Project 021 Improving Climate Policy Analysis Tools

Final Report

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University Participants

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- PI(s): Steven R. H. Barrett, Florian Allroggen (co-PI)
- FAA Award Number: 13-C-AJFE-MIT, Amendment Nos. 004, 017, 024, 037, and 042
- Period of Performance: August 1, 2014 to August 31, 2020 (including no-cost extension)
- Consolidated tasks:
  1. Investigate regional temperature responses to aviation emissions using a global systems model and global chemistry model.
  2. Investigate the role of contrail and contrail-cirrus in aviation climate models through exploring the physical and chemical mechanisms of contrail formation and aviation-induced cloudiness.
  3. Continue development of APMT-IC, a reduced-order model capturing the climate response of aviation emissions. These tasks included:
     a. Develop APMT-IC version 24 to (1) reflect recent advances in climate research such as updated atmosphere response to non-aviation emissions; (2) model additional pathways, such as a nitrate pathway (Brasseur et al. 2016); and (3) update uncertainty distributions.
     b. Expand the capabilities of the code to model the impact of life cycle emissions of CH_4 and N_2O while accounting for each of their unique timescales.
     c. Enhance the spatial resolution of reported damages in the model.
     d. Conceptualize how regional differences in impacts, e.g. due to regional differences in aviation growth, can be captured in APMT-IC
     e. Summarize ongoing contrail research and propose a plan for development of a reduced-order contrail model in APMT-IC
     f. Use APMT-IC to derive metrics for rapid policy assessment: Prepare damage metrics which quantify the aviation-induced climate impacts of short-lived climate forcers relative to the impacts of aviation-induced CO_2 emissions.

4. Support FAA analyses of national and global policies, such as the preparation of the aircraft CO_2 standard during the ICAO CAEP/10 cycle; and the nonvolatile particulate matter standard during the ICAO CAEP/11 cycle.
5. Support and facilitate knowledge transfer to FAA-AEE and other researchers

Project Funding Level

$600,000 in FAA funding and $600,000 in matching funds. Sources of match are approximately $162,000 from Massachusetts Institute of Technology (MIT), plus third-party, in-kind contributions of $114,000 from Byogy Renewables Inc. and $324,000 from Oliver Wyman Group.

Investigation Team

Principal Investigator: Prof. Steven R. H. Barrett
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Project Overview

The objective of ASCENT Project 21 is to facilitate continued development of climate policy analysis tools that will enable impact assessments for different policy scenarios at the 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 ASCENT 21 are (1) to investigate climate response due to aviation emissions; (2) to continue the development of a reduced-order climate model for policy analysis consistent with the latest scientific understanding; and (3) to support FAA analyses of national and global policies as they relate to long-term atmospheric and environmental impacts.

During this project, these objectives were addressed through several tasks, which cover (i) the investigation of aviation's climate impacts using high-resolution physics models; (ii) the continued development of a reduced-order model for aviation's climate impacts, emulating high-resolution climate models; (iii) development of metrics for rapid assessment of aviation's climate and air quality impacts; and (iv) policy support and knowledge transfer.

Task 1 – Investigate regional temperature responses due to aviation emissions using a global system model and global chemistry model (Year 2015)

Massachusetts Institute of Technology

Objective(s)

Recent research 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 task 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-CO_2 emission species. This work 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 this task is divided into 2 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. More specifically, 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.

Research Approach

Aviation NO_x emissions in the upper troposphere and lower stratosphere (UTLS) lead to ozone (O_3) formation (with an efolding 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 volumes 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, Kohler 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 simulations, 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 the parameter distributions follow Sokolov et al. (2009).

Milestone(s)

The first milestone 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. The preliminary results of this task are documented as part of an MIT Master's Thesis.

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 aviation NO_x produces impacts that persist in the atmosphere over two different timescales, it is especially of interest for modelers as different metrics may produce impact results with different signs, depending, e.g. on the timescales considered. Here, aviation NO_x was used to explore the role of background concentrations on short-lived forcer concentrations. Aviation NO_x 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. An example of the impact of background emissions on ozone concentration is shown in Figure 1.

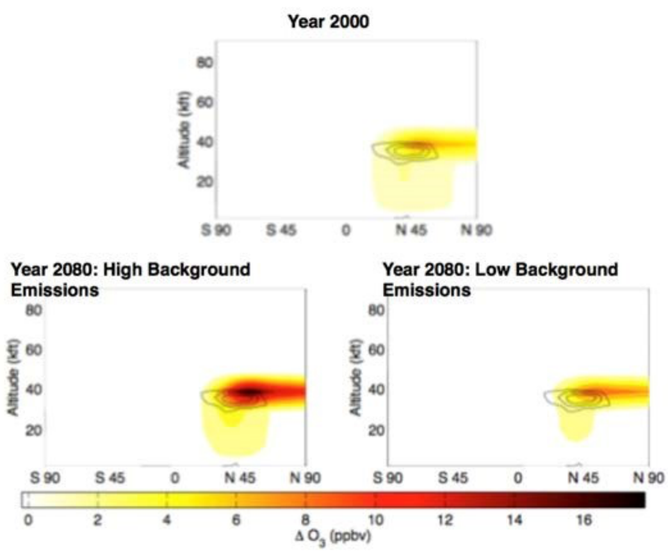

Figure 1: Exemplary representation of zonal changes in concentrations of ozone from aviation emissions in year 2000 and in year 2080 under two different background scenario projections.

Figure 1 outlines ozone responses from aviation emissions to be (1) potentially dependent on background concentration; and (2) 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. This suggests that the role of aviation in climate change should be modeled for several scenarios accounting for the uncertainty in the background concentration of other species to correctly capture these feedbacks. We note that additional research is necessary to understand how these uncertainties will impact the costs and benefits of aviation environmental policies. Further work could provide guidance on how these feedbacks and spatial performance are accounted for in other chemical transport and climate models. As an example, the ASCENT 21 team examined dispersion performance of a NO_x-Ozone-like tracer in both the IGSM and GEOS-Chem. 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. Future work would include comparing additional models to the performance of the IGSM for a variety of short-lived forcers.

As part of the second subtask, we quantified the role of short-lived forcers in 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 Hansen et al. (2005). The efficacies of aviation-specific species are 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 Ponater (2009), the ASCENT 21 team characterized the non-uniform temperature response of climate forcers. In particular, the role of aviation NO_x was examined. The findings indicate that the temperature response is dependent on the efficacies of upper-tropospheric ozone and methane.

Publications

Peer reviewed literature

- Brasseur, et al. "Impact of Aviation on Climate: FAA's Aviation Climate Change Research Initiative (ACCRI) Phase II." *BAMS*. 2015.

