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

## Massachusetts Institute of Technology

## Project Lead Investigator

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## University Participants

**Massachusetts Institute of Technology (MIT)**

- P.I.: Dr. Raymond Speth
- FAA Award Number: 13-C-AJFE-MIT, Amendment Nos. 064, 089, 099, 115, 120, 128, 133, and 140
- Period of Performance: February 5, 2020, to January 20, 2026
- Tasks:
    1. Implement an improved temperature response model in Aviation Portfolio Management Tool – Impacts Climate (APMT-IC)
    2. Extend Goddard Earth Observing System (GEOS)-Chem sensitivities to regions with high current emission intensity
    3. Develop a reduced order model and parametrization of contrails for simplified climate models
    4. Conduct a robust comparison between current contrail models

## Project Funding Level

The Federal Aviation Administration (FAA) provided $2,170,000 in funding and $2,170,000 were received in matching funds. Sources of match are approximately $383,094 from MIT, plus third-party in-kind contributions of $391,000 from NuFuels, LLC, and $127,000 from Savion Aerospace Corp., and $414,000 from Google, LLC, and $854,906 from Earth Force Technologies.

## Investigation Team

Dr. Raymond Speth, (P.I.), All Tasks
Dr. Prakash Prashanth, All Tasks
Shreya Sharma, (graduate research assistant), Tasks 1-2
China Hagström, (graduate research assistant), Tasks 3-4

## Project Overview

Future aircraft technologies may include aircraft operating at higher altitudes such as commercial supersonic aircraft and high-altitude, long-endurance (HALE) unmanned aerial vehicles, which 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. Furthermore, new developments in emissions impact estimation have enabled a more nuanced view of the environmental consequences of conventional aircraft activity. This includes the recognition that both their atmospheric impacts vary depending on the prevailing conditions of the emission and the time horizon of the assessment. In ASCENT Project 058, our team is working to quantify the environmental consequences of aviation emissions, incorporating information about altitude, location, and timing.

The current project goals are as follows:

- (i) Develop and update operational tools capable of quantifying environmental impacts of aviation.
- (ii) Improve global chemical transport model (GEOS-Chem) sensitivity analysis methods for enhanced resolution.
- (iii) Develop a parametrization method for contrail models.
- (iv) Investigate the dependence of aviation emissions impacts on non-aviation factors.

## Task 1 – Implement an Improved Temperature Response Model in APMT-IC

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### Objective

The objective of this task it to align the APMT-IC with the state-of-the-art methods for deriving social cost of greenhouse gases, which includes various updates such as the surface temperature model, updated Equilibrium Climate Sensitivity and Transient Climate Response values (EPA, 2023)

### Research Approach

We implement a three-box model for the temperature response following Cummins et al. (2020). The following formulation for a temperature model with k number of boxes is used:

$$
\begin{aligned}
C_1 \frac{dT_1}{dt} &= F(t) - \kappa_1 T_1 - \kappa_2 (T_1 - T_2) + \xi(t) \\
C_2 \frac{dT_2}{dt} &= \kappa_2 (T_1 - T_2) - \kappa_3 (T_2 - T_3) \\
&\vdots \\
C_{k-1} \frac{dT_{k-1}}{dt} &= \kappa_{k-1} (T_{k-2} - T_{k-1}) - \epsilon \kappa_k (T_{k-1} - T_k) \\
C_k \frac{dT_k}{dt} &= \kappa_k (T_{k-1} - T_k)
\end{aligned}
$$

Each box *i* has a temperature $T_i$ and heat capacity $C_i$ and is coupled to adjacent boxes above and below; heat transfer coefficients $\kappa_i > 0$ determine the strength of thermal coupling between boxes *i* and $i - 1$. The heat transfer coefficient $\kappa_k$ in the equation for box $k - 1$ is multiplied by an efficacy factor $\varepsilon > 0$ to simulate variation in the effective strength of $\kappa_1$ during periods of transient (non-equilibrium) warming. The term $F(t)$ denotes radiative forcing measured at the top of the atmosphere and $\xi(t)$ is a stochastic disturbance. For a three-box model, the above equations can be simplified to write:

$$\dot{X}(t) = AX(t) + bF(t) \qquad \text{(Eq. 1)}$$

where X(t) is the vector of the temperature of the three boxes.

