Project 021 Improving Climate Policy Analysis Tools

Massachusetts Institute of Technology

Project Lead Investigator

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- P.I.(s): Steven R. H. Barrett
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- Task(s):
    1. Investigate efficacies of short-lived climate forcers
    2. Explore contrail and cirrus cloudiness modeling in APMT-Impacts Climate
    3. Expand alternative fuel modeling capability in APMT-Impacts Climate
    4. Improve characterization of zonal and regional climate characteristics

Project Funding Level

$300,000 FAA funding and $300,000 matching funds. Sources of match are approximately $82,000 from MIT, plus 3rd party in-kind contributions of $114,000 from Byogy Renewables, Inc and $104,000 from Oliver Wyman Group.

Investigation Team

Dr. Steven R. H. Barrett, Principal Investigator
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Project Overview

The objective of ASCENT Project 2014-21 is to facilitate continued development of climate policy analysis tools that will enable climate impacts for different policy scenarios at global, zonal and regional scales and will enable FAA to address its strategic vision on sustainable aviation growth. Following this overall objective, the particular objectives of the MIT proposal are (1) to continue the development of a rapid reduced-order climate model for policy analysis consistent with the latest literature and scientific understanding and (2) contribute to the development and use of a more complex model appropriate at finer spatial and temporal scales and to validate this model as a supplemental tool for scientific and policy analysis.

In the proposed project, we will further investigate the role of aviation short-lived forcers on the earth climate system. First, we will use the IGSM to understand how heterogeneities in the temporal, spatial, and altitudinal distribution of climate forcing radiative forcings impact the induced climate response and temperature change. Using IGSM results and results from the published literature and current research (e.g. Ponater et al. 2009) we will develop probabilistic estimates of short-lived forcer efficacies.

Second, we will continue to advance the alternative fuel modeling capability in the APMT-Impacts model, with a focus on improving non-CO_2 combustion modeling and the development of relevant metrics that go beyond current CO_2 equivalents based on Global Warming Potential (GWP). Furthermore, we will develop and apply simplified metrics for the potential climate impacts from alternative fuels to better understand alternative fuel impacts on temperature and societal damages.

Third, we will use the IGSM to better characterize the zonal and regional climate response (emissions, concentrations, radiative forcing, and temperature) of aviation-induced climate change over time. We will use these zonal and regional projections to develop a requirements document for a zonal rapid assessment tool that can be used in policy analysis.

Objective(s)

Recent research at the FAA through the Aviation Climate Change Research Initiative (ACCRI) Phase II as well as in the field at large has focused on quantifying the global bulk behavior and radiative impact of short-lived climate forcers. The objective of this work is to understand how the radiative forcing of aviation-induced climate forcers leads to temperature change. Further, the work looks to understand how reactive species, like aviation NO_x, impact longer-lived species in the atmosphere. Feedback mechanisms with other climate forcers; changes in concentrations of O_3, OH, and CH_4; and spatially-non-uniform concentrations can all impact the global climate response induced by non-CO2 emission species. This work seeks to better understand these impacts in a way that is useful for global policy analysis. Unlike the work in ACCRI Phase II, the work here seeks not to constrain the uncertainty related to the radiative forcing from short-lived species, but to better understand how the remaining uncertainty in radiative forcing impacts uncertainty in downstream impacts. The research of task 1is divided into 3 important subtasks:

1.1 Modeling the role of short-lived climate forcers in producing temperature responses, such as through quantifying equilibrium climate efficacies.
1.2 Assessing the impact of non-linear climate responses from short-lived forcers. This task focuses on the impact of projections of background concentrations of reactive species on aviation-induced ozone concentrations, an aviation climate forcer where non-linearity and system feedbacks could be expected to be significant.
1.3 Comparing the future temperature response from aviation short-lived forcers across models with different accounting for feedbacks, non-linearity, background concentrations, and efficacies.

Second, the role of aviation on producing climate forcing through direct and indirect cloudiness impacts is one of the most uncertain environmental impacts of aviation. Aviation induced cloudiness has the largest instantaneous forcing on the atmosphere, but little is known about future performance of aviation contrails or potential feedbacks with operational or technology changes in the aviation fleet. Thus, the objective of this research is to better understand how contrails and cloudiness are modeled in simplified climate tools and how these assumptions influence policy assessment.