Reports and Theses

- Wong, L. et al., 2014. Climate impact of aviation NOx emissions : radiative forcing, temperature, and temporal heterogeneity. MIT Thesis. http://hdl.handle.net/1721.1/93802
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Shine, Keith P., et al. (2005). Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases. *Climatic Change* 68(3), 281-302.

Sokolov, Andrei P., et al. (2005). *MIT integrated global system model (IGSM) version 2: model description and baseline evaluation*. MIT Joint Program on the Science and Policy of Global Change.

Sokolov, Andrei P., et al. (2009). Probabilistic forecast for twenty-first-century climate based on uncertainties in emissions (without policy) and climate parameters. *Journal of Climate* 22(19), 5175-5204.

Wolfe, Philip James (2012). *Aviation environmental policy effects on national-and regional-scale air quality, noise, and climate impacts*. Diss. Massachusetts Institute of Technology, 2012.

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) focused on using the APMT-Impacts climate code and a literature review of Aviation NO_x studies to understand the economic impact of NO_x induced climate change in policy tools and policy analysis.
- Lawrence Wong (Ph.D. Student, MIT) led IGSM applications and code implementation for ASCENT Project 21. His research focused on the climate impacts of short-lived climate forcers and their impact on the climate system.

Task 2 – Investigate the role of contrail and contrail-cirrus in aviation climate models (Year 2016)

Massachusetts Institute of Technology

Objective(s)

Aviation-induced contrail and contrail-cirrus, referred to as aviation-induced cloudiness (AIC), have been found to potentially be the largest radiative forcing impact of aviation (Lee et al., 2009; Burkhardt and Kärcher, 2011). At the same time, AIC is one of the most uncertain environmental impacts of aviation (Burkhardt et al., 2011). Further research is needed to understand the role of AIC on the climate, and the impact of modeling assumptions on temperature and damage projections. The objective of this research is to follow and summarize the current scientific literature and to report on other research projects which aim to explore the physical and chemical mechanisms of contrail formation and aviation-induced cloudiness. This leads to threefold objectives for ASCENT 21 under this task.

2.1 Apply and support the extension of a 3D contrail model, which has been used for the US and for the global domain, and offers the potential to ultimately develop a reduced-order contrail model.
2.2 Explore how published satellite contrail observations data could be used for validation of the contrail code.
2.3 Enhance the understanding of contrail impacts from changes in engine technology and alternative fuels.

Research Approach and Accomplishments

The ASCENT 21 team has investigated the significance of contrail and contrail-cirrus to aviation climate models. More specifically, the Contrail Evolution and Radiation Model (CERM), a physically realistic 3D model of dynamical and microphysical processes from the jet phase at contrail formation to the diffusion phase as contrail-cirrus (Caiazzo, 2015), has been applied to explore the physical and chemical mechanisms of contrail formation and aviation-induced cloudiness.

The ASCENT 21 team has been trained to use CERM and supported the extension of CERM from the US domain to the global domain. This model offers the potential to facilitate the development of a reduced-order model to estimate climate impact from global contrail and contrail-cirrus. Furthermore, the ASCENT 21 team supported the development of a novel computation scheme to assess sub-grid variation in ice supersaturation in CERM. This novel scheme uses a fine set of reanalyzed meteorological data coupled with a probability density function approach to estimate the proportion of a cell that is expected to be supersaturated and to drive contrail formation and growth.

Lastly, to validate the contrail code and to further constrain the uncertainty of contrail- and contrail-cirrus-induced climate impacts, a comparison of contrail coverage, and microphysical properties between CERM modeled results and satellite observation for northern hemisphere was initiated. The work aimed at developing an extensive comparison study between observed and simulated contrails in the northern hemisphere.

Milestones

The research team delivered a comprehensive status update on modelling aviation cloudiness and contrails in Spring 2016. In the Summer of 2017, the team delivered a comprehensive status update to the FAA focusing on the impact of fuel properties and engine characteristics. Furthermore, the ASCENT 21 team has repeatedly briefed FAA on the observational contrail study conducted at MIT (not funded by FAA).

Publications

Peer-reviewed literature

Brasseur, et al. (2016). Impact of Aviation on Climate: FAA's Aviation Climate Change Research Initiative (ACCRI) Phase II. BAMS. 2016.

Outreach Efforts

ASCENT advisory board presentation (Spring 2016)

Student Involvement

Lawrence Wong (Ph.D. Student, MIT) has led research on contrail and aviation-induced cirrus for ASCENT Project 21. He supported the development of CERM and has compiled the FAA progress briefing on contrail modeling efforts at MIT. His research focused on exploring the physical and chemical mechanisms of contrail formation and aviation-induced cloudiness in the present and under future conditions.

References

Burkhardt, U., and Karcher, B. (2011). Global radiative forcing from contrail cirrus. *Nature Clim. Change* 1, 54-58.

Caiazzo, F., Agarwal, A., Speth, R., Barrett, S. (2017). Impact of biofuels on contrail warming. *Environmental Research Letters*, 12(11).

Duda, D. P., Minnis, P., Khlopenkov, K., Chee, T.L., Boeke, R. (2013). Estimation of 2006 Northern Hemisphere contrail coverage using MODIS data. *Geophysical Research Letters*, 40(3), 612-617.

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Task 3a – Development of APMT-Impacts Climate Version 24 (Year 2016-2017)

Massachusetts Institute of Technology

Motivation

To effectively model aviation's impact on the environment for policy analyses, fast, efficient, and robust tools are needed. The APMT-Impacts Climate Model was developed as a reduced-order model to probabilistically project aviation's impact on the climate using both physical and monetary impact metrics (see Figure 2 for an overview of the model structure). A detailed description of past versions of APMT-Impacts Climate can be found in Marais et al. (2010), Mahashabde et al. (2011) and Wolfe (2012). To be effective for policy analysis, this tool must be kept up to date to reflect the most recent advances in the science.

