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

Massachusetts Institute of Technology

Project Lead Investigator

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- FAA Award Number: 13-C-AJFE-MIT, Amendment Nos. 007, 018, and 025.
- Period of Performance: August 19, 2014 to August 31, 2017. (reporting with the exception of funding levels and cost share only for period from October 1, 2015 to September 30, 2016)
- Tasks:
    1. Update and extend the global GEOS-Chem adjoint tool to include global ozone impacts calculations
    2. Calculate and analyze second-order sensitivities
    3. Provide assistance to FAA as needed

Project Funding Level

$550,000 FAA funding and $50,000 Transport Canada funding, with $550,000 matching funds. Sources of match are that same $50,000 Transport Canada funding which constitutes both sponsoring funds and matching funds, plus approximately $146,000 from MIT, and 3rd party in-kind contributions of $114,000 from Byogy Renewables, Inc. and $240,000 from Oliver Wyman Group.

Investigation Team (all MIT)

Principal Investigator: Prof. Steven Barrett
Co-Investigator: Dr. Raymond L. Speth
Co-Investigator: Dr. Robert Malina
Graduate students: Irene Dedoussi, Guillaume Chossiere

Project Overview

The aim of this project is to develop tools that enable the rapid assessment of the health impacts of aviation emissions. The focus of the project is on aviation-attributable $PM_{2.5}$ and ozone at the NAS-wide and global scales. These tools should allow for rapid policy analysis and scenario comparison. 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, and allow for detailed and quantified policy analyses.

Tasks and Plans for Next Period

Current Period

- **Task 1:** Update and extend the global GEOS-Chem adjoint tool to include global ozone impacts calculations
- **Task 2:** Calculate and analyze second-order sensitivities
- **Task 3:** Provide assistance to FAA as needed

Next Period

- **Task 1:** Extend second-order sensitivities to future years
- **Task 2:** Evaluate sources of uncertainty within the tool
- **Task 3:** Extend North American nested grid focused to represent Canadian impacts
- **Task 4:** Develop nested grids for Europe and southeast Asia

Objectives

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 include the global health impacts of aviation-attributable ozone. This will complement the existing PM capability and provide more extensive quantification.
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 to support policy analysis as requested by the FAA.

Research Approach

Sensitivity calculations

The first task for this period of performance consisted in extending the adjoint tool to include the calculation of global ozone impacts caused by aviation emissions at the global level. This capability complements the PM capability and allows for more extensive analysis. As was already the case previously, the global rapid assessment tool will allow to distinguish LTO from non-LTO impacts and capture differential scenarios. This also allows the study of transport of cruise emissions between regions in the global domain as per Koo et al. 2013. The spatial domain that is covered by this extended tool is shown below (Figure 1).

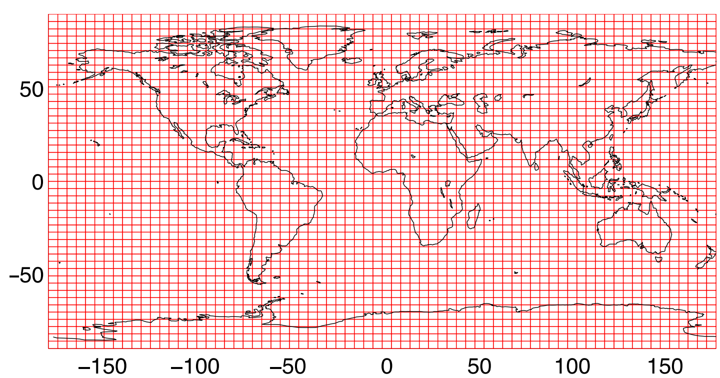

Figure 1: GEOS-Chem global 4°×5° grid

Before completing this task, we updated the version of the GEOS-Chem model that we are using, in order to produce up-to-date results. The aviation emissions inventory that are used in our calculations also needed to be updated, and we have been in contact with VOLPE to obtain and validate the new inventory data.