Third, alternative fuels have the ability to mitigate some of the climate impacts of aviation if developed sustainably. However, current methods for evaluating alternative fuel impacts on the climate are incomplete focusing either on single metrics (like the Global Warming Potential CO_2 equivalent) that fail to capture the temporal evolution of the climate system or ignore several physical and chemical impacts of alternative fuel adoption such as combustion-induced short-lived forcers or biogeophysical impacts. The objective of this research is three-fold

3.1 Expand the modeling capability of alternative fuels in APMT-Impacts Climate to better capture a wide range of fuel choice options
3.2 Explore alternative metrics for quantifying and describing the climate impacts of aviation alternative fuels
3.3 Assess the potential importance of contrails in alternative fuel modeling

A final objective of this research is to assess the regional and zonal implications of the climate system. Aviation emissions are spatially and temporally non-uniform, and explaining their impact in terms of yearly integrated global averages may fail to capture the importance of these heterogeneities. Thus, while modeling approaches like APMT-Impacts Climate are important for global policy analysis, they may not be appropriate for regional analyses. Understanding the requirements for a regional model of the earth’s climate is important for future tool development.

Research Approach

Aviation NO_x emissions in the upper troposphere and lower stratosphere (UTLS) lead to ozone (O_3) formation (with an e-folding time of 2-3 months (Stevenson *et al* 2009)). Grewe *et al* (2002) estimated the increase in O_3 in the upper atmosphere to be 3-4% and 6-8% for 1990 and 2015 air traffic respectively. Khodayari *et al* (2014) computed the annual tropospheric mean O_3 perturbation from 2006 air traffic to be between 1.9% and 2.4%. These short-lived O_3 perturbations shift the tropospheric balance of hydrogen radicals (HO_x) from perhydroxyl radical (HO_2) towards hydroxyl radical (OH), thereby increasing the oxidative capacity of the atmosphere and reducing the atmospheric lifetime of methane (CH_4) by 1.4% to 3% (Khodayari *et al* 2014, Ko□hler *et al* 2008). This long-lived (11.5-14.2 years (Stevenson *et al* 2009)) effect is associated with an equally long-lived reduction in tropospheric O_3. Further, climate forcers producing identical radiative forcing may produce dissimilar globally averaged temperature impacts, which is often referred to as the efficacy of the climate forcer (Ponater 2009).

The primary approach for this task is to evaluate the earth's climate response to different levels of background emissions and aviation emissions broken down by species. Atmospheric gas concentration and temperature projections are modeled using the MIT Integrated Global System Model (IGSM) Version 2.2. The IGSM includes 33 species in the atmospheric chemistry scheme and has a horizontal resolution of 4°, with 11 vertical levels extending from the surface to 17 hPa. Full details of the model can be found in Sokolov *et al* (2005). The use of IGSM to assess the impact of atmospheric O_3 and CH_4 from aviation emissions was previously validated (Olsen *et al* 2013b), showing that IGSM's estimates of aviation's impacts falls in the middle of a range of fully coupled three-dimensional chemistry-climate models.

A 400-member Monte Carlo ensemble simulation approach is used to separate the small signal of aviation from noise and to quantify statistical uncertainty. In each of the member simulation, climate sensitivity, the rate of heat mixing into the ocean, and aerosol forcing are varied from probability distributions using Latin hypercube sampling. The design of experiment and parameter distributions follows that of Sokolov *et al* (2009).

To effectively model aviation's impact on the environment for policy analysis, fast, efficient, and robust tools are needed. A reduced-order climate model is essential for modeling aviation's impact on climate as fully-coupled models may take months to run a single deterministic projection, whereas policy-relevant results could require the modeling of hundreds of projections in a few days. Therefore, the APMT-Impacts Climate Model was developed to probabilistically project aviation's impact on climate using both physical and monetary metrics of impact. The APMT-I Climate Module adopts the impulse response modeling approach based on the work by Hasselmann et al. (1997), Sausen and Schumann (2000), and Shine et al. (2005). The module determines the climate system response by superimposing a time series of yearly impulse response curves onto prescribed background anthropogenic emissions. The aviation impacts are calculated by taking the difference of total emissions and total emissions less aviation. The temporal resolution of the APMT-I Climate Module is one year while the spatial resolution is at the global mean level. The effects modeled include long-lived CO_2, the intermediate-lived impact of NO_x on methane (NO_x-CH_4) and its associated primary mode interaction on ozone (NO_x-O_3 long), the short-lived effects of NO_x on ozone (NO_x-O_3 short), the production of aviation induced cloudiness, sulfates, soot, and H_2O. Long- and intermediate-lived radiative forcing impacts associated with yearly pulses of CO_2 and NO_x emissions decay according to their atmospheric lifetimes while the RF from short-lived effects including the warming NO_x-O_3 short effect is assumed to last only during the year of emissions.