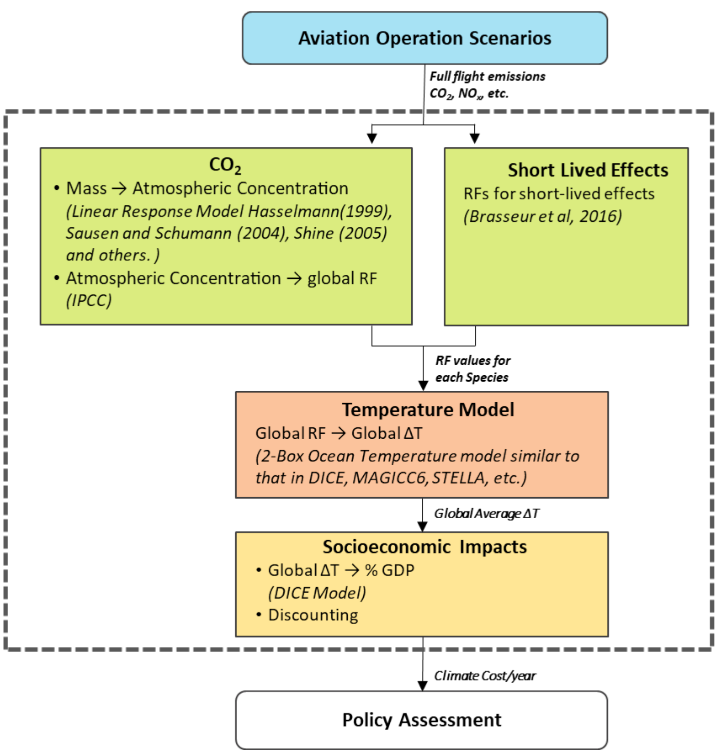

Figure 2: APMT-Impacts Climate Architecture

Objectives

As part of this task, the ASCENT 21 team focused on developing version 24 of the APMT-Impacts Climate code in an effort to update the year-2015 operational version of APMT-Impacts Climate (version 23). With the update, APMT-Impacts Climate reflects the most recent scientific consensus regarding aviation's impact on climate change. The team identified three main areas for updates:

1.1 FAA's Aviation Climate Change Research Initiative (ACCRI) Phase II (Brasseur et al., 2016) identified significant climate responses from tropospheric nitrate, which were not modeled in APMT-Impacts Climate version 23. In APMT-Impacts Climate version 24, this additional climate forcer pathway and its uncertainties are considered.

1.2 After evaluating APMT-Impacts Climate with the Office of Management and Budget (OMB), the ASCENT 21 team identified changes which will bring APMT-Impacts Climate more in line with the OMB's guidance. As a result, APMT-IC aims to produce output more consistent with the results from the US government's Interagency Working Group (IAWG)'s Social Cost of Carbon (SCC). Furthermore, a comparison between the SCC as estimated by APMT-Impacts Climate version 24 and the IAWG's SCC estimates was completed.

1.3 In order to bring APMT-Impacts Climate in line with the current consensus regarding the understanding of aviation's climate impacts, parts of the model (e.g. the modelling of atmospheric CO_2 concentrations), some uncertainty distributions (e.g. the underlying climate sensitivity distributions), and some parameter values (e.g. economic growth and inflation) needed to be updated.

Research Approach and Accomplishments

The APMT-Impacts Climate Module adopts the impulse response approach (Hasselmann et al., 1997; Sausen and Schumann, 2000; Shine et al., 2005). 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 (see Figure 2).

APMT-Impacts Climate was updated to reflect the most recent scientific understanding regarding aviation's climate impacts. These updates are outlined in the following subsections. We note that previous modeling methods have been functionally retained in APMT-Impacts Climate version 24.

Improved CO_2 Model

To model CO_2 removal from the atmosphere, APMT-I Climate version 23 uses a linear Impulse Response Function (IRF) approach, which assumes that the removal of (marginal) CO_2 emissions over time is independent of the level of CO_2 background concentrations. However, recent work (e.g. Joos et al, 2013) shows that background CO_2 concentrations alter the CO_2 removal mechanisms from the atmosphere, resulting in non-linear IRFs over time, which vary with assumed background CO_2 concentrations. To reflect this non-linearity in APMT-Impacts Climate, the tool has been updated to consider IRFs for each background CO_2 scenario as defined in the RCP scenarios and for emission pulses in different years. The IRFs applied in APMT-Impacts Climate version 24 were generated by modeling the impact of an emission pulse in a range of years between 2000 and 2500 on atmospheric CO_2 concentrations under different CO_2 background scenarios using the Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC6, Meinshausen et al. 2011). The resulting IRFs were then implemented into APMT-Impacts Climate version 24.

Equilibrium Climate Sensitivity Distribution

Equilibrium Climate Sensitivity is the expected surface-level temperature response from a doubling of atmospheric CO_2 concentrations relative to the pre-industrial atmospheric CO_2 concentrations. As such, this parameter is one of the key variables, which drives the temperature response in a reduced-order climate model like APMT-Impacts Climate. This parameter still has a large uncertainty. For example, the IPCC's most recent assessment (IPCC, 2013) reports medium confidence that this parameter is between 1.5˚C and 4.5˚C. It is driven primarily by a number of temperature feedback effects. A textbook derivation, using these feedback effects, is presented in Seinfeld and Pandis (2016). Roe and Baker (2007) put forward an uncertainty distribution for Equilibrium Climate Sensitivity based on the uncertainty in the feedback factors. This distribution has been used extensively in the literature, for example by the IAWG on the Social Cost of Carbon. To bring APMT-Impacts Climate in closer agreement with the IAWG on SCC approach, the climate sensitivity uncertainty distribution as suggested by Roe and Baker (2007) was implemented into APMT-I Climate version 24.

Improved Background Temperature Model

Previous versions of APMT-I Climate computed background temperature change within APMT-Impacts Climate by using background CO_2 emissions in combination with APMT-Impact Climate's IRF, radiative forcing model, and temperature response model. While this approach captures most of the expected background temperature change, it leads to inconsistencies to the RCP scenarios, as it does not account for (i) the temperature impact of other climate forcers such as methane, nitrous oxide, and aerosols; and (ii) the interdependencies of CO_2 IRFs with background CO_2 emissions as discussed above. To account for the additional impacts and to save computational time, MAGICC6 (Meinshausen et al., 2011) was used to generate background temperature change sequences for each RCP scenario considered in APMT-Impacts Climate. To capture the uncertainties in background temperature change, MAGICC6 was run for different values of the Climate Sensitivity parameter. The resulting look-up table of the background temperature values was then implemented into APMT-I Climate version 24. We note that APMT-Impacts Climate ensures the consistency of the underlying climate sensitivity for the background temperature change and for aviation-attributable temperature change by correlating climate sensitivity parameters to background temperature change under each RCP scenario.

Short-Lived Forcer Distributions
In APMT-I Climate, the climate impacts of short-lived forcers, caused by aviation black carbon (or soot), contrail-cirrus, stratospheric water vapor, sulfates, and nitrates, is modeled based on radiative forcing values presented in the Aviation Climate Change Research Initiative (ACCRI) Phase II report (Brasseur et al. 2016). APMT-I Climate version 23 used triangular uncertainty distributions, which were derived from the set of impact estimates for each forcer as reported in the ACCRI report. However, given the limited data available in the ACCRI report, consistently using triangular uncertainty distributions might underestimate the uncertainty for some short-lived forcers. APMT-Impacts Climate consequently uses: (i) a uniform uncertainty distribution if only two radiative forcing estimates are available for a specific short-lived forcer in the ACCRI report; and (ii) a triangular distribution if three or more radiative forcing estimates are published for a specific short-lived forcer in the ACCRI report.

