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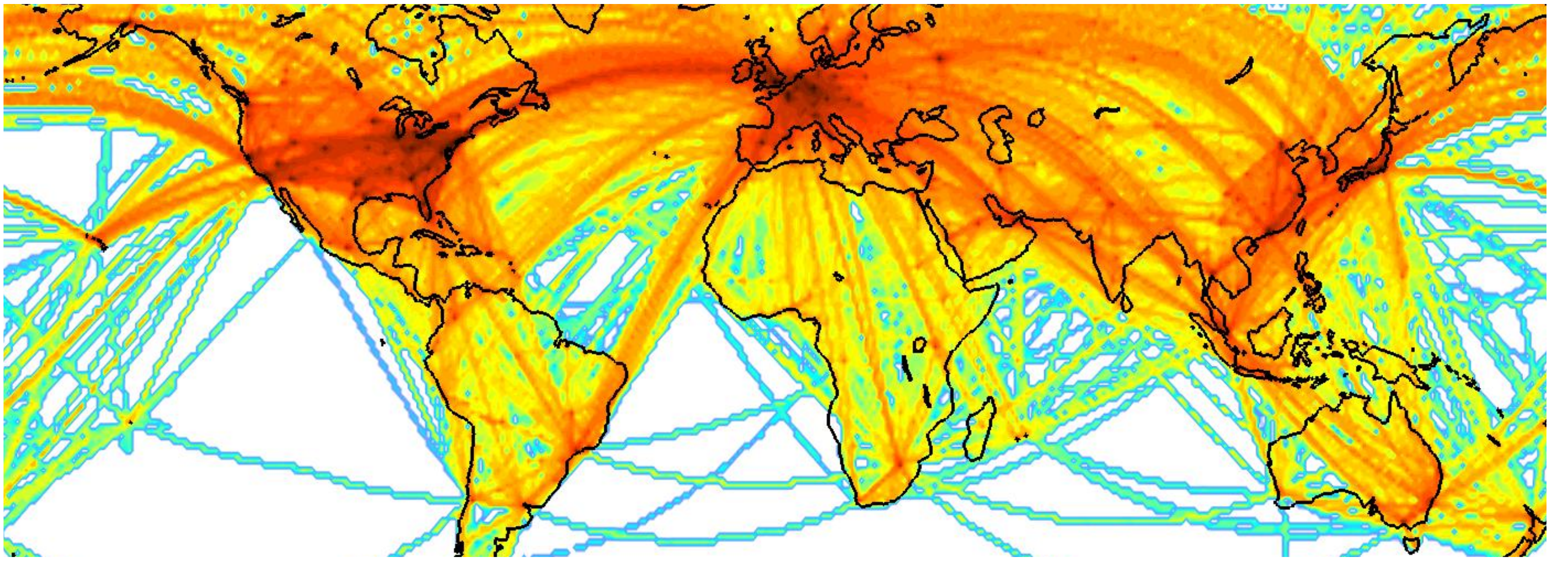

An open global civil aviation emissions dataset for 2005 (R1)

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Document Purpose

This document describes the methodology, data sources, and emissions totals for a 2005 civil aviation emission inventory generated using AEIC (Aviation Emissions Inventory Code) for use in atmospheric chemistry and climate models. A comparison to previous studies and guidance on the use of the inventory are also provided. Revised versions of this document will be released as needed.

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Methodology & Data Sources

A brief overview of the methodology used to calculate the emissions inventory is provided here. A paper will be published in the near future with more details.

AEIC (Aviation Emissions Inventory Code) is an open source emissions inventory tool written in MATLAB and first developed for LTO operations by Stettler, et al. For information on the LTO methodology, please refer to that publication [*Stettler et al.,* 2011].

The main addition to AEIC for this release is a methodology for calculating cruise emissions. In order to calculate fuel burn and emissions for a given year (2005), the following steps are taken:

1. Flight Scheduling
2. Flight Track Generation
3. Aircraft Performance Calculations
4. Emissions Calculations
5. Lateral Inefficiency Adjustments

A large requirement of AEIC has been to keep run times down as low as possible for calculating global fuel burn, in order to allow for uncertainty quantification (e.g. running Monte Carlos, etc.). To accomplish this, several simplifying assumptions are made in the analysis. The first area where the modeling is simplified is in Flight Scheduling and Flight Track Generation.

The Official Airline Guide (OAG) has been used to generate a schedule of flights for the year 2005. The OAG contains only scheduled civil air traffic; no adjustment is made to the resulting output for unscheduled or canceled flights. OAG data is used to generate unique Aircraft-Airport directional pairs and calculate the number of times each pair is flown.