A detailed description of past versions of the APMT-I Climate Module can be found in Marais et al. (2010), Mahashabde et al. (2011) and Wolfe (2012). Version 23 of the APMT-Impacts Climate code has three areas of improvement over past models: structural and formatting changes that aid usability and increase speed and flexibility, parameter updates to better reflect current literature and more fully account for uncertainty, and improved functionality in determining the life-cycle costs of conventional and alternative fuels. This model can then be used to examine the sensitivity of policy results to different scientific and input assumptions

Milestone(s)

The first milestone surpassed this year for Ascent-21-2014 was to assess the capability of the IGSM to project climate temperature responses and determine short-lived climate forcer efficacies from 2000 through 2100 and to provide a briefing to the FAA of the results of the project by Month 6 of the project. This milestone was achieved in February, 2015. In addition to an FAA briefing, a journal paper is in preparation as a result of this research milestone. While the paper was originally completed in Spring 2015, under guidance from the FAA, the paper is being revised to include a wider variety of NOx emissions scenarios and to include comparisons to other climate models.

The second milestone was to undergo V&V testing of the APMT-Impacts Climate v23 code with external review to produce an operational version of the climate code. At the same time, an internal development code was also developed to explore potential modeling opportunities for APMT-Impacts climate, in particular looking at expanded alternative fuel modeling capabilities and uncertain climate forcers. The APMT-Impacts Climate v23 code underwent external review in the Spring of 2015. The code was then disseminated to other research groups (such as Ascent Project 14) for use in policy analysis. The Developmental version of the APMT-Impacts climate code was first developed in the Summer of 2015 with expanded alternative fuel capabilities and exploratory approaches for new short-lived forcer relationships.

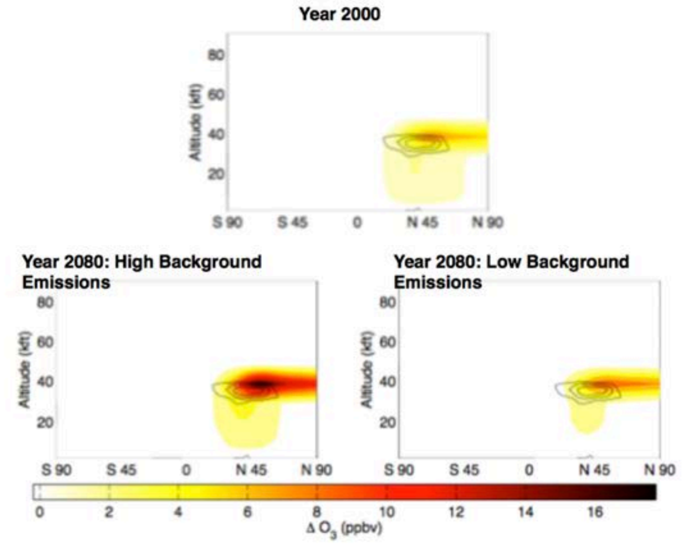
The third milestone was to provide a briefing to the FAA on short-lived climate forcers in APMT-Impacts and other models by month 9 of the project year. The Ascent 21 team first presented a briefing to FAA project leadership on developmental capabilities of the APMT-Impacts code in Fall of 2014. From this briefing, the team developed 3 presentations for the research community on APMT-Impacts v23, APMT-Impacts Development Code, and short-lived forcers and contrail research and its impact on APMT-Impacts climate. These presentations were delivered both to FAA leadership following discussions from the original briefing and then presented at the FAA Tools Seminar.

The fourth milestone was to prepare a paper on climate metrics for alternative fuels. A paper on climate metrics for alternative fuels is currently in preparation. Because the climate impact of alternative fuels is dependent on their contrail forming properties, the paper will necessarily be for internal use only until more research is published on the alternative fuel contrail properties.