Nitrate Aerosol Pathway
Estimation of aviation-induced climate impacts related to NO_x emissions requires modeling different pathways since NO_x does not follow a well-defined gas cycle model such as the carbon cycle. APMT-Impacts Climate version 23 considered three pathways of aviation NO_x-induced climate impacts: (1) the short-term (1 year) increase in tropospheric ozone concentrations, (2) the longer-term (10-12 year) decrease of methane concentrations, and (3) the longer-term (10-12 year) reduction in ozone concentrations. The Aviation Climate Change Research Initiative (ACCRI) Phase II report (Brasseur et al., 2016) presented evidence for a fourth aviation-induced NO_x pathway, the nitrate aerosols pathway. It is initiated by NO_x emissions reacting with atmospheric hydroxyl radicals to form nitric acid, which reacts with available ammonia to form nitrate aerosols. These aerosols have been found to result in cooling. To reflect the most recent scientific consensus on the aviation-induced climate impacts in APMT-Impacts Climate version 24, the nitrate cooling pathway has been added to the tool. The uncertainties associated with this pathway have been considered using the method described above.

APMT-I Climate Measure of Inflation
The Shared Socioeconomic Pathway (SSP) scenarios, used by APMT-I Climate for future GDP estimates, are defined in year-2005 USD. To convert monetary values to another year's USD values, APMT-I Climate uses inflation metrics. For this purpose, APMT-I Climate version 23 applied the Consumer Price Index. To not only capture price changes in goods for consumption, APMT-I Climate version 24 uses the GDP deflator.

Comparison to the Interagency Working Group Social Cost of Carbon
Based on feedback obtained from the OMB, APMT-Impacts Climate includes code to compute the climate costs for CO_2 emissions by using the IAWG's Social Cost of Carbon (SCC) values in addition to APMT-I Climate's climate cost estimates. The additional outputs facilitate comparisons and validation for APMT-I Climate as its results can be compared directly to estimates based on the IAWG SCC.

Validation and Verification
Internal validation and verification were performed for each one of the updates, by comparing the APMT-I Climate output before and after the updates. Furthermore, validation included detailed comparisons between the APMT-I Climate Social Cost of Carbon estimates and the IAWG Social cost of carbon.

Documentation
Documentation of APMT-Impacts Climate version 24 was completed using two documents.

1. A presentation outlining the motivation and implementation for all updates was compiled. The slide deck also provides insights into the impact of each update on result metrics.
2. The user documentation describes the version 24 model in the context of previous APMT-I Climate releases.

Together, the documentation and the presentation form the documentation for APMT-I Climate.

Milestone(s)

The first milestone of this task was to prepare a draft of the Requirements Document for the Development of APMT-Impacts Climate Version 24. This milestone was achieved in February 2016. FAA-AEE provided feedback to this document during the year. Concurrently, a developmental version of APMT-IC v23 was started to test implement some of these features, along with enhanced life cycle capabilities.

The second milestone, which entails updating the code in line with the requirements, was completed by end of July 2017.

Finally, verification, validation, and documentation were subsequently completed in August 2017. A comparison of APMT-IC to the SCC published by the IAWG was also completed by August 2017. The documentation and code were made available to the FAA in August 2017.

Publications

Reports

Wolfe, P., Barrett, S. R. H., Wong, L. M. K., Jacob, S. D. (2016). Requirements Document for Future Iterations of the Aviation Environmental Portfolio Management Tool – Impacts Climate Model, Laboratory of Aviation and the Environment.

Grobler, C., Allroggen, F., Agarwal, A., Speth, R., Staples, M., Barrett, S. (2017). APMT-I Climate version 24 Algorithm Description Document, Laboratory of Aviation and the Environment.

Peer-reviewed literature

Brasseur, et al. (2016). Impact of Aviation on Climate: FAA's Aviation Climate Change Research Initiative (ACCRI) Phase II. BAMS. 2016.

Outreach Efforts

- ASCENT advisory board presentation (Fall 2015, Spring 2016, Fall 2016, Spring 2017, and Fall 2017)
- AGU Conference: Aviation Panel Attendance (Fall 2015)
- Office of Management and Budget Briefing (Winter 2015/2016)
- Presentation of APMT-Impacts version 24 updates to FAA AEE (September 21st, 2017)
- FAA AEE Tools Coordination Meeting (Spring 2017)

Student Involvement

Before 2016, Philip Wolfe (former Ph.D. student, MIT) was the primary developer of the APMT-Impacts Climate code, and has led the entirety of the APMT-Impacts V23 code revision, implementation, and validation and verification. Philip Wolfe graduated in September 2015. During this time, he contributed towards scoping the development process of APMT-Impacts Climate Version 24.

Carla Grobler (Ph.D. Student, MIT) led the development of APMT-Impacts Climate Version 24 since Fall 2016. She completed updates, validation and verification. The model documentation was prepared by Carla Grobler, and was based on an APMT literature study by Akshat Agarwal (Ph.D. Student, MIT).

References

Brasseur, G. P., Gupta, M., Anderson, B. E., Balasubramanian, S., Barrett, S., Duda, D., ... & Halthore, R. N. (2016). Impact of Aviation on Climate: FAA's Aviation Climate Change Research Initiative (ACCRI) Phase II. *Bulletin of the American Meteorological Society 97*(4), 561-583.

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Task 3b – Modeling the life cycle impacts of methane and nitrous oxide in APMT-IC (Year 2017-2018)

Massachusetts Institute of Technology

Objective(s)

The objective of this task is to enhance the capabilities of APMT-IC in modeling the life-cycle impacts of alternative aviation fuels through adding emissions-to-impact pathways for methane and nitrous oxide (Stratton et al. 2011, Seber et al. 2014, Suresh 2016, Bond et al. 2014, Staples et al. 2014). The latest release of APMT-IC, version 24, already includes a simplified assessment module, which quantifies the life-cycle impacts in terms of 100-year global warming potential (GWP) CO_2 equivalents. Under this task, a more detailed model is developed and implemented. The new implementation improves the accuracy of APMT-IC, particularly with regard to the magnitude and timescales of life-cycle emissions scenarios. As a result, the new version of APMT-IC does not only capture the long-term atmospheric and environmental impacts of in-flight emissions, but can also be applied to evaluate life cycle-related ground-level emissions. The flexibility of this modeling method enables APMT-IC to model non-aviation methane, nitrous oxide, and carbon dioxide emissions scenarios.

