A key task performed during this period of performance was to estimate, from a literature review, the uncertainty associated with these regional ammonia inventories. The results are shown in Table 2. The column "Applied to" refers to the region to which the uncertainty was applied.

Table 2. Regionalized uncertainty in ammonia emissions

Region	Relative uncertainty	Applied to	Source
Global	(−18.75 %, +18.75 %)	Other	Beusen et al. (2008)
China	(−43 %, +50 %)	China, Other Asia	Zheng et al. (2012)
Europe	(−30 %, +30 %)	Europe	EMEP (2009)
USA	(−36 %, +36 %)	USA, Other NA	Zhu et al. (2012)

To compute the impact of these uncertainties in ammonia emissions on aviation-attributable health impacts, we first compute the first-order sensitivities of the desired health impacts to NH_3 emissions with and without aviation emissions. By multiplying the difference of these two matrices (whose values are expressed in units of $\frac{\mu g(PM_{2.5})/m^3}{kg(NH_3)/hr}$) by the uncertainty in ammonia emissions (in $\frac{kg\,(NH_3)}{hr}$), we compute, in each grid cell, the share of the uncertainty in the calculated total aviation-attributable impacts that can be traced back to uncertainties in ammonia emissions. The application of this method yielded the results shown in Table 3.

Table 3. Uncertainty in aviation impacts due to uncertainty in ammonia emissions

Summary	
Aviation-attributable, population-weighted $PM_{2.5}$	59.6 ng/m^3 (*baseline*)
NH_3-driven uncertainty	(−24.0, +27.0) ng/m^3 *(−40.2%, +45.5%)*
Regional Contributions to NH_3-Driven Uncertainty	**China:** (−11.9, +13.8) ng/m^3 *(−43.9%, +51.1%)* **Other Asia:** (−6.6, +7.7) ng/m^3 *(−24.5%, +28.5%)* **Europe:** ± 4.0 ng/m^3 *(± 6.7%)* **USA:** ± 1.1 ng/m^3 *(± 1.8%)* **Other NA:** ± 0.1 ng/m^3 *(± 0.4%)* **Other:** ± 0.2 ng/m^3 *(± 0.7%)*

Multi-scale adjoint tool

The development of a multiscale sensitivity analysis framework would combine the advantages of low-resolution global modeling for cruise sensitivity analysis with the advantages of high-resolution local modeling for resolving surface-level variations. Based on the work completed in this period of performance, a potential solution has been identified which would require to implement substantial modifications of the adjoint tool.

The proposed solution would involve re-engineering the adjoint to directly include sensitivity to changes in boundary conditions, supported by a finite-difference forward simulation to evaluate how the boundary conditions are affected by aviation. This effort would be supported by a multi-tier forward analysis to evaluate the difference in calculated impacts between the forward global, adjoint global, forward nested, and adjoint nested simulations.

Milestones

- *Surface air quality impacts of aviation*: Updated sensitivity to aviation emissions have been produced and used along with the AEDT 2015 inventory of aviation emissions to produce updated estimates of the health impacts of aviation emissions in different regions.
- *Nested domains and tool validation:* Work has continued on extending the capabilities of the tool to include high resolution modeling over various key regions. The tool was fully validated against the forward version of the GEOS-Chem model over all the operational domains.
- *Operationalize tools*: The various model updates and the additions of the new nested domains were packaged and wrapped into a user-friendly Matlab script that we passed to the FAA along with a brief guidance document.
- *Support PM standard analysis*: Support and assistance to the PM standard analysis team have continued, ensuring data consistency and providing help in result interpretation.
- *Ammonia uncertainty:* A full uncertainty quantification has estimated the share of the uncertainty in aviation-attributable health impacts that can be traced back to uncertainties in inventories of ammonia emissions.
- *Multi-scale adjoint modeling*: Scoping work was conducted for developing a multi-scale adjoint tool that will enable the calculation of impacts from emissions occurring outside of the current nested domains, at the global scale.

Major Accomplishments

During this period of performance, a validation of the tool in all of the operational geographical domain was performed. The tool was compared to calculations using the forward model of the global Chemical Transport Model GEOS-Chem. In addition, work has continued to enable higher resolution modeling over the European domain. Another key accomplishment during this period of performance was the quantification of the uncertainty in aviation-attributable health impacts that be linked to uncertainties in regional ammonia inventories. Finally, the tool was operationalized and packaged in a user-friendly MATLAB script, allowing the FAA to conduct air quality impacts analysis using up-to-date outputs from the air quality assessment tool.