A final milestone was to prepare a draft of a requirements document for the regional analyses of the climate system for aviation. The draft requirements document is a living document that will likely continuously undergo revision as the modeling needs of the FAA change and as research into aviation short-lived forcers and zonal and regional responses to aviation continues to improve and mature.

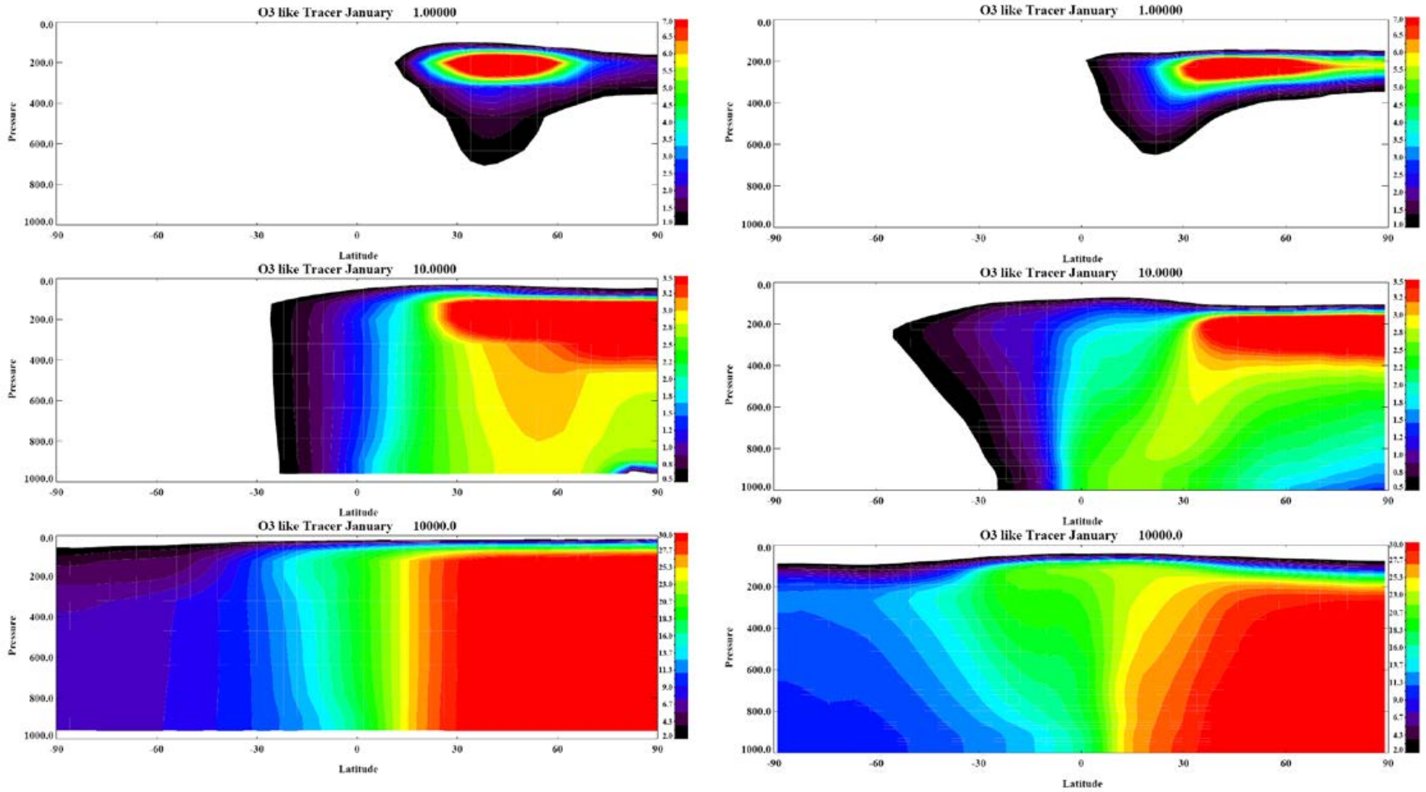
Major Accomplishments

The first major accomplishment was the quantification of short-lived forcer concentrations from aviation and their dependency on background concentrations of reactive gas species. Building on findings from the Aviation Climate Change Research Initiative (ACCRI) Phase II, the Ascent Project 21 team investigated the variability in climate response for non-CO_2 aviation species as a function of background concentrations, using different projections of emissions from literature. Because it produces impacts that persist in the atmosphere over two different timescales, aviation NOx is especially of interest for modelers as its net impact can depend upon the point of view of the modeler, and different metrics may produce impact results with different signs. Thus, aviation NOx was used to explore the role of background concentrations on short-lived forcer concentrations. Aviation NOx produces a primary response of short-lived ozone formation. However, this formation is dependent upon background concentrations of reactive gases in the atmosphere as well as the quantity and location of the aviation emissions. The impact of background emissions on ozone concentration is shown in the figure below.



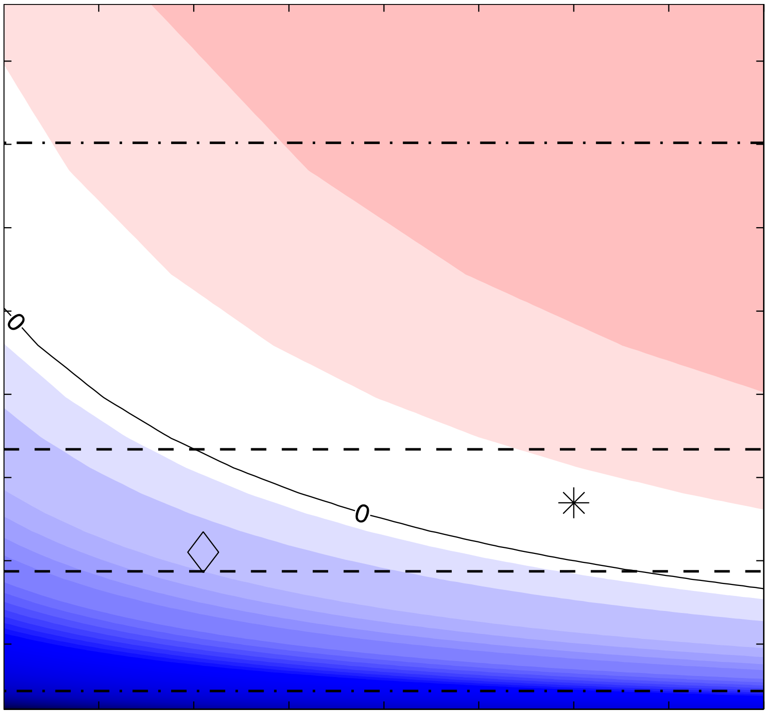
Zonal changes in concentrations of ozone from aviation emissions in year 2000 and in year 2080 under two different background scenario projections.