APMT-IC can now run three options to run the temperature-response model:

- (i) The original two-box model.
- (ii) An unconstrained three-box model: For this model, the distributions for the equilibrium climate sensitivity and transient climate response are as defined in Leach et al. (2021). These parameters are specified directly in the APMT-IC configuration file.
- (iii) A constrained three-box model: Additionally, Leach et al. (2021) introduces a constrained formulation which ensures that the selected parameters result in a distribution similar enough to the historical temperature record. This constrained formulation only affects how the input parameter samples are selected, and not the mathematical formulation of the temperature model solver. For APMT-IC, these parameters are derived using the code from Leach et al. (2021).

### Milestone

- Updated the temperature-response model in APMT-IC to a three-box model which incorporates the temperature change due to the atmosphere-ocean mixed layer, the shallow ocean layer, and the deep ocean layer which acts as a heat sink.

## Publications

None.

## Outreach Efforts

None.

## Awards

None.

## Student Involvement

The research and communication for this task were conducted primarily by Carla Grobler

## Plans for Next Period

Short-term:

- Update other parts of the climate sub-module such as the time-varying carbon dioxide ($CO_2$) sinks, as modeled in FAIR (Leach et al., 2021).
- Update the damage functions in APMT-IC to incorporate more recent studies such as an updated social cost of carbon from Rennert et al. (2022).

Long-term:

- Use the harmonized version of the APMT-IC model to derive updated climate and air quality cost metrics, such as those published in Grobler et al. (2019)

## References

EPA. (2023). *EPA Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances*. U.S. Environmental Protection Agency. https://www.epa.gov/system/files/documents/2023-12/epa_scghg_2023_report_final.pdf

Cummins, D. P., Stephenson, D. B., & Stott, P. A. (2020). Optimal Estimation of Stochastic Energy Balance Model Parameters. *Journal of Climate, 33*(18), 7909–7926, https://doi.org/10.1175/JCLI-D-19-0589.1.

Grobler et al., (2019) Marginal Climate and Air Quality Costs of Aviation Emissions. *Environmental Research Letters*, 14(11) https://doi.org/10.1088/1748-9326/ab4942

Leach, N. J., Jenkins, S., Nicholls, Z., Smith, C. J., Lynch, J., Cain, M., Walsh, T., Wu, B., Tsutsui, J., & Allen, M. R. (2021). FaIRv2. 0.0: a generalized impulse response model for climate uncertainty and future scenario exploration. *Geoscientific Model Development*, *14*(5), 3007-3036. https://doi.org/10.5194/gmd-14-3007-2021

Rennert, K., Errickson, F., Prest, B. C., Rennels, L., Newell, R. G., Pizer, W., Kingdon, C., Wingenroth, J., Cooke, R., Parthum, B., Smith, D., Cromar, K., Diaz, D., Moore, F. C., Müller, U. K., Plevin, R. J., Raftery, A. E., Ševčíková, H., Sheets, H., Stock, J. H., Tan, T., Watson, M., Wong, T. E., & Anthoff, D. (2022). Comprehensive evidence implies a higher social cost of CO2. *Nature*, *610*(7933), 687-692. https://doi.org/10.1038/s41586-022-05224-9

# Task 2 – Extend GEOS-Chem Sensitivities to Regions with High Current Emission Intensity

**Massachusetts Institute of Technology**

## Objective

The objective of this task is to extend the GEOS-Chem analysis by focusing on the specific high emission regions of South and East Asia. In addition, we evaluated the downstream air quality impacts in terms of population weighted exposure to ozone and Particulate Matter ($PM_{2.5}$), as well as the associated increase in mortalities. In addition to this, we hope to evaluate the sensitivities of these impacts to key routes and aircraft types.