Outreach Efforts

Results were presented at the 2018 ASCENT Spring and Fall meetings.

Student Involvement

Graduate students involved in this project are: Irene Dedoussi and Guillaume Chossière, PhD candidates in the Department of Aeronautics and Astronautics at MIT, and Kingshuk Dasidhakari, Masters student in the Department of Aeronautics and Astronautics at MIT.

Plans for Next Period

Over the next period of performance, we aim to improve our global impact assessment capabilities while quantifying key uncertainties in aviation's impacts on surface air quality. This includes novel applications of existing capabilities and the development of new capabilities, in order to both better characterize known uncertainties and to provide initial assessments of previously unquantified uncertainties. Data and model updated developed during the next period of performance will be packaged at the end of the year and passed to the FAA as updates to the MATLAB-based scripts provided during this period of performance. It will provide the FAA the ability to rapidly assess multiple aviation emissions scenarios in the context of uncertainties both internal and external to the aviation sector, as quantified by the work in this proposal. Following these overall objectives, we anticipate three major tasks to be undertaken by the ASCENT Project 20 team during the 2018/19 and 2019/2020 years.

Task 1 concerns the extension of the ASCENT 20 air quality assessment tool to account for high altitude aviation, including supersonic emissions. The adjoint model currently used for ASCENT project 20 to estimate sensitivity of population exposure to aviation was designed to capture the impacts of emissions within the troposphere and lower stratosphere. It is not yet capable of capturing impacts due to aviation at higher altitudes, particularly in the mid- or upper stratosphere, where supersonic aircraft would be expected to operate. The MIT Laboratory for Aviation and the Environment (LAE) has successfully extended the GEOS-Chem forward model, on which the adjoint is based, to simulate stratospheric chemistry and physics through the GEOS-Chem Unified Chemistry eXtension (UCX) (Eastham et al 2014). In order to accomplish this task, we will conduct a two-stage study to assess the impacts of projected supersonic aviation scenarios on surface air quality, including the differences in spatial pattern and in the timescale required to resolve the impacts. The first stage of the study will focus on single-case impact estimation using the validated forward model. The second stage of Task 1 will adapt and validate the adjointed version of the GEOS-Chem UCX model, which is currently under development at LAE for climate assessment purposes, to capture the sensitivity of air quality with respect to supersonic aviation.

Task 2 is an in-depth evaluation of the degree to which uncertainty in specific emissions related to non-aviation activities might affect the calculated impact of aviation. An initial estimate of the impact of uncertainty in ammonia emissions has revealed spatially heterogeneous relationships between ammonia emissions uncertainty and aviation emissions impacts. This pilot analysis has established a template for a broader assessment of these cross-sector second-order sensitivities, which are mathematically similar but functionally distinct from existing single-sector ("self") second-order sensitivities. In this task, we will use a combination of global and regional modeling to establish the degree of uncertainty which is propagated from background inventories of both anthropogenic ammonia, established during the previous project years as a key source of uncertainty in aviation's impacts, and in anthropogenic NO_x. This will require a thorough review of national- and regional-level uncertainties in emissions inventories for NO_x beyond the review for ammonia already underway.

For Task 3 we intend to package the sensitivity results from this year's and the previous years' efforts, to provide intuitive and consistent sensitivity matrices suitable for use in policy assessment. This includes not only the raw data but also MATLAB-based packages capable of accepting specific emissions scenarios and returning the expected air quality impacts. A central objective of this year's work would be to add multi-dimensional uncertainty quantification to the tool, including uncertainties in aviation emissions, uncertainty in background emissions of both ammonia and NO_x, and the impact functions themselves. This multi-dimensional assessment will be interpreted using a Monte Carlo analysis framework, which will provide the ability for any uncertainties already quantified through ASCENT project 20 to be propagated to the final impact estimate. Concurrent with this, we will provide an update to MIT's previous overview of the APMT-I Air Quality functionality in order to better reflect the latest air-quality-related functionalities. Ongoing work to enable European regional simulations, expected to be completed within the 2018-2020 period of performance, is included in this task.

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