Given that the ozone Concentration Response Function (CRF), unlike the one for $PM_{2.5}$, is non-linear, the adjoint model needed to be modified to be able to capture global ozone impacts. The forward GEOS-Chem was used to select the portion of the day when O_3 contributes to the health impacts.

The calculation of the ozone impacts of aviation emissions required a careful definition of the metric used to measure exposure. On that front, we collaborated with the ASCENT 18 project contributors. Jon Levy and his team suggested an appropriate metric for ozone exposure, and helped us with the choice of the concentration-response function to be used. The one that was chosen ensures consistency with previous FAA work.

Once these data were obtained and the model properly updated and validated, we needed to implement the calculation of the ozone impacts in the code, test our implementation, and finally run the model to obtain sensitivities. The computational process that we use can be summarized as follows (Figure 2).

Figure 2: Computational workflow

The sensitivities calculated allow us to quantify the speciated, temporal, and spatial origins of the population exposure to aviation-attributable ozone. Specifically, they measure how much the emissions in each grid cell contribute to the total population exposure to ozone and to the resulting health impacts. This allows us to identify the LTO impacts and differentiate them from non-LTO impacts, as well as to calculate what percentage of the total aviation impacts originates from each aviation emissions species. The sensitivities also provide information about the temporal aspect of emissions and can be used to identify seasonality effect. These effects were shown to be important in the case of $PM_{2.5}$ impacts. For instance, SO_2 emissions over the summer months (April to September) are approximately twice as impactful in terms of $PM_{2.5}$ exposure as 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.

The 3D sensitivities matrices can be used to assess the impacts of different emissions scenarios. The health impacts associated with a specific emissions scenario are given by the 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. This is the main benefit of the adjoint approach.

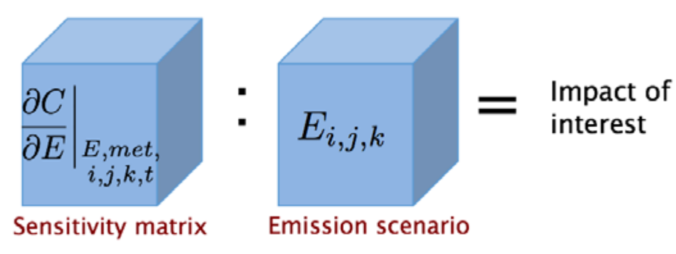

Figure 3: Application of sensitivities

In addition to the ozone work, we conducted preliminary research in order to eventually extend our modeling capacities to the fine resolution South-East Asian and European domains (0.5°×0.667°). Besides the nested North American domain, which is functional and already transitioned to the FAA, the development of the two other geographical domains is underway too. We identified the code development and modifications that need to be performed, and investigated the emissions inventories and other inputs to be used.

Application of the sensitivities to the ICAO CAEP 10 CO_2 standard

The rapid air quality policy assessment tool was for the first time applied in the ICAO CAEP CO_2 standard work, where multiple scenarios were analyzed and compared. The ASCENT 20 team supported the ASCENT 14 team in interpreting the results and compiling the Information Paper that was presented at the CAEP meeting.

FAA training

In the context of supporting the FAA in using the policy assessment tools, MIT organized and performed a series of trainings, one of which was on the adjoint air quality tool for the global and nested NA domains. The training consisted of two parts: an information session (performed remotely on Oct 27th 2015) and a hands-on training (performed at the FAA office on Oct 29th 2015). The information session aimed to present the motivation behind this (global and nested NA) tool, and to provide an overview of the application of the tool. It was aimed for people who are going to run or interpret the tool, and for people who are going to manage projects that involve the use of this adjoint tool. The broader capabilities and limitations of the tool and some of the future work aspects were also mentioned. This WebEx presentation has been recorded and transferred to the FAA in order to assist with future training later on and/or serve as a reference for how to use the tool. The hands-on training involved the application of the tool to a set of sample inputs, and the transfer of the tool (code and examples) to the FAA server/workstations.