## Research Approach

The International Civil Aviation Organization (ICAO) air passenger forecasts predict the Asia Pacific region to account for almost half the total share of fuel burn in 2043 (this region in 2023 only accounted for about one third of the total aviation fuel burn). For our analysis, this region is defined to be a combination of two groups of countries as defined by the world bank: (1) South Asia and (2) East Asia and Pacific. The traffic in this region was further divided into three mission sizes: short haul (<500 nmi), mid haul (>500 nmi to <2,000 nmi) and long haul (>2,000 nmi). The Aviation Emissions Inventory Code (AEIC) was used to generate the emissions inventories corresponding to each case.

GEOS-Chem High Performance (GCHP) simulations were run using these inventories and the change in surface concentration due to each case was evaluated along with the population distribution to obtain population-weighted exposure to ozone and PM2.5. This exposure was aggregated in the same regions (within the Asia set, outside the Asia set, global average) as presented in Figure 1.

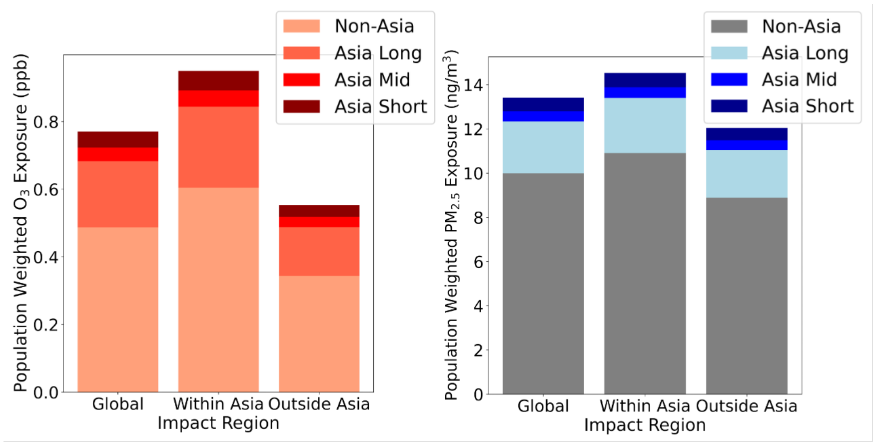

**Figure 1.** Share of population weighted ozone and $PM_{2.5}$ exposure for flights outside the Asia set (non-Asia) and the share within the Asia set (short/mid/long haul) for flights in 2019.

The largest exposure was from the non-Asia flights, followed by long haul flights in Asia. For both ozone and $PM_{2.5}$, the population weighted exposure within Asia was greater than that outside Asia. This exposure was further normalized by the total amount of fuel burned occurring in each mission size, since different types of aircraft – widebody, narrowbody, regional jets – fly in these different mission classes. The resulting data are shown in Figure 2.