This work is an area of critical research need for aviation policy modeling, and the results of this work will be highly influential in determining future modeling capabilities of reduced-order policy tools. As shown in the above figure, the ozone responses from aviation emissions are highly dependent on background concentration and spatially non-uniform. As ozone is a short-lived climate warmer, the role of anthropogenic emissions in other sectors will influence the climate performance of aviation in the future. Thus, the role of aviation in climate change must be modeled for several scenarios accounting for the uncertainty in the background concentration of other species to correctly capture these feedbacks. Additional research is necessary to understand how these uncertainties will impact the costs and benefits of aviation environmental policies and decisions impacting future aviation emissions. In addition to being an important research finding in its own right, the research from Ascent 21 will serve as the necessary inputs for these future studies. Further work must be done to understand how these feedbacks and spatial performance are accounted for in other chemical-transport and climate models. A preliminary framework for this comparison was already performed as part of the validation of the IGSM for modeling aviation. For example, the dispersion performance of a NOx-Ozone-like tracer was examined for both the IGSM and GEOS-Chem as shown in the figure below. While there are notable differences in the performance of the two models, the comparison shows an agreement in the bulk transport characteristics of the two models, despite significant differences in model complexity. Future work will look at comparing additional models to the performance of the IGSM for a variety of short-lived forcers.