2nd-order sensitivities

We also investigated how the adjoint sensitivities, that the tool is based on, depend on the background concentrations (and thereby the level of background emissions. This is of interest as, in particular in the US, there have been significant anthropogenic emissions reductions over the past 15 years, as shown in Figure 4. The aim of this part of the project is to capture the impacts of the change in background emissions to the GEOS-Chem adjoint particulate matter ($PM_{2.5}$) sensitivity values. In order to calculate this impact, we are calculated the sensitivities for a different year, specifically 2011, taking into account changes in background emissions and meteorology. By comparing the 2011 sensitivities with the sensitivities of 2006 (that we already have), we were able to quantify the impacts that the changing atmospheric composition has on the atmospheric response to emissions (i.e. the adjoint sensitivities).

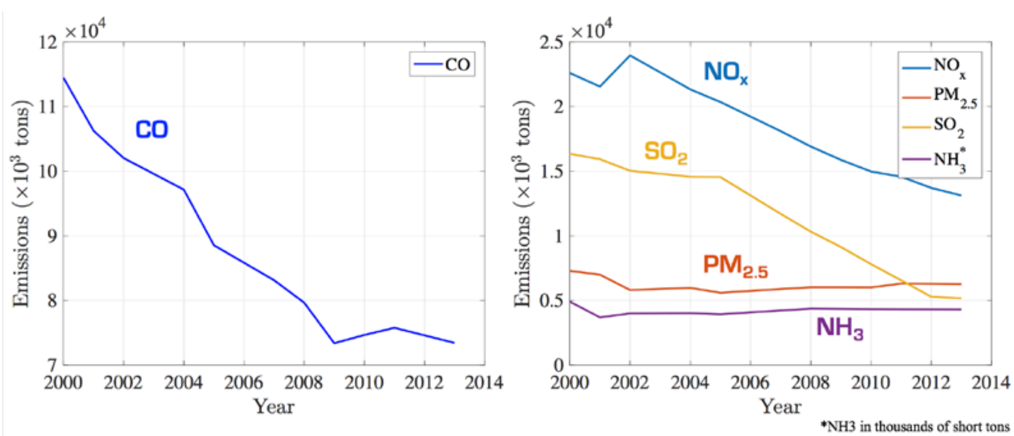

Figure 4: Anthropogenic emissions reductions in the US [USA EPA 2016]

The major findings are presented in figures 5 and 6 below. We find that the sensitivities to NO_x emissions increase between 2006 and 2011. In addition, we find that the sensitivities to SO_2 emissions decrease between 2006 and 2011, with some increases in the coasts. The sensitivity changes are the superposition of a variety of phenomena, including the changing emissions (in particular those of SO_2 and NO_x), meteorology and population.