Research Approach and Accomplishments

The new modeling capabilities were developed by leveraging recent work on the atmospheric response to methane and nitrous oxide (Meinshausen et al., 2011; Myhre et al., 2013). Based on this work, the impacts of the two climate forcers are modeled in APMT-IC through deriving atmospheric concentrations for all years under investigation using perturbation lifetimes (Myhre et al., 2013). More specifically, both the concentration due to the life-cycle emissions as well background concentrations are quantified, with background concentrations being taken from Representative Concentration Pathway (RCP) scenarios.

To derive the radiative forcing impacts from both methane and nitrous oxide, APMT-IC considers that both forcers lead to a direct radiative warming impact, with overlaps in radiative bands for methane, nitrous oxide, and carbon dioxide. As such, interaction effects are captured by using the radiative transfer function by Etminan et al. (2016). In addition, the indirect warming impacts of methane are computed using the methods described in Meinshausen et al. (2011). These methods capture the impacts resulting from increases in tropospheric ozone concentrations, additional stratospheric water vapor, and CO_2 impacts.

The results obtained from the APMT-IC were verified through comparisons to the literature. More specifically, impact magnitude and time responses were compared to results from the Model for Greenhouse Gas Induced Climate Change (MAGICC6) (Meinshausen et al., 2011), and the global warming potential was compared to results published in the IPCC Fifth Assessment Report (Myhre et al. 2013) and Cherubini et al. (2013). In both cases, the implemented model was found to align with results in the literature.

These additional capabilities enable APMT-IC to not only evaluate aviation life-cycle emissions scenarios, but also to evaluate non-aviation emissions scenarios for ground emissions of methane, nitrous oxide, and carbon dioxide. In addition, while the previous life-cycle modeling capability in APMT-IC was capable of capturing life-cycle impacts in accurate time scales, the current method is capable of capturing the impacts on their characteristic time scales. These new capabilities have been applied in a paper accepted for publication in GCB Bioenergy. The paper illustrates the importance of capturing the emissions time scales, especially with regard to land use change emissions.

The code documentation was updated to include these new capabilities, which will be considered to be incorporated in a potential next release of APMT-IC (version 25).

Milestone(s)
Under this task, the team successfully implemented the new capabilities into APMT-IC and presented the methods to the FAA. In addition, the novel modeling capabilities were documented in a peer-reviewed publication.

Publications
A paper titled *Using relative climate impact curves to quantify the climate impact of bioenergy production systems over time* was accepted to the journal GCB Bioenergy. The authors are Sierk de Jong, Mark Staples, Carla Grobler, Vassilis Daioglou, Robert Malina, Steven Barrett, Ric Hoefnagels, André Faaij, and Martin Junginger. FAA support under ASCENT Project 1 and ASCENT Project 21 was acknowledged.

Outreach Efforts
The modeling approach was presented at ASCENT advisory board meetings (Spring 2018 and Fall 2018).

Student Involvement
The updates, validation and verification were completed by Carla Grobler (Ph.D. Student, MIT).

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Task 3c – Enhance the spatial resolution of damages and benefits in APMT-IC (Year 2018)

Massachusetts Institute of Technology

Objective(s)

As shown by previous work, regional differences in global climate impacts can result from heterogeneities in current conditions, atmospheric responses and economic conditions, among others. For example, Tol (2009) shows that warm equatorial countries are projected to suffer the highest losses (measured as a percentage of their GDP) from climate change, while colder regions, such as eastern Europe or the former Soviet Union, might even benefit. The objective of this task is (i) to assess if there is consensus in the literature on how to derive the spatial distribution of benefits and damages; and (ii) if a suitable approach can be identified to amend APMT-IC for quantifying the distribution of global impacts.

Research Approach and Accomplishments

The Interagency Working Group on Social Cost of Greenhouse Gases used three models to quantify the global benefits and damages of a changing climate:

1. Dynamic Integrated model of Climate and the Economy (DICE) (William Nordhaus),
2. Policy Analysis of the Greenhouse Effect (PAGE) (Chris Hope with John Anderson, Paul Wenman, and Erica Plambeck),
3. Climate Framework for Uncertainty, Negotiation and Distribution (FUND) (David Anthoff and Richard Tol).

Each of these models also provides a regional break-down of benefits and damages. However, upon further investigation, no transparent documentation of the methods and assumptions for the regionalized models could be found, which is in line with the conclusions of the National Academies of Sciences (2017). Beyond that, Nordhaus (2017) compared the results of the regionalized benefit and damage models, and found little agreement in their results. As such, the ASCENT 21 team concluded that there is currently insufficient scientific consensus on these top-down quantification approaches. In turn, regionalized benefit and damage models are not recommended for implementation into APMT-IC at this point.

However, recent work by Hsiang et al. (2017) quantified the US-based damages due to global mean surface temperature increases. The study uses a bottom-up approach where global mean surface temperature is translated to county-level changes in precipitation and temperature. The resulting benefits and damages are then quantified considering both market and non-market costs or benefits in agriculture yields, mortality, energy expenditure, labor changes, coastal damages, and crime. By computing the benefits and damages for different levels of global mean surface temperature changes, a US-based damage function is derived. This damage function reasonably corresponds to the shape of the DICE damage function, although different approaches were followed to derive them.

Given reasonable similarity to DICE, the US-based damage function by Hsiang et al. (2017) was implemented into APMT-IC alongside the global damage model. As such, APMT-IC now outputs both global and U.S.-based benefits and damages.

To calculate the US-based benefits and damages, the temperature anomaly between preindustrial and the reference period used by Hsiang et al. (2017) is determined. Temperature change as modeled in APMT-IC can then be translated to temperature change for use in the US damage function and US damages can be estimated. Uncertainty at all levels of mean surface temperature is quantified by fitting continuous uncertainty distributions to the uncertainty estimates presented by Hsiang et al. for specific temperature changes. Finally, the US GDP Shared Socioeconomic pathway scenarios were incorporated into APMT-IC to infer total US-based benefits and damages.

Using this approach, we find a US-based social cost of carbon of $3 and $1 (per tonne of CO_2, 2007 USD) for aviation emissions in 2015 and for a 3% and 7% discount rate respectively. According to our results, these US-based social cost of carbon values increase to $6 and $1.8 for aviation emissions in 2050. We note that due to differences in approaches between the global and the US-based model, these results should not be used to derive US damages as a fraction of global damages. In addition, the US-based damage function does not capture indirect economic impacts, e.g, from reduced trade, migration, and conflict.

The documentation of APMT-IC was updated to include this capability and underlying assumptions. The new capabilities are considered for being incorporated in a potential next release of APMT-IC (version 25).

