Project 021 Improving Climate Policy Analysis Tools

Massachusetts Institute of Technology

Project Lead Investigator

PI: Steven R. H. Barrett
Raymond L. Bisplinghoff Professor of Aeronautics and Astronautics
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology
77 Massachusetts Avenue, 33-316
Cambridge, MA 02139
+1 (617) 452-2550
sbarrett@mit.edu

co-PI: Florian Allroggen
Research Scientist
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology
77 Massachusetts Avenue, 33-115A
Cambridge, MA 02139
+1 (617) 715-4472
fallrogg@mit.edu

University Participants

Massachusetts Institute of Technology

- P.I.: 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: Aug. 1, 2014 to Aug. 31, 2020
- Tasks:
    1. Modeling the life-cycle impacts of methane and nitrous oxide;
    2. Enhance the spatial resolution of damages and benefits in APMT-IC;
    3. Analyze approaches for modeling physical impacts at increased spatial resolution in APMT-IC;
    4. Investigate state-of-the-art and reduced-order approaches for contrail and contrail-cirrus modeling;
    5. 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

Prof. Steven R. H. Barrett, Principal Investigator
Dr. Florian Allroggen, co-PI
Dr. Raymond Speth, co-I
Dr. Mark Staples, co-I
Dr. Sebastian Eastham
Carla Grobler (Ph.D. Student)

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 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 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 long-term atmospheric and environmental impacts.

In the current reporting period, these objectives have been addressed by: (i) extending the capabilities of the Aviation environmental Portfolio Management Tool – Impacts Climate (APMT-IC), specifically to assess the aviation fuel life-cycle impacts associated with life-cycle emissions of N_2O and CH_4; (ii) enhancing the spatial resolution of reported damages in the model; (iii) performing research investigating the regionalization of the physical atmospheric impacts; (iv) summarizing ongoing contrail research and propose a plan for development of a reduced-order contrail model; (v) facilitating knowledge transfer to FAA-AEE and other researchers.

Task 1 – Modeling the Life-cycle Impacts of Methane and Nitrous Oxide

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 which 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 also 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). On the basis of 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 and 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, the model implemented in APMT-IC now 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 newly implemented model 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 already 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 used in a publication. As such, Task 1 was completed.

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, 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).

Plans for Next Period
During the next period, the literature will be surveyed continuously for updated methods and data.

References

Bond, J; Upadhye, A; Olcay, H; Tompsett, G; Jae, J; Xing, R; Alonso, D; Wang, D; Zhang, T; Kumar, R; Foster, A; Sen, S; Maravelias, C; Malina, R; Barrett, S; Lobo, R; Wyman, C; Dumesic, J; Huber, G. (2014). Production of renewable jet fuel range alkanes and commodity chemicals from integrated catalytic processing of biomass. *Energy & Environmental Science* 7(4), 1500-1523.

Cherubini, F., Bright, R.M. and Strømman, A.H., 2013. Global climate impacts of forest bioenergy: what, when and how to measure? *Environmental Research Letters* 8(1), p.014049.

Etminan, M. et al. (2016). Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. *Geophysical Research Letters* 43(24), pp. 614–623. doi: 10.1002/2016GL071930.

Meinshausen, M., Raper, S. C. B. and Wigley, T. M. L. (2011). Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 - Part 1: Model description and calibration. *Atmospheric Chemistry and Physics* 11(4), pp. 1417–1456. doi: 10.5194/acp-11-1417-2011.

Myhre, G. et al. (2013). Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I', in Stocker, T. F. et al. (eds) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Seber, G., Malina, R., Pearlson, M. N., Olcay, H., Hileman, J. I., & Barrett, S. R. (2014). Environmental and economic assessment of producing hydroprocessed jet and diesel fuel from waste oils and tallow. *Biomass and Bioenergy* 67, 108-118.

Staples, M. D., Malina, R., Olcay, H., Pearlson, M. N., Hileman, J. I., Boies, A., & Barrett, S. R. (2014). Lifecycle greenhouse gas footprint and minimum selling price of renewable diesel and jet fuel from fermentation and advanced fermentation production technologies. *Energy & Environmental Science* 7(5), 1545-1554.

Stratton, R. W., Wong, H. M., & Hileman, J. I. (2011). Quantifying variability in life cycle greenhouse gas inventories of alternative middle distillate transportation fuels. *Environmental Science & Technology* 45(10), 4637-4644.

Suresh, P. (2016). Environmental and economic assessment of transportation fuels from municipal solid waste. SM Thesis, Massachusetts Institute of Technology.

Task 2 – Enhance the Spatial Resolution of Damages and Benefits in APMT-IC

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 provide 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 project 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 then 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 time period used by Hsiang et al. (2017) is determined. Using this data, temperature change as modeled in APMT-IC can 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 in an effort 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 will be 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. As such, Task 2 is completed.

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).

Plans for Next Period
Continue to monitor new literature which attempts to provide a regionalized breakdown of global damage functions. As such, work on extensions of Task 2 is ongoing.

References
Hsiang, S. M. et al. (2017). Estimating economic damage from climate change in the United States. *Science* 356(6345), pp. 1362–1369. doi: 10.1126/science.aal4369.
National Academies of Sciences, Engineering, and Medicine. (2017). Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide. Washington, DC: The National Academies Press. doi: 10.17226/24651.
Nordhaus, W. D. (2017). Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences*, 114(7), pp. 1518–1523. doi: 10.1073/pnas.1609244114.
Tol, R. S. (2009). The economic effects of climate change. *The Journal of Economic Perspectives* 23(2), 29-51.