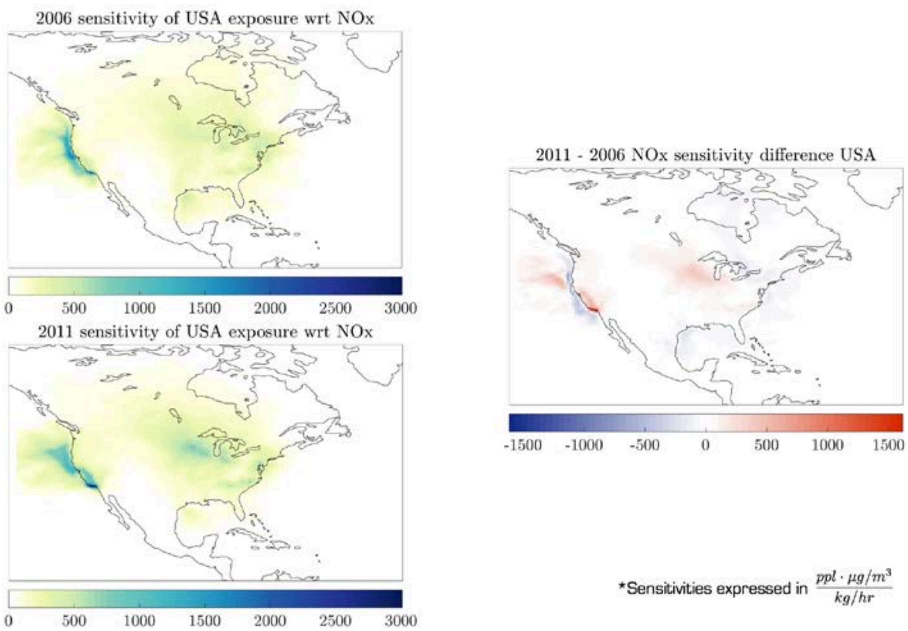

Figure 5: Sensitivity of US population exposure to $PM_{2.5}$ with respect to a unit of near-surface NO_x emissions for 2006, 2011 and the difference between the two

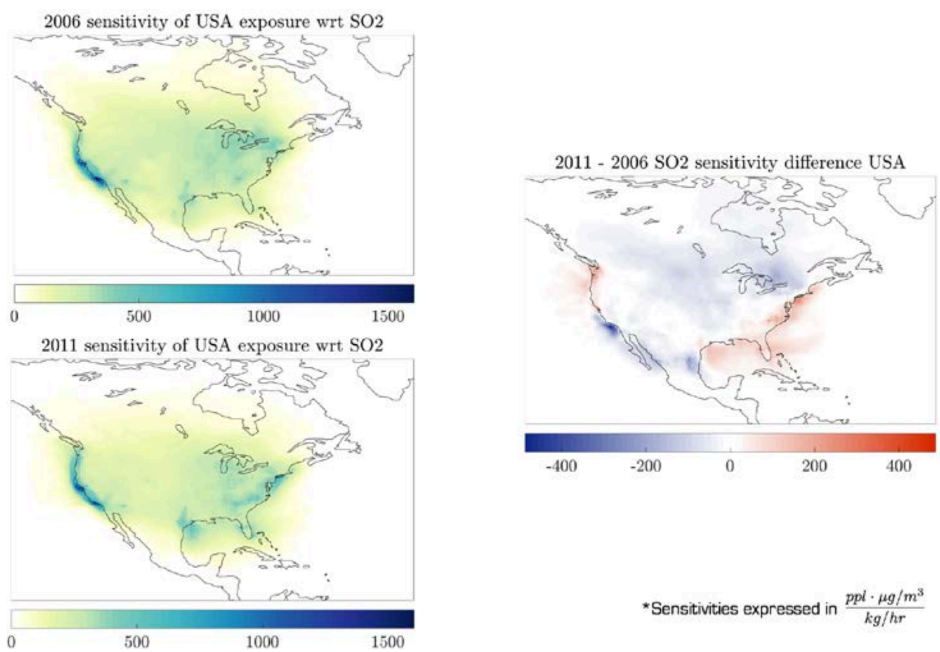

Figure 6: Sensitivity of US population exposure to $PM_{2.5}$ with respect to a unit of near-surface SO_2 emissions for 2006, 2011 and the difference between the two

Milestones

- *Add the ozone capability to the adjoint air quality tool, and make this available for use outside MIT:* The ozone sensitivity calculation methodology was developed and tested during this reporting period. The model update and data collection from various sources are in progress under the next period of work.
- *Provide FAA with a briefing on the progress regarding the non-US nested domains (in project month 12)*: This was accomplished on schedule.
- *Brief FAA on second order sensitivities progress:* The FAA is aware of the progress made regarding the sensitivities work.
- *CO_2 work:* Contributed to the ICAO CAEP Information Paper on the cost-benefit analysis of the ICAO CO_2 stringency options
- *Training:* We performed a series of training to the FAA on using the adjoint air quality tool and interpreting results. The training material and recordings were also passed to the FAA.

Major Accomplishments

During this period of performance, we conducted a complete update of our model and the input data used to compute sensitivities, in order to produce up-to-date results.
In addition, we quantified the impacts of the changing atmospheric composition on the adjoint sensitivities, thus allowing us to gain understanding of how the sensitivities are affected from the reductions of other anthropogenic combustion emissions sources (e.g. road transportation, power plants, etc.).
The tool was for the first time applied on a real-world policy assessment, and was used to quantify the air quality impacts of the CO_2 standard stringency options. The FAA was also trained on using the model and interpreting the outputs.