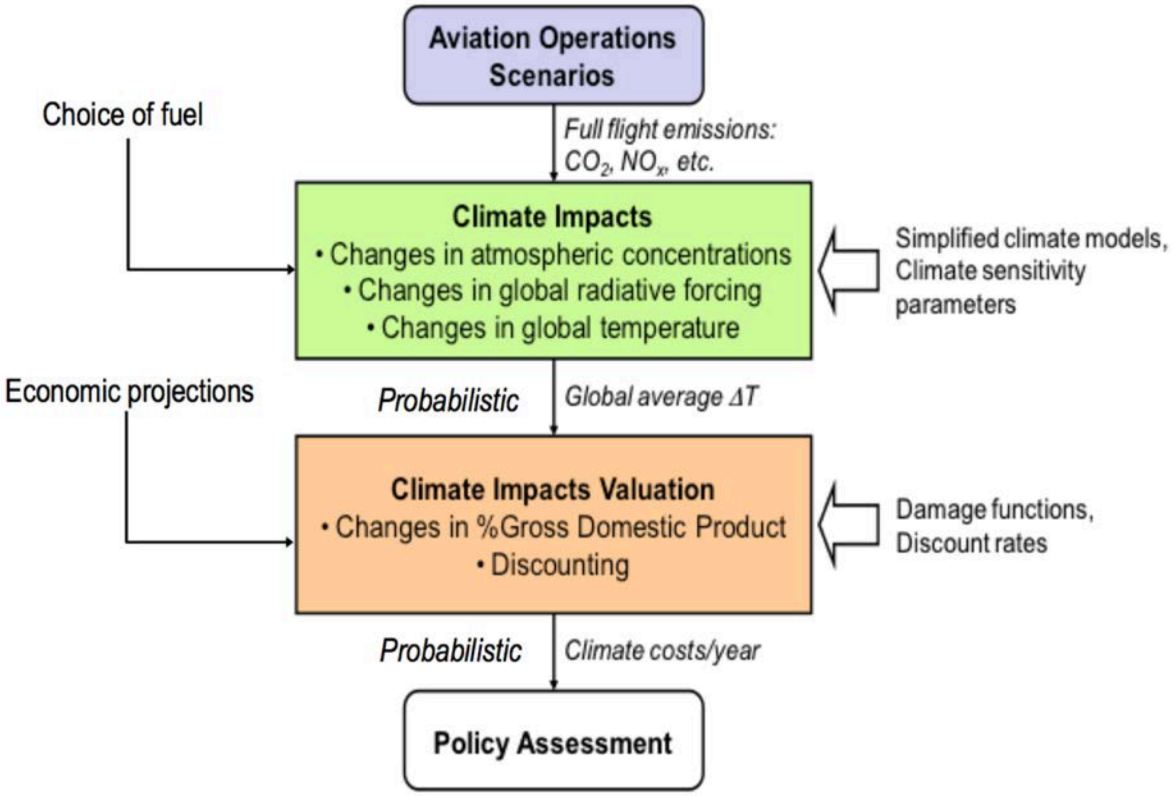
Performance of an Ozone-like tracer in IGSM (left) and Geos-Chem (right) for three different time windows.

A second accomplishment of this work has been quantifying the role of short-lived forcers on creating non-uniform responses to the climate system. The role of different climate forcers in producing non-uniform temperature impacts on the climate has been developed over the past 20 years, beginning with work by Hansen et. al (2005) in measuring the “efficaciousness” of different forcers to produce temperature change. The efficacies of aviation-specific species is highly uncertain as the climate signal of many of these forcers is small enough that integrated climate models have difficulty resolving the difference between changes in temperature from individual forcers and statistical variability. Drawing on the work of Ponater (2009), this work looked to characterize the non-uniform temperature response of climate forcers. In particular, the role of aviation NOx was examined because it leads to both cooling and warming responses Thus, while the expected radiative response of aviation NOx is positive (Holmes et al. 2012), the temperature response is dependent on the efficacies of upper-tropospheric ozone and methane. This work produced was the first to produce probabilistic projections of temperature change from aviation NOx as shown in the figure below. The dashed lines in the figure show the 1-σ range of expected radiative responses from literature for ozone and methane and the dot-dashed lines show the 2-σ range. The temperature response is then shown as a function of the ratio between the ozone and methane efficacy. The figure shows that where the efficacy of ozone is greater than efficacy of methane, the probability of a warming temperature increases. At a ratio of 1.2, there is an 84% chance of warming from aviation NOx. Alternatively, as the efficacy ratio becomes smaller, the probability of aviation NOx producing a cooling impact increases.