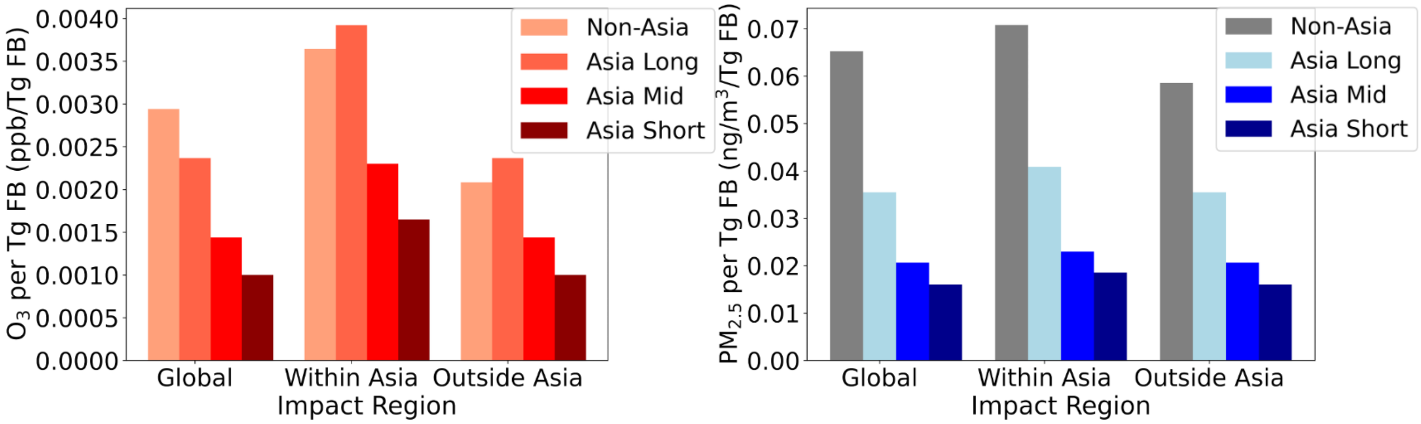

**Figure 2.** The relative population weighted ozone and $PM_{2.5}$ exposures per Tg fuel burn for flights outside the Asia set (non-Asia) and the share within the Asia set (short/mid/long haul) for flights in 2019.

When normalized by fuel burned, the non-Asia flights result in the highest exposure, and this trend is more prominent for $PM_{2.5}$ than ozone. We also find that long haul flights within Asia result in a relatively high ozone exposure within Asia.

Further, we use relative risk rates from epidemiological studies to estimate an increase in incidence rates of certain diseases like COPD, asthma, and upper respiratory infections. For ozone, we use the Turner et al. (2016) study which correlates the maximum daily 8-hour exposure to ozone, to negative health outcomes. For PM2.5, we use the GEMM (Burnett et al., 2018) meta-analysis, which is multi cohort study from 16 countries. We use data from the World Health Organization global burden of disease for this purpose. The countries with the five highest mortalities due to ozone are India, China, USA, Japan, and the UK, primarily due to high population density, and topology (ozone is more concentrated at higher altitudes). For $PM_{2.5}$, these are China, India, USA, Germany, and the UK due to similar reasons, along with a higher prevalence of precursor gases in these countries.

## Milestones

For the high emission intensity region of South and East Asia, we now have the emissions inventory, the simulated changes in surface concentration of ozone and $PM_{2.5}$, along with the population weighted exposure and country-wise share of mortalities.

## Publications

Shreya Sharma, Prakash Prashanth, Raymond Speth. Regional Differences in Surface Ozone and $PM_{2.5}$ due to Aviation in Growing Markets. ESS Open Archive. March 05, 2025. DOI: 10.22541/essoar.174120418.84924481/v1

## Outreach Efforts

None.

## Awards

None.

## Student Involvement

The research and communication for this task were conducted primarily by MIT graduate research assistant Shreya Sharma.

## Plans for Next Period

Short-term:

- Monetize the mortalities due to air quality degradation using a country-specific value of statistical life.
- Evaluate the climate impacts of these flight operations in terms of a temperature rise and use a damage function to evaluate the monetized cost.

Long-term:

- Extend a similar analysis to other global regions and different aircraft types and missions.

## References

Burnett, R., Chen, H., Szyszkowicz, M., Fann, N., Hubbell, B., Pope III, C. A., ... & Spadaro, J. V. (2018). Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter. Proceedings of the National Academy of Sciences, 115(38), 9592-9597.

Turner, M. C., Jerrett, M., Pope III, C. A., Krewski, D., Gapstur, S. M., Diver, W. R., ... & Burnett, R. T. (2016). Long-term ozone exposure and mortality in a large prospective study. American journal of respiratory and critical care medicine, 193(10), 1134-1142.

# Task 3 - Develop a Reduced Order Model and Parametrization of Contrails for Simplified Climate Models

**Massachusetts Institute of Technology**

## Objective

Contrail impacts are heavily influenced by their surrounding properties during and after formation. We find that current reanalysis estimates of the properties defining these ice supersaturated regions (ISSRs) are not in good agreement with experimental data. To quantify these effects, we compute upper and lower bounds of expected contrail radiative forcing impacts. We aim to develop reduced order models of high-resolution plume-based contrail models (Aircraft Plume

Chemistry, Emissions, and Microphysics Model [APCEMM]) and radiative transfer codes (libRadtran) which can then be used to understand the relative contribution of various uncertainty sources. Once completed, this method can be implemented as a fast surrogate for efficient contrail parametrizations in APMT-IC.

