Project 020 Development of NAS wide and Global Rapid Aviation Air Quality

Massachusetts Institute of Technology

Project Lead Investigator

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- FAA Award Number: 13-C-AJFE-MIT, Amendment Nos. 007 and 018
- Period of Performance: August 19, 2014 to August 31, 2016 (reporting with the exception of funding levels and cost share only for August 19, 2014 to August 31, 2015)
- Task(s):
    1. Update and validate the global GEOS-Chem adjoint tool, and prepare the tool for use outside MIT
    2. Calculate and analyze second-order sensitivities
    3. Assess policy scenarios defined in agreement with FAA

Project Funding Level

$350,000 FAA funding and $350,000 matching funds. Sources of match are approximately $81,000 from MIT, plus 3rd party in-kind contributions of $114,000 from Byogy Renewables, Inc and $155,000 from Oliver Wyman Group.

Investigation Team

Principal Investigator: Prof. Steven R.H. Barrett (MIT)
Co-Investigator: Dr. Raymond L. Speth (MIT), task1-2
Co-Investigator: Dr. Robert Malina (MIT), task 3
Graduate student: Irene Dedoussi (MIT), tasks 1-3

Project Overview

The project aims to develop tools that enable rapid assessment of NAS wide and global impacts of aviation emissions on aviation-attributable PM, and resultant health outcomes for different policy scenarios. The adjoint method, which the tools are based on, provides a computationally efficient way of calculating the sensitivities of an objective function with respect to multiple model inputs. The project enhances the existing tools in terms of the domains and impacts covered, and in terms of uncertainty quantification. The enhanced tools support the FAA in its strategic vision to reduce the significant health impacts of aviation emissions, by providing a rapid way of assessing the significant health impacts of any present or future aviation emissions scenario.

Objective(s)

The aim of the project is to enhance the capabilities of the existing rapid assessment tool. The main objectives of this cycle are aligned with the aforementioned tasks. Specifically:

1. To expand the scope of the current policy tool to cover the global domain as per Koo et al. 2013. This will enable to assess international policy scenarios, such as the ones provided in the CO_2 standard analysis.
2. To provide understanding about how the change in the background concentrations affects the values of the sensitivities. This will eventually allow us to assess more accurately the impacts of future policy scenarios.

3. To apply the tool in a real-life policy.

Research Approach

First, we expand the scope of the current tool to cover the global domain. The resulting global rapid assessment tool will allow for separation of LTO and non-LTO impacts and capturing differential scenarios. This also allows the study of transport of cruise emissions between regions in the global domain as per Koo et al. 2013. Together with the existing NA nested grid, this will allow studies of the impact of cruise emissions in the NA domain at a higher resolution. The two grids are shown in Figures 1 and 2 below. We wrapped these tools in a Matlab package for both the nested and the global policy tool for use outside of MIT, and for easier application of the tools to policy scenarios.

