Project 021 Improving Climate Policy Analysis Tools

Massachusetts Institute of Technology

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- Tasks:
    1. Development of APMT-Impacts Climate version 24
    2. Investigation of contrail and contrail-cirrus in aviation climate models
    3. Computation of climate metrics indicating the relative importance of short-lived climate forcers
    4. Support knowledge transfer

Project Funding Level

$600,000 FAA funding and $600,000 matching funds. Sources of match are approximately $162,000 from MIT, plus 3rd party in-kind contributions of $114,000 from Byogy Renewables, Inc. and $324,000 from Oliver Wyman Group.

Investigation Team

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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 impact assessments 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 ASCENT 2014-21 are (1) to continue the development of a reduced-order climate model for policy analysis consistent with the latest scientific understanding; and (2) to support FAA analyses of national and global policies as they relate to climate change and environmental impacts.

In the current reporting period, these objectives have been addressed (i) through the development of version 24 of the APMT-Impacts Climate code to replace APMT-Impacts Climate version 23; (ii) by investigating 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; (iii) through preparing damage ratios which quantify the aviation-induced climate impacts of short-lived climate forcers relative to the impacts of aviation-induced CO_2 emissions; (iv) and by facilitating knowledge transfer to FAA-AEE and other research groups.

Task #1: Development of APMT-Impacts Climate Version 24

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Objective(s)

During the current reporting period, the ASCENT 21 team focused primarily 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 is supposed to reflect the most recent scientific consensus regarding aviation's impact on climate change. This task comprised 3 main sub-tasks:

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

1.2 After evaluating APMT-Impacts Climate with the Office of Management and Budget (OMB), APMT-Impacts Climate is supposed to be amended to produce output consistent with the results from the Interagency Working Group (IAWG)'s Social Cost of Carbon (SCC). Furthermore, the SCC as estimated by APMT-Impacts Climate version 24 are supposed to be compared to the IAWG's SCC estimates.

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) should be updated.

Research Approach and Accomplishments

For policy analyses, fast, efficient, and robust reduced-order tools are needed to effectively model aviation's impact on the climate under numerous future growth scenarios and/or policy scenarios. APMT-Impacts Climate was developed as such a reduced-order tool to probabilistically project aviation's impact on climate using both physical and monetary impact metrics. The APMT-Impacts Climate Module adopts the impulse response function approach (Hasselmann et al., 1997; Sausen and Schumann, 2000; Shine et al., 2005) to model the long-lived CO_2 impacts from aviation emissions. In addition, APMT-Impacts Climate version 23 included 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. 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). A summary of the architecture of APMT-Impacts Climate is presented in Fig. 1.

In the current reporting period, 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.

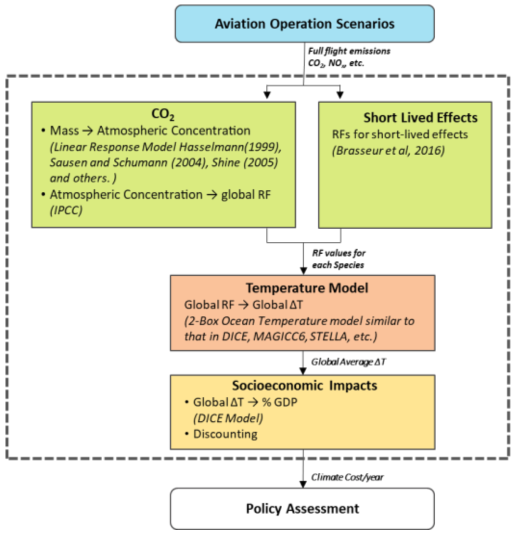

Figure 1: APMT-Impacts Climate Architecture

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. This parameter is driven primarily by a number of temperature feedback effects and 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. The distribution presented by Roe and Baker (2007) 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, to model the uncertainty associated with these impacts. 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 as 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 was 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)
Under Task 1 of ASCENT-2014-21, the APMT-Impacts Climate version 24 update was to be completed, including validation and verification of the model. The full update was completed by the end of July 2017, with individual update components becoming available earlier during the reporting period. Validation of APMT-I Climate version 24, including the comparison to the SCC published by the IAWG was subsequently completed in August 2017. The documentation and code was made available to the FAA in August 2017.

Publications
Written Reports
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.

Outreach Efforts

- ASCENT advisory board presentation (Spring 2017 and Fall 2017)
- Presentation of APMT-Impacts version 24 updates to FAA AEE (September 21st, 2017)
- FAA AEE Tools Coordination Meeting (Spring 2017)

Student Involvement

The updates, validation and verification was completed by Carla Grobler (Ph.D. Student, MIT). The documentation was prepared by Carla Grobler, and was based on an APMT literature study by Akshat Agarwal (Ph.D. Student, MIT).

Plans for Next Period

In the next year, the team will further enhance FAA's capabilities to perform rapid environmental policy assessment. In particular, the team aims to:

(1) develop capabilities to quantify the impact of life cycle emissions for different alternative fuels. Production of biofuels often results in methane and nitrous oxide emissions. The climate impacts of these emissions will be considered in APMT-Impacts Climate. As such, the model extension will facilitate comparisons of climate impacts under different alternative fuel scenarios for aviation.

(2) regionalize the damage function used within the APMT-Impacts climate framework. Currently the damage function only provides an estimate of global damages, but does not give an indication of the regional distribution of damages.

