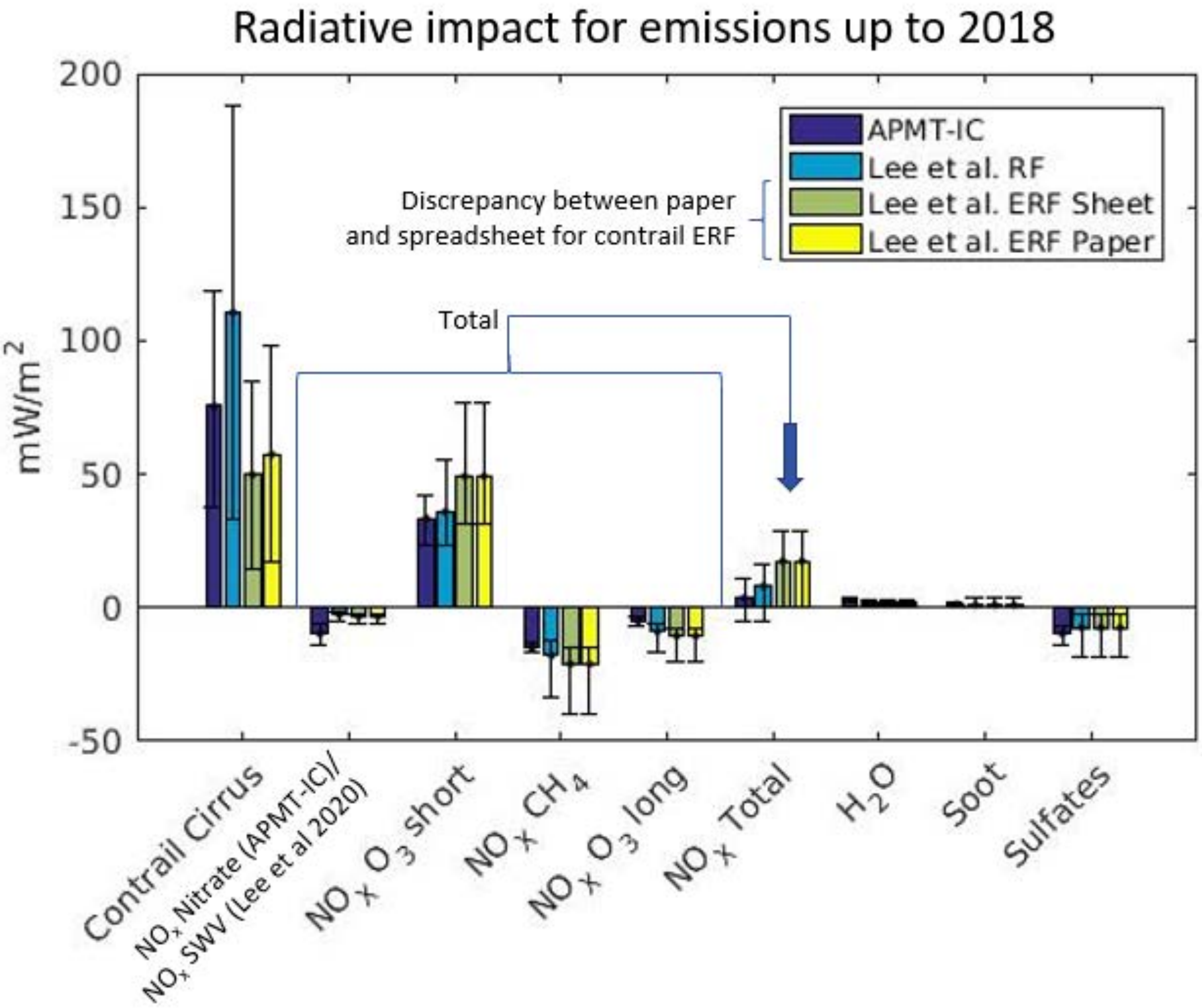

Figure 2. RF, in mW/m^2, estimated as a consequence of aviation to date using APMT-IC (dark blue) and compared to estimates from Lee et al. (2020). Results in light blue are for RF only and are most appropriate for comparison to APMT. Results in green and yellow show the “effective RF”, which includes tropospheric temperature adjustments. Two values are reported because the Lee et al. (2020) paper and supplementary information give conflicting results. The four NO_x components are summed to provide the “NO_x total” bar. SWV refers to stratospheric water vapor; SWV impacts were reported for Lee et al. (2020) but not for APMT, while nitrate formation due to NO_x is reported by APMT but not Lee et al. (2020). These are therefore provided together here for the sake of brevity.

Based on this comparison, a number of follow-up tasks—including separation of studies inside APMT-IC which estimate contrail RF from those which estimate contrail effective radiative forcing (ERF)—have been identified for future work.

Milestones

- Work has begun on familiarizing both members of the student team with APMT, including both the climate and air quality assessment components.
- An initial assessment of the modifications required for APMT to incorporate higher-altitude aviation has been completed.

Major Accomplishments

- A comparison of the Lee et al. (2020) results to those from APMT-IC has been completed.

Publications

None

Outreach Efforts

Progress on all tasks was communicated during bi-weekly briefing calls with the FAA.

Awards

None

Student Involvement

During the reporting period of AY 2019/20, the MIT graduate students involved in this task were Inés Sanz-Morère and Joonhee Kim.

Plans for Next Period

The project team will incorporate updates to APMT-IC based on the comparison to Lee et al. (2020). The team also aims to generate a development plan to enable an upgraded version of APMT to quantify climate and air quality impacts for a range of higher-altitude aviation options.

References

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. and Wilcox, L. J.: The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018, Atmos. Environ., 117834, 2020.