For flight tracks, all aircraft are assumed to follow a great circle path between the departure and arrival airports. The error introduced by using this assumption is reduced afterwards by incorporating lateral inefficiency metrics available in the literature (to be discussed shortly).

Aircraft performance calculations are done using EUROCONTROL's BADA (Base of Aircraft Data) Version 3.9 [*Eurocontrol Experimental Center,* 2011]. To optimize calculations in this area, Performance Table Files (PTFs) are used to calculate aircraft fuel burn instead of a ground up aircraft performance model. The PTF is a unique file for each BADA supported aircraft that includes TAS, fuel flow rate, and rate of climb/descent for various flight levels and aircraft weight. The PTFs allow fuel burn to be calculated quickly for each flight chord by using a table look up.

Wind data from GEOS-5 consisting of the prevailing wind direction and average wind speed has also been incorporated into the model. This serves to change the relationship between the TAS (True Air Speed) and GS (Ground Speed) for an aircraft depending on its spatial location and heading.

After the aircraft performance calculations are complete, emissions indices from the ICAO Engine Emissions Databank [*CAA,* 2005] are used along with Boeing's Fuel Flow Method 2 (BFFM2) [*Baughcum et al.*, 1996] to calculate the emissions for the flight. The ICAO databank contains information on emissions from engines certified for flight. BFFM2 provides a method to extrapolate between the thrust points in the databank, as well as from sea level to altitude.

To finalize the numbers and help minimize the effect of the simplifying assumptions made during the analysis, the fuel burn and emissions calculated are adjusted according to lateral inefficiency factors [*Reynolds,* 2008; *Reynolds*, 2009]. Reynolds looked at several sets of flight data to determine the average increase in ground track from optimal for various flights. The portion utilized in AEIC is referred to as "Ground Track Extension". That is, the added distance flown by an aircraft when compared to leaving the terminal area in a straight line, flying enroute to the arrival airport on a great circle path, and approaching the terminal area in a straight line. No adjustments are made for inefficiencies due to less than optimum altitude or speed.

Comparison to Published Emissions Inventories

A comparison has been completed with published results to help verify the accuracy of the AEIC emissions database. The publication used for comparison is Wilkerson et al. (2010). For that study, AEDT (Aviation Environmental Design Tool), an extremely high fidelity modeling tool, was used to generate emission data for the years 2004 and 2006 [Wilkerson et al., 2010]. Table 1 contains a quantitative comparison of AEIC totals, while Figures 1-3 contain a qualitative comparison of the spatial distributions.

AEIC Year 2005	Wilkerson et al. Year 2004	Wilkerson et al. Year 2006	Delta 2004	Delta 2006
Fuel Burn (Tg)				
180.6	174.1	188.2	4%	-4%
NOx as NO_2 (Tg)				
2.69	2.46	2.66	6%	-2%
CO (Tg)				
0.7	0.63	0.68	19%	10%
HC as CH_4 (Tg)				
0.201	0.090	0.098	123%	105%