Contour plot of change in equilibrium non-dimensional SAT given modeled ratios between ozone (o) and methane (c) radiative forcings (F) and efficacies (r). Non-dimensional SAT is calculated by dividing the mean SAT by $(r_o \times I_o \times F_o)$. The star indicates model mean RFs from the most recent meta-analysis of aviation NO_x RF studies with assumed efficacies of unity The dashed lines show +/- 1 standard deviation from the meta-analysis model means, and the dot-dashed lines show +/-2 standard deviations. The diamond indicates the results from the present study.

A major accomplishment of the research was producing a development version of the APMT-Impacts Climate code and the transfer of the APMT-Impacts climate code v23 to different research groups at the FAA and in ASCENT. APMT-Impacts v23 was first developed under Ascent Project 21-2013 building on research of PARTNER project 46. This research indentified gaps in the current modeling approach and identified new research that improved the understanding and uncertainty quantification of aviation short-lived climate forcers. Ascent 21 interfaced and worked directly with researchers in the Aviation Climate Change Research Initiative (ACCRI) Phase II to translate recent studies on climate-forcer uncertainty into parameter inputs to simplified climate modeling codes for policy assessment. The APMT-Impacts Climate v23 code was validated from an external research panel at University of Illinois Urbana Champagne in Spring of 2015, and became the operational version of the climate code for policy analysis thereafter. Briefings to transfer code capabilities to policy research teams began in tandem with the validation and external review process to speed up adoption of the new code, particularly in analyses for ICAO-CAEP environmental policy negotiations. A functional diagram of the APMT Impacts-Climate code is shown in the figure below.



APMT-Impacts Climate Code v23 Functional Diagram

Finally, major accomplishments of this work have been exploring the sensitivity of climate results and metrics to different assumptions of short-lived climate forcer uncertainty. In particular, monetary metrics of the impact of aviation on climate change are sensitive to short-lived forcers that may not be captured in the current modeling framework. Nitrates from NOx emissions may have an additional cooling impact on the climate, whereas stratospheric water vapor may have an additional warming impact. Sensitivity analyses performed as part of Ascent Project 21 have shown that the inclusion of these short-lived forcers and their projections in the future can influence expected climate damage estimates. As a result of this work, it was proposed that future versions of the APMT-Impacts climate code (v24) include modules that estimate these impacts. However, it is important that these newer uncertain mechanisms be treated probabilistically to capture the significant uncertainty associated with them. Further, it is important for policy assessment that outputs of the APMT-Impacts Climate code distinguish between impacts that have reached a level of scientific consensus and those that represent novel pathways.

Publications

- Brasseur, et al. “Impact of Aviation on Climate: FAA’s Aviation Climate Change Research Initiative (ACCRI) Phase II.” *BAMS*. 2015.
- Jacob, D.J, P.J. Wolfe, S.R.H. Barrett, “Requirements Document for Regional Assessment of Climate.” Report.
- Wong, L. et al. “Long-term atmospheric chemistry and temperature impacts of aviation NOx” In Preparation (Revision).
- Wolfe, P.J. “Aviation Environmental Policy and Issues of Timescale.” Chapter 3: Climate Modeling. Dissertation.
- Wolfe, P.J. APMT-Impacts Climate Code Algorithm Design Document (APMT-I Climate v23). 2015. Report.

Outreach Efforts

FAA Tools Team Presentation on APMT-Impacts Climate (Fall 2014, Spring 2015)

FAA Tools Team Presentation on Short-Lived Climate Forcer Modeling (Summer 2015)
MIT Technical Communications Seminar (Spring 2015)
Ascent 14 Climate Tools Briefing (Fall 2014), Climate Modeling Briefing (Winter 2014/2015)

Awards

MIT Technical Communications Seminar Best Student Research (2015)

Student Involvement

Philip Wolfe (Ph.D. Candidate, MIT) worked primarily under tasks 2 and 4 of this work. His work focused on using the APMT-Impacts climate code and a literature review of Aviation NOx studies to understand the economic impact of NOx-induced climate change in policy tools and policy analysis. He has been the primary developer of the APMT-Impacts Climate code for the past 5 years, and has overseen the entirety of the APMT-Impacts V23 code revision, implementation, and validation and verification. Philip Wolfe graduated in September and accepted a post-doctoral research position through the MIT Department of Aeronautics and Astronautics. He will continue to be involved in Ascent research in 2015.