Milestone(s)
Modeling capabilities to compute the US benefits and damages were implemented into APMT-IC. The approach and results were presented to the FAA.

Outreach Efforts
The new modeling capability was presented at an ASCENT advisory board meeting (Fall 2018).

Student Involvement
The additional feature, and its verification and documentation were completed by Carla Grobler (Ph.D. Student, MIT).

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Task 3d – Conceptualize how regional heterogeneous aviation growth can be captured in APMT-IC (Year 2019)
Massachusetts Institute of Technology

Objective(s)
The objective of this task is to conceptualize a potential approach for increasing the spatial resolution of estimating radiative forcing (RF) impacts associated with aviation emissions in APMT-IC. Because APMT-IC is set up as a global model, global emissions are used as inputs and globally averaged results are the main output. Although this approach leads to reliable results for current-year assessments, it potentially biases results for future scenarios that assume significantly changed aircraft technologies and/or traffic patterns. More specifically, biases due to changing traffic patterns can result from heterogeneities in atmospheric sensitivities. For example, NO_x emissions are estimated to result in 4 to 5 times more tropospheric ozone formation per unit of NO_x over the Pacific compared with a unit of NO_x emissions over Europe or North America (Gilmore et al., 2013).

Research Approach
Firstly, the ASCENT 21 team preformed a literature study of the state of the art for analyzing regional heterogeneities in the radiative forcing impacts associated with aviation emissions. For this purpose, two studies were found to provide particularly relevant insights. First, Fuglestvedt et al. (2010) present a review of regionalized physical impacts and find little agreement between the regionalized temperature responses. Second, more recent work by Lund et al. (2017) analyzes regionalized global warming potential and regionalized temperature potential of aviation emissions. They find global warming and global temperature potential vary by a factor of 2-4 between different source regions. The global warming potentials by source region presented in Lund et al. (2017) can be used to derive an emissions region weighted global radiative forcing, which could, in turn be used to compute globally averaged temperature change.

As such, the second part of this task entailed conceptualizing how APMT-IC can be adapted to incorporate the results from Lund et al. (2017), to capture these regional heterogeneities in the model. The current structure of APMT-IC is presented in Figure 2. As inputs, the model requires global fuel burn, CO_2 emissions, and NO_x emissions. Subsequently, global CO_2 radiative impacts are calculated by using impulse response functions and a radiative transfer function included in the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment report (Myhre et al., 2013). The global radiative impacts of the short-lived climate forcers are calculated by scaling the radiative impacts from the aviation climate change research initiative (ACCRI) phase two report (Brasseur et al., 2016) to the global fuel burn of the emission scenario. RF is linked to temperature change through a two-box temperature model based on Berntsen and Fuglestvedt (2008). Finally, global temperature change is linked to damages using the Dynamic Integrated model of Climate and the Economy (DICE) damage function (Nordhaus, 2017).

In this task, potential changes to APMT-IC that enable capturing the impacts of regional heterogeneous growth are discussed. Because there is no evidence pointing toward regional heterogeneities of the RF impacts associated with CO_2 emissions, these changes are centered around the modeling of short-lived climate forcers. Changes are not proposed to the damage function. This is because in a previous task, the project team could not identify consensus on the reduced-order modeling of regionalized damages from regionalized temperature change (Nordhaus, 2017). Therefore, the proposed changes are constrained to linking regional emissions to global mean temperature change, which can subsequently be linked to global damages.

Milestone(s)

The literature study was completed during 2018, and the proposed concept was completed during 2019.

Major Accomplishments

First, we identified two studies with potentially relevant results. Fuglestvedt et al. (2010) presented a review of regionalized physical impacts and found little agreement between the regionalized temperature responses. Lund et al. (2017) analyzed regionalized global warming potential and regionalized temperature potential of aviation emissions. They found that global warming and global temperature potentials varied by a factor of 2 to 4 between different source regions.

The second milestone of this task was to conceptualize how the impact of different emissions regions can be accounted for in APMT-IC. The proposed structural updates are presented in Figure 3. Most importantly, the proposed modeling structure will require APMT-IC to accept precursor emissions of short-lived forcers broken down by region, where the regions are defined according Lund et al. (2017). The specified local emissions would be linked to local RF in four latitude bands by scaling the local radiative impacts to the local emissions presented by Lund et al. (2017). In turn, these local RF values will be linked to temperature change using the temperature change function and the matrix of regionalized climate sensitivities presented in Lund et al. (2017). Finally, these local temperature changes can be converted to a global mean temperature change using an area-weighted average. These steps will be taken individually for each short-lived forcer pathway. Uncertainty estimates for these parameters are presented in Lund et al. (2017) and will also be incorporated into the Monte Carlo simulation.

As a result of these changes, we expect a 17-fold increase in the number of Monte Carlo variables for each short-lived forcer. This will lead to increased run times and memory requirements. Furthermore, the current version of APMT-IC saves results from all Monte Carlo members as output, so further changes might be necessary to reduce the size of the output storage. Another potential challenge is either a loss of backward compatibility between APMT-IC versions or significant additional implementation costs and loss of flexibility in the current implementation, which result from the fundamentally different architectures. Finally, we note a potential caveat to the proposed approach results from Lund et al. (2017), who calculated their results for year-2006 emissions patterns. The proposed model will subsequently not be capable of capturing the impact of any sub-regional-scale changes in emissions, such as changes in landing and take-off (LTO) and cruise emissions fractions.