## Research Approach

Consider an example case study for an initial ISSR condition *m,* where the initial ISSR condition is defined by the relative humidity with respect to ice ($RH_i$) and moist layer depth (MLD). This simulated ISSR state is static with the exception of the wind field. Assuming cruise conditions, pressure levels are considered constant within the ISSR. For a specific mission APCEMM produces a single contrail evolution. This model provides time-resolved ice water content (IWC) and contrail width estimates for the contrail lifetime in increments of 1 min.

The incorporation of uncertainty into this case study structure requires estimation of associated uncertainty with specific ISSR baseline initial condition pairings of $RH_i$ and MLD. For an example case study with initial ISSR condition *m,* we perform multiple studies. Each study is identical except for the perturbations applied to the ISSR initial conditions. To perform these studies at lower computational cost we utilize the polynomial chaos expansion (PCE) method, a mathematical technique used to represent uncertain parameters in computational models by expanding them in terms of orthogonal polynomials. These polynomials are selected based on the probability distribution of the uncertain inputs, allowing for efficient approximation of complex stochastic systems. PCE is particularly effective for uncertainty quantification, as it provides a systematic way to propagate input uncertainties through a model while significantly reducing computational costs compared to traditional Monte Carlo methods. Additionally, PCE enables sensitivity analysis by identifying which input variables have the most influence on the model's output, thereby aiding in decision-making and optimization.

### Preliminary Results

We run the surrogate for many initial conditions varying around the baseline initial conditions. The magnitude of the variations is based on the amount of uncertainty ascribed to the initial $RH_i$ condition using the GRUAN/ERA5[1] average absolute difference. The time-resolved ice water content and contrail width results for each perturbed case study are then used as inputs to libRadtran. Each perturbed set of case studies results in an upper and lower bound estimate of the possible radiative forcing estimates for a contrail produced in an ISSR predicted by uncertain ERA5 meteorological parameters $RH_i$ and MLD. The described workflow is shown in Figure 3. Repeating this methodology for additional ISSR initial conditions provides insights into the impacts of uncertainty in ERA5 provided initial conditions on contrail properties throughout its lifetime. The processes described above have been completed for a mean $RH_i$ of 123% and a B737-800 with a CFM56 engine.

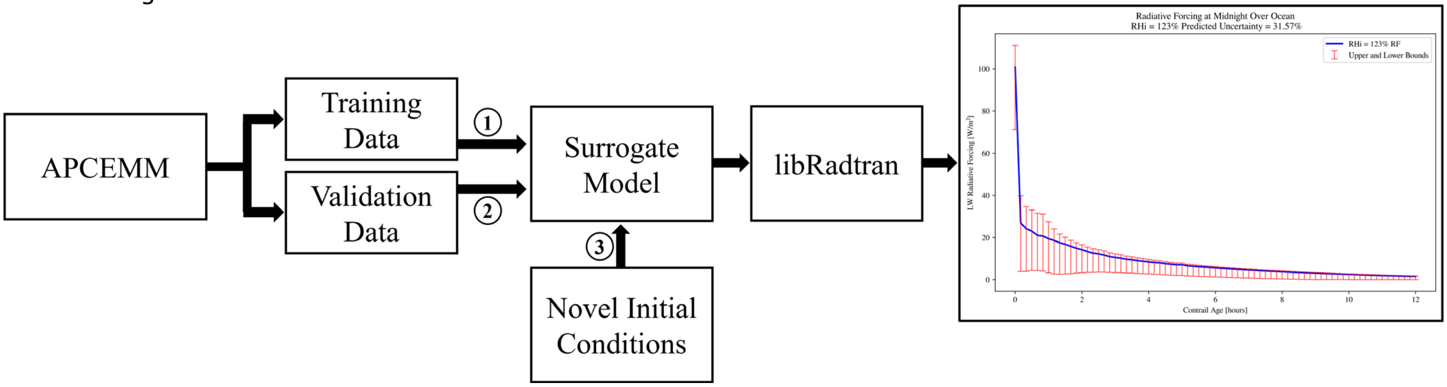

**Figure 3.** Workflow for training, validating, and utilizing a surrogate contrail model using polynomial chaos expansion (PCE) to produce an envelope of contrail radiative forcing based on uncertainty in the meteorological input data. APCEMM: Aircraft Plume Chemistry, Emissions, and Microphysics Model.