Lawrence Wong (Ph.D. Student, MIT) has lead IGSM applications and code implementation for Ascent Project 21. His research is in the climate impacts of short-lived climate forcers and their impact on the climate system with a focus on feedbacks and non-linearity.

Plans for Next Period

In the next period for this project, we will enhance the capabilities of the existing rapid assessment tool by developing a v24 of the APMT-Impacts Climate Code. First, we will expand the scope of the current tool to capture the tropospheric nitrate impacts and stratospheric water vapor impacts identified in the ACCRI phase 2 research. This will involve updating the code to allow for additional short-lived forcer species, to account for significant uncertainty in these “new” forcers, and scoping work to consider interactions with other short-lived forcers (such as the interaction between sulfur and nitrate emissions or the interaction between aviation-induced methane and water vapor enhancement). The resulting global rapid assessment tool will allow for more comprehensively considered impacts of aviation on climate. Further, v24 of the climate code will quantitatively consider the impact of different damage functions and physical metrics from literature. Finally, the updated code will more fully consider the life-cycle impacts of alternative fuels. Version-23 of the climate code introduced a life-cycle impact sub-model that calculates physical and economic metrics of climate damages from non-combustion emissions related to fuel choice. The v24 of the code will expand the available alternative fuel choice options to consider other alternative fuels once the required data becomes available from ASCENT Projects 1, 24a and 24b. Interim work as part of ASCENT Project 21 has characterized the time-dependence of CH_4 and N_2O emissions using reduced-order modeling techniques and anthropogenic emissions forecasts from the IPCC. For APMTv24, these models will be fully integrated into APMT to better account for the temporally heterogeneous impacts of alternative fuel life-cycle impacts. Finally, the v24 of the climate code will utilize recent research on LTO and cruise emission black carbon relationships to capture differences in combustion emissions between conventional and alternative fuels (Speth et al., 2014).

Second, we will evaluate a global 3-D model as a tool for both calibrating the rapid reduced-order model and for enhancing the understanding of aviation’s impact on the future climate. This work will explore the ability of 3-D models to resolve a statistically significant climate signal from aviation, the ability of 2-D models to be an effective proxy for 3-D models, and the role of aviation-induced climate feedbacks. This work will compare a suite of deterministic and probabilistic model outputs ranging from atmospheric chemistry to local temperature anomaly from models such as the MIT IGSM, GATOR, ModelE, and CAM. This will complement the model inter-comparison work performed as part of ACCRI phase 2 and year 1 of ASCENT project 21.

Third, we plan to further investigate the role of contrail and contrail-cirrus in aviation climate models. Recent work from ACCRI phase 2 has better constrained the current climate-related uncertainty from aviation-induced cloudiness. By constraining this uncertainty, radiative forcing, temperature projections, and economic damages from aviation have improved, resulting in a mean change in metrics of up to 15%. Further work is necessary to understand the role of contrails and cirrus cloudiness on the climate, and the impact of modeling assumptions on temperature and damage projections. The climate efficacy of contrail-induced radiative forcing, the potential of future contrail saturation changing the relationship between fuel burn and radiative forcing, and the impact of alternative fuels on contrail formation are all highly uncertain. This work will focus on exploring the physical and chemical mechanisms of contrail formation and aviation-induced cloudiness in the present and under future conditions. Further, it will explore modeling approaches for better estimating the relationship between future operations and policies and the expected coverage and radiative forcing of contrail and contrail cirrus.

Fourth, we will continue to support FAA analyses of national and global policies as they relate to climate change and environmental impacts. We will continue to provide modeling support and expertise as well as technical and analysis experience. In addition to developing and transferring a v24 of the APMT-Impacts climate model to relevant research groups, we will continue to assess policy-related co-benefits and tradeoffs, for example by continuing to support the APMT-Impacts Air Quality and APMT-Impacts Noise tools. We will continue to collaborate with the research team that will be continuing ASCENT project 20 to ensure that all emissions assumptions are consistent across policy-relevant models. We will continue to support ASCENT project 20 and ASCENT project 14 with the analysis of the international CO2 standard, whose researchers are applying ASCENT Project 21 tools in assessing the climate, air quality, and noise impacts of proposed policy options.

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