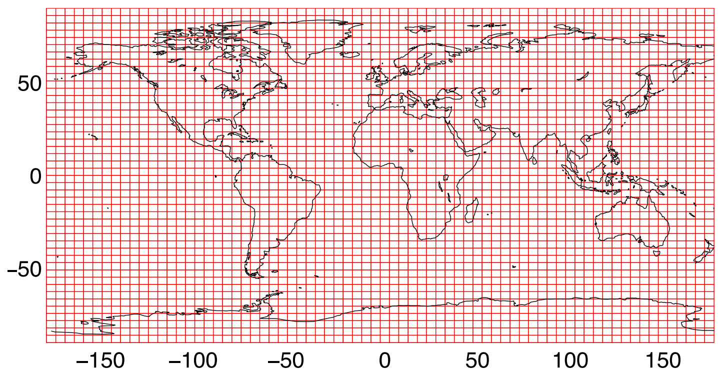

Figure 1: GEOS-Chem global 4x5 grid

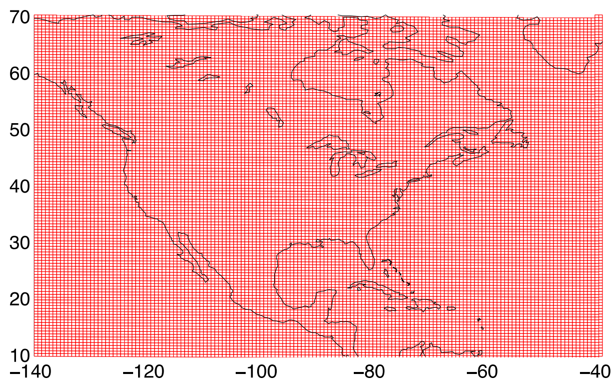

Figure 2: GEOS-Chem NA nested 0.5x0.666 grid

It should be noted that the sensitivities calculated allow us to quantify the speciated, temporal, and spatial origins of the population exposure to $PM_{2.5}$. Specifically, they allow us to decouple the LTO and non-LTO impacts, as well as to calculate what percentage of the total aviation impacts originates from each aviation emissions species. In terms of the temporal aspect, they allow us to see if there is any seasonality in the importance of emissions in driving the $PM_{2.5}$ exposure and hence premature morality impacts. Specifically, we find that the SO_2 sensitivity over the full flight altitude layers exhibits significant seasonality. Particularly emissions over the summer months (April to September) are approximately twice as impactful in terms of $PM_{2.5}$ exposure than those over the winter months (October to March). This implies that the benefit of sulfur emissions control (e.g. using alternative fuels, or low sulfur jet fuel) over the summer is twice as high as that of the winter.

$$\frac{\partial \mathrm{J}}{\partial(\mathrm{SO_2})}(i,j,k,t)$$

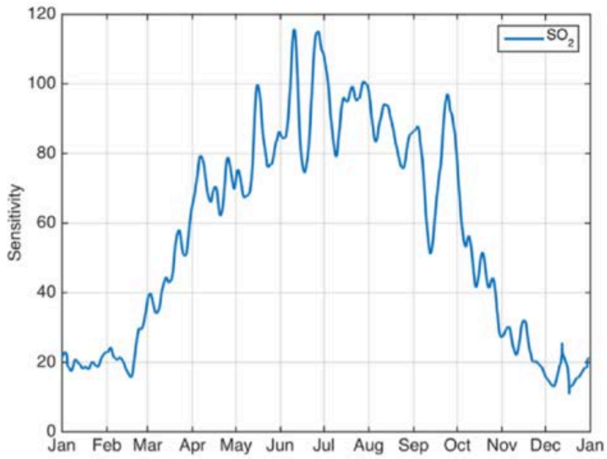

Figure 3: Seasonality in the SO2 sensitivity

The 3D sensitivities are used to assess the impacts of different emissions scenarios by performing an inner matrix multiplication of the sensitivity matrix with the emissions matrix as shown in Figure 4 below. This computation is of negligible computational cost, compared to the 3D Chemical Transport Model (CTM) tools that have been conventionally used until now in assessing air quality impacts of different emissions.