Task 3 – Analyze Approaches for Modeling Physical Impacts at Increased Spatial Resolution in APMT-IC
Massachusetts Institute of Technology

Objective(s)
The objective of this task is to study potential approaches for increasing the spatial resolution of radiative forcing impacts associated with aviation emissions in APMT-IC. Since APMT-IC is currently set up as a global model, global emissions are used as an input and globally averaged results are the model's main output. While this approach leads to reliable results for current-year assessments, it potentially biases results for future scenarios, which 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 have been estimated to result in 4-5 times more tropospheric ozone formation per unit NO_x over the Pacific as compared to a unit of NO_x emissions over Europe or North America (Gilmore et al. 2013).

The objective of this task is to lay the groundwork for modeling the global impact due to changes in emissions region, and furthermore modeling regionalized temperature changes, and their impacts. This task should investigate literature on regionalized emissions-to-impacts pathways, and if sufficient scientific consensus is found, outline a concept for a regionalized version of APMT-IC.

Research Approach and Accomplishments
In a literature study, the ASCENT 21 team investigated 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. Because the resulting model would only be based on a single study, it is currently not being implemented in APMT-IC.

While studying potential implementation approaches for APMT-IC, the project team found that there is currently no conclusive evidence in the literature which could support reduced-order modeling of regionalized damages from regionalized temperature change. In turn, analyses of regionalized temperature change would currently be of little value within APMT-IC. As such, a model for regionalizing the temperature change impacts of aviation was not recommended for implementation at this point.

Milestone(s)
The literature study and model conception were completed.

Student Involvement
This preliminary research was completed by Carla Grobler (Ph.D. Student, MIT).

Plans for Next Period
Continue to follow current research which aims to model regional heterogeneities in atmospheric responses to aviation emissions. Additionally, continue to follow research to identify when regionalized damage functions become available that can translate regionalized temperature change to damages.

References
Fuglestvedt, J. S. et al. (2010). Transport impacts on atmosphere and climate: Metrics. *Atmospheric Environment* 44(37), pp. 4648–4677. doi: 10.1016/j.atmosenv.2009.04.044.

Lund, M. T. et al. (2017). Emission metrics for quantifying regional climate impacts of aviation. *Earth System Dynamics*, 8(3), pp. 547–563. doi: 10.5194/esd-8-547-2017.

Task 4 – Investigate State-of-the-Art and Reduced-order Approaches for Contrail and Contrail-Cirrus Simulations
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. Therefore, 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 outline 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, Task 4 as proposed for the current period of performance was completed.

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.

Plans for Next Period
If additional funding was provided, research could be pursued to develop a reduced-order contrail model as outlined in the report.

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), pp.561-583.

Fuglestvedt, J.S., Shine, K.P., Berntsen, T., Cook, J., Lee, D.S., Stenke, A., Skeie, R.B., Velders, G.J.M. and Waitz, I.A., 2010. Transport impacts on atmosphere and climate: Metrics. *Atmospheric Environment* 44(37), pp.4648-4677.

Lund, M. T. et al. (2017). Emission metrics for quantifying regional climate impacts of aviation. *Earth System Dynamics* 8(3), pp. 547–563. doi: 10.5194/esd-8-547-2017.

Task 5 – Support Knowledge Transfer
Massachusetts Institute of Technology

Objective(s)
The objective of this task is to support FAA analyses of national and global policies as they relate to long-term atmospheric impacts. APMT-IC version 24 builds upon the tool that was used to assess international aircraft and engine stringencies at CAEP 8, 9 and 10. Under ASCENT 21 (together with its predecessor, PARTNER 46), the ASCENT 21 team was directly involved in the analysis of all three standards. ICAO CAEP is currently considering the introduction of an nvPM-emission standard for international aviation, for which air quality impacts will be a driver of the cost-benefit-ratio, and for which trade-offs or co-benefits in climate are expected. While the analyses of the nvPM standard are conducted by a dedicated project team (ASCENT Project 48), the ASCENT 21 team was tasked to assist the ASCENT 48 team with the application of APMT-IC in order to ensure that inputs and outputs are handled correctly, assumptions are clearly stated, and outputs are correctly interpreted.

Furthermore, validation and verification of APMT-IC was performed by the ASCENT 22 project team during this reporting period. The objective under this task was to communicate all assumptions, methods, and to support the ASCENT 22 project team in using APMT-IC for validation and verification.

Research Approach and Accomplishments
APMT-IC and documentation were transferred to the ASCENT 22 team, and training was provided regarding the use of the model. Furthermore, regular meetings were held with members of the ASCENT 48 team to ensure APMT-IC is applied correctly.

Milestone(s)
Training has been provided to researchers as needed, including tools training for UIUC to review climate code capabilities, and for the ASCENT 48 team. As such, Task 5 as defined for this period of performance was completed.

Student Involvement
Carla Grobler (Ph.D. Student, MIT), who has been responsible for updating APMT-Impacts Climate to version 24 during the previous reporting period, provided training to a student UIUC, and has continued to provide support to the ASCENT 48 team.

Plans for Next Period
The ASCENT 21 team will continue to provide training and guidance on APMT-Impacts Climate as necessary.