(3) assess as to whether regionalized climate sensitivities can be modeled in APMT-Impacts Climate.

References

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Task #2: Investigation of Contrail and Contrail-Cirrus in Aviation Climate Models

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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). Recent work from ACCRI Phase II has better constrained the current climate-related uncertainty from aviation-induced cloudiness. However, further work is needed to understand the role of AIC on the climate as well as to improve our understanding of the impacts of modeling assumptions on temperature and damage projections. The objective of research under Task 2 of the ASCENT 21 project is to explore the physical and chemical mechanisms of contrail formation and aviation-induced cloudiness. This leads to two sub-tasks for the current reporting period.

2.1 Apply and support the extension of a contrail model, which has been used for the US (Caiazzo et al., 2017) and, more recently, for the global domain.

2.2 Enhance the understanding of contrail impacts from changes in engine technology and alternative fuels.

Research Approach

The ASCENT 21 team is supporting the investigations of the significance of contrail and contrail-cirrus to aviation climate models. More specifically, the Contrail Evolution and Radiation Model (CERM) has been developed at MIT. This is a physically realistic 3D model that can simulate the dynamical and microphysical processes of all stages of a contrail's lifetime from initial formation to the diffusion, advection and growth into a contrail-cirrus (Caiazzo et al., 2017). This model has been and will be used to explore the physical and chemical mechanisms of aviation-induced cloudiness and to understand their impact on the climate.

The ASCENT 21 team has been trained to use CERM and is supporting the extension of CERM from the US domain to the global domain. This model, once validated, can be used to facilitate the development of a reduced-order model to estimate climate impacts from aviation-induced cloudiness on a global scale in the future.

Milestone(s)

Under Task 2 of ASCENT-2014-21, the research team delivered a comprehensive status update on modelling aviation cloudiness and contrails with a particular focus on the impact of fuel properties and engine characteristics in the summer of 2017.

Major Accomplishments

During the reporting period, the team has contributed to three accomplishments.

(1) The ASCENT 21 team is supporting the validation of the CERM code. For this purpose, the team has been working to obtain contrail coverage data for the northern hemisphere, which will be used to compare contrail coverage and microphysical properties between CERM modeled results and satellite observations. This validation will further constrain the uncertainty of contrail- and contrail-cirrus-induced climate impacts.

(2) The global implementation of the contrail model CERM relies on meteorological data which is typically only available on 2° x 2.5° resolution, particularly for future forecasts. This resolution is too coarse for accurately modeling contrails. To solve this problem, research at MIT has set out to develop an approach that attempts to model sub-grid scale variations by statistically analyzing 1 year of fine meteorological data at a 0.25° x 0.3125° resolution. The ASCENT 21 team has supported these efforts and has briefed FAA on progress of these efforts.

(3) Future engine and fuel technologies impact on contrail formation and contrail properties. Biofuels, for example, reduce PM number emissions by more than half thereby decreasing the contrail-related climate impacts, but increase water emissions which leads to an increase in contrail formation. In addition, engines with higher fuel efficiency might reduce CO_2 emissions, but are also more likely to create contrails. The ASCENT 21 team has briefed FAA on current modeling efforts by MIT researchers to analyze these trade-offs.

Outreach Efforts

- ASCENT advisory board presentation (Spring 2017)
- FAA AEE Tools Coordination Meeting (Spring 2017)

Student Involvement
Lawrence Wong (Ph.D. Student, MIT) has supported the development of CERM and has compiled the FAA progress briefing on contrail modeling efforts at MIT. Akshat Agarwal (Ph.D. Student, MIT) and Ines Sanz Morère (Ph.D. Student, MIT) have further supported the team, particularly while briefing the FAA on the effects of alternative fuels and of engine efficiency on contrail-related climate impact.

Plans for Next Period
During the next period, the team aims to support the validation of the contrail modeling efforts at MIT. In particular, a comparison study between observed and simulated contrails is currently being ramped up. This project will compare contrail coverage as modeled using CERM to the satellite data as analyzed by Duda et al. (2013) and a novel computational approach for identifying contrail cirrus from satellite imagery.

Furthermore, the team will observe ongoing research on improving CERM, for example with regards to improving the accuracy of the radiative forcing effects of contrails which overlap with other contrails or with natural cirrus clouds.

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

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Task #3: Computation of Climate Metrics Indicating the Relative Importance of Short-lived Climate Forcers
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 the 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 also 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 Task 3 of the ASCENT Project 21, the team aimed to create an updated set of the relative significance metrics of short-lived forcers using APMT-Impacts Climate version 24.

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 and the impacts attributable to the emission pulse are 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 then 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.

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.

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

Student Involvement
Carla Grobler (Ph.D. Student, MIT) computed the ratios and documented the results.

Plans for Next Period
During the next period, the team intends to prepare an assessments of the climate cost per unit of emission species, which can guide future first-order assessments of policies and novel technologies which change the composition of aviation emissions.

References
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 Knowledge Transfer
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.

Milestone(s)
Training has been provided to researchers as needed, including tools training for UIUC to review climate code capabilities (Fall 2017).

Student Involvement
Carla Grobler (Ph.D. Student, MIT), who has been responsible for updating APMT-Impacts Climate to version 24, has transferred APMT-Impacts Climate to FAA and UIUC.

Plans for Next Period
The ASCENT 21 team will provide coaching on APMT-Impacts Climate as requested.