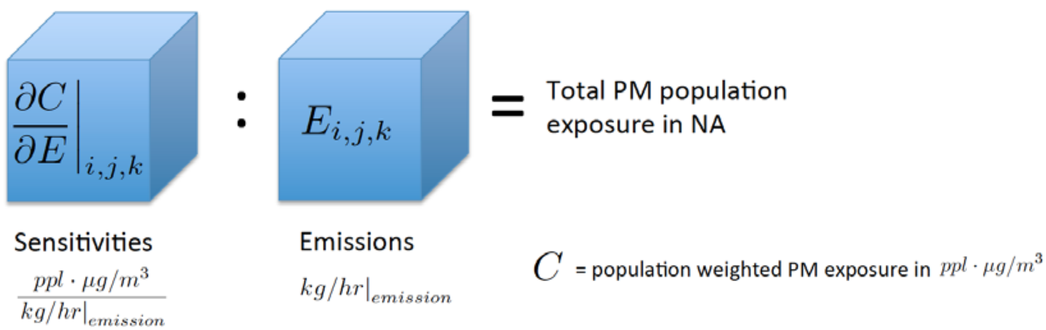

Figure 4: Application of sensitivities

This global adjoint air quality tool, due to its source oriented focus, as well as the minimal computational cost involved in applying the sensitivities to assess the impacts of emissions scenarios, was applied in the CO_2 standard policy assessment project (ASCENT 14), in order to quantify the air quality impacts of the proposed scenarios. Given that this was the first time that this tool was applied in a real-life policy, the interaction of the tool with upstream (emissions modeling) and downstream (monetization) processes had to be streamlined. The different process steps followed from emissions data to monetized scenario impacts are shown in the flow diagram below (Figure 5). The gridded emissions provided by VOLPE had to be re-gridded into the GEOS-Chem global grid. The emissions preprocessor was thus developed to perform this task. The adjoint tool was also accompanied with some Monte Carlo simulations to estimate how the different sources of uncertainty (e.g. emissions uncertainties, CRF uncertainty, etc) propagate throughout the process.

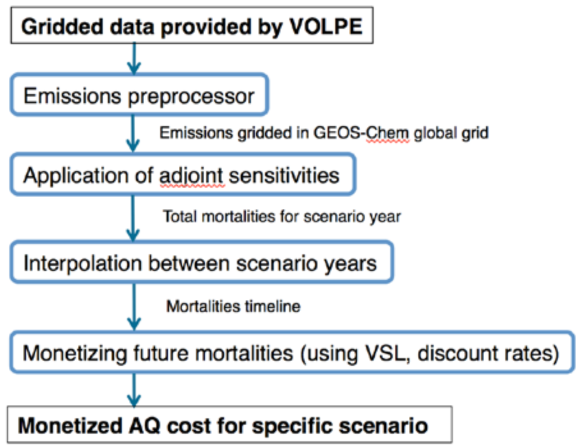

Figure 5: Process flow for scenario assessment

Given the significant involvement in the application of the global tool for the CO_2, the second order sensitivity study was decelerated in order to be able to provide assistance with the aforementioned process steps for this high priority project. However, this second order sensitivities work was performed in parallel to that. The aim of this part of the project is to capture the impacts of the change in background emissions on the GEOS-Chem adjoint sensitivity values. The computation of the second-order sensitivities can be performed by applying a finite difference approach to the adjoint model. This will also enable assessment of how any potential non-linearities affect the policy tool, which at present assumes a linear relationship between health impacts and emissions.

In order to calculate the impact of the change in background emissions to the sensitivity values, we are calculating the sensitivities for a different year, specifically 2011. By comparing the 2011 sensitivities with the sensitivities of 2006 (that we already have), we will be able to estimate the second order sensitivities (as the baseline emissions changes between 2006 and 2011 are known). In order to calculate the 2011 sensitivities, we are implementing into the GEOS-Chem adjoint model the EPA National Emissions Inventory (NEI) for 2011, with the goal of calculating sensitivities with these 2011 NEI baseline emissions. The implementation involves adding a new module to the currently existing GEOS-Chem adjoint model. This module is a modified version of a module developed by the GEOS-Chem developers for the forward model. We have performed the forward model run and generated the corresponding checkpoint data that is needed for the adjoint. We are currently working on the adjoint model, and developing and testing some code to accommodate for this new inventory of emissions. This second order sensitivites task will be concluded in the next period.

Milestone(s)

- *Make the global rapid assessment tool available and provide FAA with a briefing on its capabilities:* This was accomplished on time. The FAA was briefed on the capabilities of the tools, and was also trained on how to use it. Accompanying documents of 'how to use the tool' were also provided.
- *Provide FAA with a briefing on the results of the policy scenario assessment:* Throughout the application of the tool in the policy context the FAA has been continuously briefed and informed about the progress and the results.
- *Brief FAA on second order sensitivities progress:* The FAA was briefed on the progress made regarding the sensitivities work.