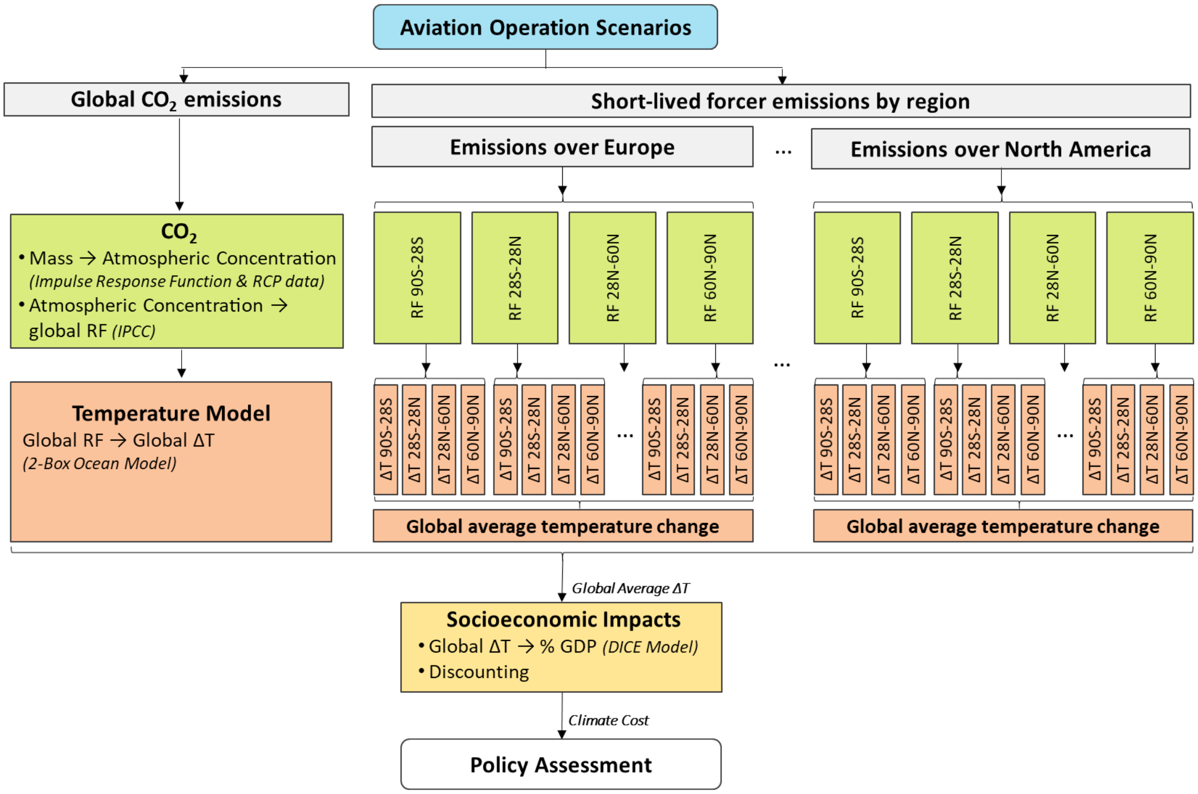

Figure 3. Conceptualization of structure for Aviation environmental Portfolio Management Tool - Impacts Climate (APMT-IC) using regionalized results from Lund et al. (2017) for one Monte Carlo member. RF, radiative forcing; ΔT, temperature change; GDP, gross domestic product; DICE, Dynamic Integrated model of Climate and the Economy.

Student Involvement

The literature study and conceptualization of methods were prepared by Carla Grobler (PhD student, MIT).

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Task 3e – Investigate state-of-the-art and reduced-order approaches for contrail and contrail-cirrus simulations (Year 2018)

Massachusetts Institute of Technology

Objective(s)

APMT-IC currently quantifies the radiative forcing impacts associated with contrails by scaling the overall impact derived in the ACCRI Phase 2 project (Brasseur et al., 2016) with fuel burn. This approach is consistent with other approaches in the literature (Fuglestvedt et al., 2010, Lund et al., 2016), but disregards a number of factors affecting contrail formation and persistence, including (i) differing geographical, diurnal, or seasonal distributions of flights, (ii) improved engine or fuel technologies, (iii) non-linearities between traffic growth and contrail formation, and (iv) changing climate conditions. As a result, if future emissions patterns differ from present day emissions, the contrail impacts will likely change without necessarily changing fuel burn numbers. The computational cost and complexity of detailed contrail models, which could consider these impacts, render such models infeasible to be included in a tool designed for informing decision-making like APMT-IC. The objective of this task is to summarize the current state of contrail research, specifically at the MIT Laboratory for Aviation and the Environment (LAE), and to work towards outlining a plan for developing a reduced-order contrail model suitable for implementation in APMT-IC.

Research Approach and Accomplishments

Aircraft condensation trails, often referred to as contrails, are line-shaped ice clouds that form in the exhaust of aircraft engines. If linear contrails persist for several hours, they can grow and evolve into large, diffuse clouds called contrail-induced cirrus or contrail cirrus clouds. Overall, contrail and contrail-cirrus are potentially the largest component of the total radiative forcing (RF) from aviation (Lee et al. 2009).

LAE conducts research to model and understand contrail properties, and to quantify their global radiative forcing impact. Modeling contrail impacts through simulation involves scales ranging from the micron level for ice crystal microphysics to the kilometer level for atmospheric bulk motion. In addition, LAE undertakes research to validate the model results by using satellite imagery to estimate contrail coverage.

A report summarizing contrail research at LAE was compiled. In addition, the factors which affect contrail properties were identified and a proposed plan for development of a reduce order contrail model was outlined.

Milestone(s)

A report outlining contrail research and a proposed approach to develop a reduced-order contrail model was finalized and handed over to the FAA. As such, this task was completed as proposed.

Publications

Internal report covering current state of contrail research and proposed plan for development of a reduced-order contrail model was compiled and made available to the FAA.

Student Involvement

The report was prepared by Carla Grobler with support from other members of LAE.

References

Brasseur, G.P., Gupta, M., Anderson, B.E., Balasubramanian, S., Barrett, S., Duda, D., Fleming, G., Forster, P.M., Fuglestvedt, J., Gettelman, A. and Halthore, R.N., 2016. Impact of aviation on climate: FAA's aviation climate change research initiative (ACCRI) phase ii. *Bulletin of the American Meteorological Society* 97 (4), 561-583.

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Task 3f – Metrics to inform rapid assessments of climate impacts for policy assessments (Year 2016-2019)

Massachusetts Institute of Technology

Objective(s)

Aircraft emission do not only impact on climate through CO_2-related impacts, but also through short-lived climate forcers such as contrails, sulfates, soot, stratospheric water vapor and other greenhouse gasses or greenhouse gas precursors such as NO_x (Brasseur et al., 2016). The climate impacts resulting from each short-lived forcer differ in magnitude and in time scale.

To facilitate rapid comparisons of the relative significance of short-lived forcers for the aviation sector, Dorbian et al. (2011) developed a method for estimating the climate impacts of the short-lived forcers relative to the climate impacts of aviation-attributable CO_2 emissions. The results of this approach can be used to compute the impacts of short-lived forcers on the basis of aviation-attributable climate damage estimates resulting from CO_2 emissions as quantified, for example, with the IAWG SCC.

However, the results in Dorbian et al. (2011) were computed using an earlier version of APMT- Impacts Climate. Since then, APMT-Impacts Climates has undergone multiple update cycles to reflect the most recent scientific understanding of the aviation-induced climate impacts in the tool. Under this task, the team aimed to create an updated set of the relative significance metrics of short-lived forcers using APMT-Impacts Climate version 24. In addition, the team computed aviation's marginal climate per tonne of species emitted during different flight stages and by emission location. In collaboration with ASCENT Project 20, air quality damages were computed accordingly.