## Milestones

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[1] European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (fifth generation ECMWF atmospheric reanalysis of the global climate). Produced by the Copernicus Climate Change Service (C3S) at ECMWF, it provides hourly, high-resolution (31km) global data on atmospheric, land, and ocean-wave variables from 1940 to the present.

Developed a fast surrogate model of APCEMM using non-intrusive polynomial chaos expansion to estimate internally limited contrail width and ice water content.

## Major Accomplishments

Quantified the effects of uncertainty in APCEMM meteorological inputs on radiative forcing impacts estimates at every simulated contrail timestamp.

## Publications

None.

## Outreach Efforts

None.

## Awards

None.

## Student Involvement

The research and communication for this task were conducted primarily by MIT graduate research assistant, China G. Hagström.

## Plans for Next Period

- Include moist layer depth as stochastic variable in addition to $RH_i$.
- Scale the reported emissions of additional engines to cruise.
- Complete surrogate training for an additional seven missions.
- Process additional surrogate outputs using the libRadtran ice cloud parametrization.
- Integrate tested surrogate model into APMT-IC.

## References

None.

# Task 4 – Conduct a Robust Comparison between Current Contrail Models

**Massachusetts Institute of Technology**

## Objective

Multiple approaches to representing the property evolution of an equivalent contrail are required to satisfy computational constraints and fulfill a broad range of applications. The sensitivities of computed contrail properties to different parameterizations of the same phenomena are largely unknown and exacerbated by limited experimental data. We review the three most utilized contrail models, analyzing the differences in computed contrail properties for equivalent internally limited contrails under a variety of meteorological conditions. A contrail is defined as internally limited when the contrail ends because of internal ice evolution processes, rather than external meteorology evolving to no longer being contrail supporting (Schumann, 2016).

The models studied are the Contrail Cirrus Prediction (CoCiP) model, APCEMM, and large eddy simulations (LES) as described in Lewellen et al. (2014) parts one and two (Fritz et al., 2020; Lewellen, 2014; Lewellen et al., 2014; Schumann, 2012). Utilizing model-predicted contrail properties, comparisons of estimated radiative forcing values will be computed. Understanding the effects of different model approaches on contrail radiative forcing estimates will not only identify effective areas for model development but additionally provide recommendations for future best practices in model application, reducing uncertainty within the field.

## Research Approach

The comparison of the models is based on available data from the 2014 Lewellen LES analyses (LLES). As such the meteorological and emissions conditions for APCEMM and CoCiP were chosen to match those of the LLES studies. The LLES reports provide results for six reference contrail cases, defined by the combinations of two background relative humidities (130% and 110%) and three ambient temperatures (205 K, 218 K, and 225 K), all assuming a temperature lapse rate of 2.5 km$^{-1}$K. For each of these cases, LLES outputs are available for ice crystal number and ice mass as functions of time. Ice crystal radius distributions are reported for "cold and dry" (110% 205K) and "warm and moist" (130% 225K) cases for contrails aged 5 min to 12 hr. Contrail width and ice crystal surface area, which combined produce an estimate of integrated vertical optical depth (Lewellen, 2014), are reported for the "average" contrail condition (110% 218K). Each of these scenarios is recreated in APCEMM and CoCiP for direct comparison. We find differences in contrail properties across all cases, all contributing to differences in contrail radiative forcing. Preliminary results are described below.

**Preliminary Results**

CoCiP crystal number trends indicate that the model response is strongly affected by the initial available water content. This can be explained by the parametrization of the loss rate of ice crystal number. For a constant $RH_i$, as ambient temperatures warm the available moisture increases, and the equilibrium vapor pressure over ice increases as do diffusion rates, which increase the deposition rate of water onto ice. Crystal fall velocity and contrail depth both increase with crystal growth rate. This results in accelerated crystals losses and thereby shortens the contrail lifetime. When CoCiP's representative ice crystal falls into subsaturated air the contrail quickly disappears, underrepresenting the contrail lifetime.