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.

USA EPA, 2016. Air Pollutant Emissions Trends Data. URL: https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-trends-data.

Publications

Brenner, M.; Yutko, B.; Wolfe, P.; Dedoussi. I. US cost-benefit analysis of ICAO CO_2 standard stringency options. ICAO CAEP Information paper to inform CO_2 standard work. 12/14/2015.

Outreach Efforts

Include descriptions of any and all oral presentations, electronic communications, conference presentations, or other forms of outreach.

Awards

None

Student Involvement

Irene Dedoussi is a PhD candidate in the Department of Aeronautics and Astronautics at MIT. Guillaume Chossiere is a Master's student in the Department of Aeronautics and Astronautics at MIT. Both of them are involved in this project.

Plans for Next Period

Over the next period of this project (2016-2017), we aim to analyze and improve the robustness of the GEOS-Chem Adjoint rapid policy assessment tool, as well as to further expand the capabilities of the tool, particularly with regard to spatial scope.

First, work completed thus far on second-order sensitivities between 2006 and 2011 will be extended to future years (e.g. to 2018 by using the EPA's National Emissions Inventory forecast). This will allow quantification of future changes in sensitivities to aviation emissions due to future changes in background emissions. Inclusion of these sensitivities in the tool will improve its future policy scenario assessment capability, as they enable the tool to account for the second-order effect of changes in background emissions to future aviation impacts. Furthermore, second-order sensitivities will also be used to estimate uncertainty propagation from background emissions inventories (e.g. for ammonia) to the aviation impacts computed by this tool, as well as to estimate the impact of meteorological changes to the computed aviation impacts as a first step in investigating coupling between climate and air quality.

Second, an in-depth evaluation of sources of uncertainty in the tool will be conducted through comparison of adjoint sensitivity results against forward model results with perturbed emissions as well as through tool inter-comparisons of the forward model against CMAQ. Comparisons will also be made with observational data from the EPA Air Quality System (AQS) to quantify this tool's biases in over- or under-predicting concentrations of certain pollutant species. These biases are a representation of the tool's inherent uncertainty. Once quantified, the biases can be factored in to the uncertainty calculation for the tool's aviation impact results, broadening their scope to include the model's inherent uncertainty.

Third, the tool will be extended to capture Canadian air quality and health impacts at fine resolution. This will be done by using the tool's built-in nested NA grid, which has so far been used to compute US impacts, but also extends over most of Canada, and by redefining the objective functions to be the Canadian population's exposure to $PM_{2.5}$ and O_3. The computed sensitivities of this redefined objective function can be used to attribute Canadian air quality and health impacts to species, locations, and times of emissions, as is done currently for the US.

Fourth, the tool will be extended to function with GEOS-Chem's built-in nested grids for the EU (Europe) and SEA (Southeast Asia) regions. While the adjoint model for the EU grid has yet to be developed, progress has already been made on setting up the SEA adjoint model with the relevant regional meteorological and emissions data. The coarse ($4^\circ \times 5^\circ$) global model will be used to obtain boundary conditions for these nested regional models. The nested forward models will first be validated through comparison with both global grid forward model results and observational data. The nested adjoint models can then be validated against their respective forward models. Adding these nested regional grids will greatly expand the tool's global policy assessment capability in terms of $PM_{2.5}$ and O_3 impacts to the same level as is currently done nationally for the US.

The enhanced tool will enable the assessment of the aviation-attributable $PM_{2.5}$ and O_3 impacts in a rapid manner, appropriate for policy scenario assessment. 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 second order sensitivities analyses will enable the estimation of the aviation impacts for given changes in the background emissions or meteorology, and the model uncertainty analysis will be to provide estimates of the potential biases in the calculations.

We will continue to 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 48 for the non-volatile PM standard work and ASCENT 39 for the assessment of naphthalene removal from jet fuel) who are either applying or require contributions from the adjoint tool for air quality analyses.