Research Approach

In line with Dorbian et al. (2011), APMT-Impacts Climate is run for a single pulse of aviation emissions in a specific year. The impacts attributable to the emission pulse are then captured using metrics such as the Absolute Global Warming Potential (AGWP), integrated Temperature Potential (iTP), and the Net Present Value of damages (NPV). These metrics are normalized by the CO_2 impact of a unit of fuel burn, which yields the desired output metrics. In order to capture changes in the relative significance of the climate forcers over time, the method is repeated for emissions pulses occurring every 10 years, covering the period between 2015 and 2055.

Similarly, for calculating the marginal costs of emissions, the team applied APMT-IC to calculate costs for full flight emissions by running APMT-IC for an emissions pulse in 2015. Impacts per unit of precursor emissions are derived by normalizing each of the short-lived forcers by its respective precursor emissions. Full flight results are derived by using the APMT-IC model, and LTO and cruise impacts are derived by modifying the LTO and cruise RF per unit of fuel burn. LTO RF results are based on the global warming potential values for ground emissions from the IPCC report (Myhre et al., 2013), whereas cruise radiative impacts are calculated as the difference between the ACCRI (Brasseur et al., 2016) full flight radiative impacts and the LTO results. Climate results are derived for discount rates ranging from 2% to 7%.

A detailed description of the research approach can be found in the publication (see below).

Milestone(s)

A preliminary set of climate impact ratios were computed using APMT-I Climate version 23, and were shared with the FAA in February 2017. After completing APMT-Impacts Climate version 24 in the summer of 2017, an updated set of metrics has been compiled.

Results on marginal damages were derived as described above. The journal paper was prepared and submitted to *Environmental Research Letters*, where it was reviewed, accepted, and published (Grobler et al., 2019).

Publications

Peer-reviewed journal publications:

Grobler, C., Wolfe, P.J., Dasadhikari, K., Dedoussi, I.C., Allroggen, F., Speth, R.L., Eastham, S.D., Agarwal, A., Staples, M.D., Sabnis, J. & Barrett, S.R.H. (2019). Marginal climate and air quality costs of aviation emissions. *Environmental Research Letters* 14 114031. https://doi.org/10.1088/1748-9326/ab4942

Written Reports

Grobler, C., Wolfe, P., Allroggen, F., Barrett, S. (2017). Interim Derived Climate Metrics, Laboratory of Aviation and the Environment.

Outreach Efforts

A summary of the paper approach and results were presented to the FAA and a paper was presented at the Aerospace Europe conference in Bordeaux in February 2020.

Student Involvement

Carla Grobler (Ph.D. Student, MIT) conducted the research.

Awards

Carla Grobler was awarded the Joseph Hartman best student paper award for 2020 for this work.

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Dorbian, C. S., Wolfe, P. J., & Waitz, I. A. (2011). Estimating the climate and air quality benefits of aviation fuel and emissions reductions. *Atmospheric Environment 45*(16), 2750-2759.

Task 4 – Support FAA analyses of national and global policies with relation to climate change and environmental impacts (Year 2015-2019)

Massachusetts Institute of Technology

Objective(s)

As indicated in previous tasks, APMT-Impacts Climate is a rapid assessment tool for aviation climate impact assessments. Thus, it is routinely used for analyses of national and global policies affecting aviation, such as for analyses in preparation of the ICAO CAEP/8, and ICAO-CAEP/9 meetings.

The objective of this task is to support FAA analyses of national and global policies as they relate to long-term atmospheric impacts. In particular, the objective here is to ensure correct use of APMT-IC, including that inputs and outputs are handled correctly, assumptions are clearly stated, and outputs are correctly interpreted.

Research Approach and Accomplishments

Firstly, in support of the analysis for the CAEP/10 CO_2 standard, the ASCENT 21 team provided modeling and technical support to the CAEP analysis, particularly in modeling short-lived climate forcers, in developing scientific and economic lenses, and in investigating climate-noise trade-offs and co-benefits. Furthermore, the ASCENT 21 team has supported the analysis of a CO_2 standard through usability updates to APMT-Impacts and setting up more than 100 policy scenario runs of APMT-Impacts Climate and Noise. The results have been presented as part of two US Information Papers at the 10th meeting of ICAO CAEP and has been presented to the Office of Management and Budget.

Additionally, as part of the ICAO CEAP nvPM-emission standard for international aviation, APMT-IC was used to analyze the climate benefits for the different policy scenarios. Although air quality impacts will be a driver of the cost-benefit-ratio for this policy, trade-offs or co-benefits in climate are expected. While the analyses of the the nvPM standard for CAEP 11 was conducted by a dedicated project team (ASCENT Project 48), the ASCENT 21 team was tasked to assist the ASCENT 48 team

Milestones

The MIT team provided inputs and guidance when required by FAA and other research teams. This included support for the analysis of the aviation CO2 standard and the nvPM standard.

Student Involvement

For ICAO CAEP/10, Philip Wolfe (Ph.D. student, MIT) provided input to the Policy Assessments. For the ICAO CAEP/11 nvPM standard, Carla Grobler (Ph.D. student, MIT) provided support to the ASCENT 48 team.

Task 5 – Support and facilitate knowledge transfer (Year 2015-2019)

Massachusetts Institute of Technology

Objective(s)

Through transferring APMT-Impacts Climate knowledge to FAA and other research groups, the application of a standardized assessment tool for aviation’s climate impacts is encouraged.

Research Approach and Accomplishments

Transferring APMT-Impacts Climate knowledge to FAA and other research groups has been regarded as an enabler for the application of APMT-Impacts Climate for policy analyses.

Over the course of this project, various forms of knowledge transfer occurred. These included:

- Training modules covering the assumptions and operation of APMT-IC were developed and FAA staff were trained on how to use the code.
- External review of APMT-IC was conducted by the ASCENT 22 team in the spring of 2015 and again in the fall of 2017. For these reviews, the ASCENT 21 team generated comprehensive documentation, and arranged training sessions for the ASCENT 22 reviewers.
- APMT-IC was disseminated to other research groups (such as ASCENT Project 14 and ASCENT Project 48) for use in policy analysis.
- To disseminate research to a wider audience, peer reviewed journal papers were prepared (e.g.: de Jong et al 2018, and Grobler et al. 2019), as well as contributions were made to the ACCRI Phase 2 report (Brasseur et al. 2016).
- Various presentations were prepared and presented, each of which are included under the appropriate heading for each of the tasks above.

Student Involvement

Dr. Philip Wolfe, who was a student in the ASCENT 21 team until he graduated in 2015, was responsible for the knowledge transfer until 2016. Philip Wolfe graduated in September 2015.

Carla Grobler (Ph.D. Student, MIT), who has been responsible for updating APMT-Impacts Climate since 2016, has been responsible for knowledge transfer since then.