APCEMM includes representations of multiple crystal sizes and allows for crystal stratification in a two-dimensional model, both of which lead to different loss functions. We find that larger crystals take up more water due to a reduced Kelvin effect and enhanced scavenging. As they grow their fall speed increases, allowing them to descend into new, moister air where smaller crystals reside. This process leaves behind smaller crystals in the original layer, which then compete less for the remaining water and therefore grow faster. However, when the contrail is ice water content limited, such as at 110% relative humidity, crystals do not grow and settle as rapidly as in the 130% case, resulting in longer lifetimes. Ice mass stays relatively constant for a period after initial water uptake, but at the expense of crystal number due to scavenging and coagulation. Additional mass is lost as a contrail ages and a subset of crystals begin interacting with subsaturated air.

The LLES approach uses similar mechanisms for ice evolution as APCEMM, presenting with similar ice mass and crystal number trends. In contrast to APCEMM the coupled aspect of temperature and velocity fields creates a buoyancy feedback loop. This may increase small crystals temporarily due to adiabatic heating resulting in more scavenging of small crystals to larger ones (Unterstrasser & Gierens, 2010). The LLES crystal radius tracking scheme may also over predict losses of small crystals, attributing losses to the Kelvin effect while also explicitly including a Kelvin effect term elsewhere. This may artificially inflate the concentration of larger crystals, reducing contrail lifetime estimates. Additionally, we see similar initial growth rates and trends to APCEMM, but lower total ice mass and faster mass loss. This mass loss may be attributed to the computational binning scheme used to track ice crystals, which does not conserve mass.

Through this analysis we contributed insights on mechanisms influencing contrail properties and lifetimes internal to the modeling approach chosen. We improved our understanding of individual model approaches to contrail dynamics and ice microphysics, and the associated downstream effects of resource-fidelity tradeoff decisions.

## Milestones

- Performed the first inter-model comparison between CoCiP, APCEMM, and LLES for equivalent contrail initial conditions.

## Major Accomplishments

- Analyzed and quantified impacts of model parametrization methodologies on computed radiative forcing values for internally limited equivalent contrail initial conditions under six bounding meteorological conditions.
- Provided previously unknown insights on mechanisms influencing contrail properties and lifetimes internal to the modeling approach chosen.
- Specifically improved understanding of individual model approaches to contrail dynamics and ice microphysics, and the associated downstream effects of computational resource-fidelity tradeoff decisions.

## Publications

None.

## Outreach Efforts

None.

## Awards

None.

## Student Involvement

The research and communication for this task were conducted primarily by MIT graduate research assistant, China G. Hagström.

## Plans for Next Period

- Introduce radiative forcing post-processing of computed contrail optical and physical properties.
- Produce additional comparisons and sensitivity analyses of microphysical inputs for CoCiP and APCEMM.
- Publish this work in a peer reviewed journal.

## References

Fritz, T., Eastham, S. D., Speth, R. L., & Barrett, S. R. H. (2020). The role of plume-scale processes in long-term impacts of aircraft emissions. *Atmospheric Chemistry and Physics, 20*(9), 5697–5727. https://doi.org/10.5194/acp-20-5697-2020

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Schumann, U. (2016). *The lifecycle and climate-impact of contrail cirrus.* European Planetary Science Congress 2016, EPSC2016-2385. https://ui.adsabs.harvard.edu/abs/2016EGUGA..18.2385S

Schumann, U. (2012). A contrail cirrus prediction model. *Geoscientific Model Development, 5*(3), 543–580. https://doi.org/10.5194/gmd-5-543-2012

Unterstrasser, S., & Gierens, K. (2010). Numerical simulations of contrail-to-cirrus transition – Part 1: An extensive parametric study. *Atmospheric Chemistry and Physics, 10*(4), 2017–2036. https://doi.org/10.5194/acp-10-2017-2010