Major Accomplishments

The major accomplishment during this period regarding the tool was its application to the CO_2 policy assessment. The tool allowed the assessment of the air quality impacts of ~80 scenarios in a very reasonable computational time, which would have otherwise required weeks if not months of run time in conventional air quality models.

References

Koo, Jamin, Qiqi Wang, Daven K. Henze, Ian A. Waitz, and Steven R. H. Barrett. 2013. "Spatial Sensitivities of Human Health Risk to Intercontinental and High-Altitude Pollution." *Atmospheric Environment* 71 (June): 140–147. doi:10.1016/j.atmosenv.2013.01.025. http://linkinghub.elsevier.com/retrieve/pii/S1352231013000502.

Publications
Dedoussi, IC and Barrett, SRH (2015): US aviation air quality impacts and comparison with other sectors. 2015 Aircraft Noise and Emissions Reduction Symposium (ANERS), September 22-25, 2015, La Rochelle, France.

Outreach Efforts
None

Awards
None

Student Involvement
Graduate student Irene Dedoussi is a PhD candidate in the Department of Aeronautics and Astronautics at MIT, and is the graduate student involved in this project.

Plans for Next Period
Continuing this project onto the next period, we are aiming to enhance the capabilities of the existing rapid assessment tool. First, we will expand the scope of the current tool to capture the ozone (O_3) impacts, both at a global as well as the nested US domain. The resulting global rapid assessment tool will allow for separation of LTO and non-LTO impacts and capturing differential scenarios, and will provide sensitivities of both $PM_{2.5}$ as well as ozone population exposure. We will coordinate with Prof. Jon Levy from BU, who is currently leading the health impacts effort, regarding the appropriate choice of the O_3 Concentration Response Function (CRF), to ensure consistency between the health impacts calculation of the different air quality teams. Given that the ozone Concentration Response Function (CRF), unlike the one for $PM_{2.5}$, is non-linear, the adjoint model will have to be modified to be able to capture this. The forward GEOS-Chem model will be used to select the portion of the day when O_3 contributes to the health impacts (based on the choice of the CRF). The adjoint code will then be modified to only account for that specific part of the day. In this way, the non-linearity in the CRF will be overcome, and we will be able to calculate the O_3 mortalities.

Second, we will extend the current adjoint tool to also cover the nested domains of Europe (EU), and South Eastern Asia (SEA). The global coarse model (4° × 5° resolution) will be used to obtain boundary conditions for these two sub-domains. Furthermore, we will adapt the relevant grid-specific emissions inputs and meteorology, which is needed to be able to run the forward model. In order to ensure that each subdomain runs successful benchmark runs will be performed and compared against the corresponding regions in the coarse grid. Once the forward models are tested for each subdomain, the adjoint models will also be tested against the forward model nested results. When these two additional nested domains become available, we will be able to also examine in detail EU and SEA within global aviation emissions policy assessments, similarly to the way we currently assess the US, both for $PM_{2.5}$ as well as O_3 impacts.

The enhanced tool will enable the assessment of the aviation-attributable $PM_{2.5}$ and O_3 impacts both in the NAS and globally. This tool will be capable of capturing both the LTO and non-LTO impacts, for either a subdomain or the whole of the domain, thus enabling the study of exchange of pollution between different regions. Since the adjoint sensitivities give spatial and temporal information about the sources that lead to the aggregated impacts, differential growth scenarios can be assessed as well. The computation of the second-order sensitivities will enable the estimation of the aviation impacts for given changes in the background emissions, and coupled with future year population data, will enable the study of future scenarios. The tool will be applied to assess present and future year emissions scenarios, which will be agreed on with the FAA.

We will collaborate with the research teams that will be continuing ASCENT projects 18 and 19 to maintain consistency between assumptions and inventories in the rapid assessment tools, health impacts assessments and airport-specific analyses, as we have successfully done in the past with the groups of Prof. Levy at Boston University and Prof. Arunachalam at University of North Carolina. We will also continue to assist the teams (e.g. currently ASCENT 14 for the CO_2 standard work) who are applying the adjoint tool for air quality analyses.