Table 1. Total Fuel Burn/Emissions Comparison

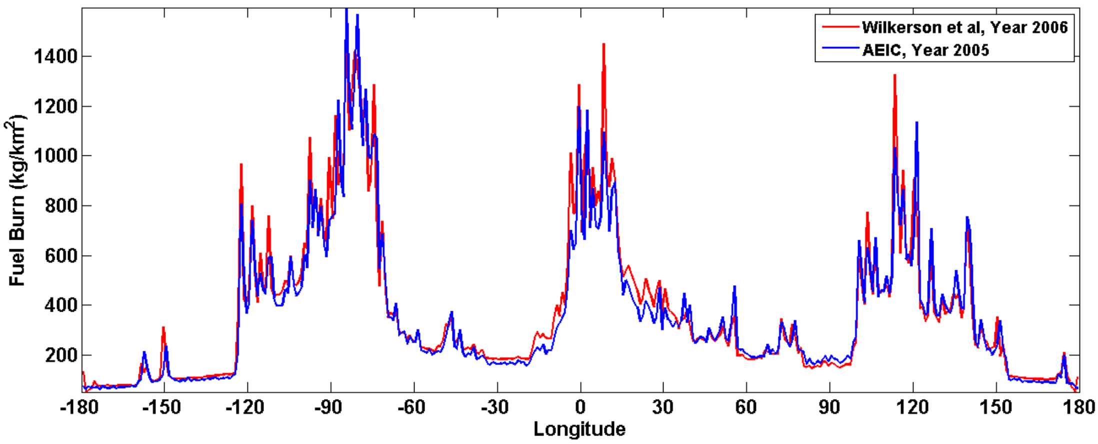

Figure 1. Longitudinal Spatial Distribution Comparison

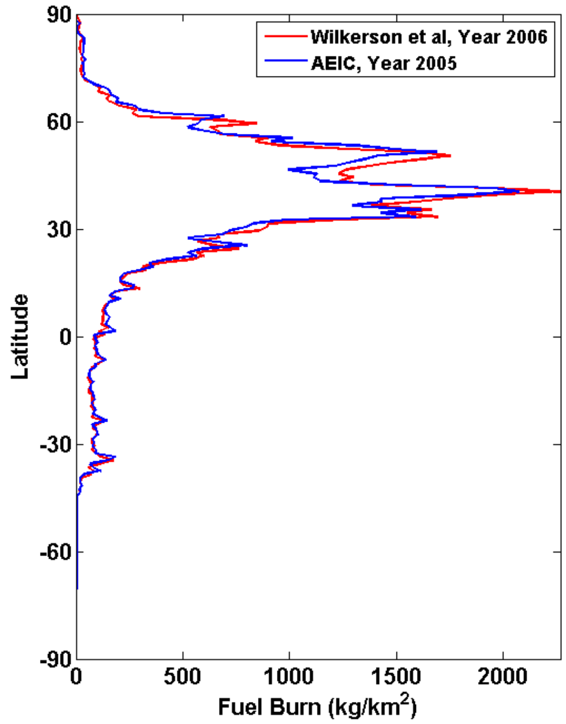

Figure 2. Latitudinal Spatial Distribution Comparison

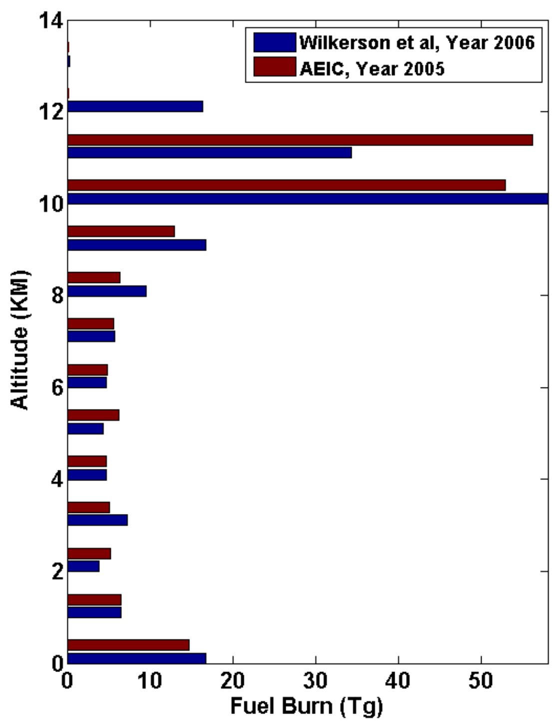

Figure 3. Altitude Spatial Distribution Comparison

Overall, both the totals and the spatial distribution agree very well. Fuel burn and NOx are very close between the two studies. The largest discrepancy exists in the HC emissions. This is due to the low fuel burn during descent and LTO cycle assumed in AEIC. The increased time at low power produces a disproportionate increase in HC emissions. While HC and CO emissions are high compared to the AEDT modeling tool used by Wilkerson, et al. (2010), it should be noted that both HC and CO emissions are on par with other studies that have been completed [Kim et al., 2007].

Vertical and Horizontal Gridding

There are three types of altitude referred to in this guidance document:

1. Nominal: altitudes in the grid data itself
2. Pressure: corresponds to the International Standard Atmosphere (ISA).
3. AGL: above ground level.

AEIC emissions are gridded onto a regular polar 3-D array. All grids have a vertical resolution of 0.2 kft from 0 kft to 50 kft (nominal altitude). Horizontal resolutions (latitude x longitude) are 1°x1°, 2°x2.5°, or 4°x5° depending on the grid (see Files section for more details).

To make implementation into atmospheric chemistry and climate models easier, the actual definition of altitude in the AEIC grid varies depending on the absolute magnitude. All points defined with a nominal altitude of 0-3 kft are AGL (above ground level). All points defined with a nominal altitude of >= 10 kft are pressure altitudes. Points between 3 kft and 10 kft are linearly "stretched" to accommodate the transition between AGL and pressure altitude. This altitude definition allows the entire AEIC grid to be imported based on a sea level vertical definition due to the terrain following characteristics of the native grids in many climate models.

This breakdown also allows LTO emissions to easily be distinguished from non-LTO emissions. LTO operations are typically defined as those below 3 kft AGL. LTO emissions therefore always consist of the emissions deposited between 0-3 kft in the AEIC grid.

It is suggested that modelers:

1. Import all emissions into the climate model based on the grid level defined at sea level. For example, AEIC emissions at 0 ft should always be placed in the first vertical grid cell

and AEIC emissions at 1 kft should always be placed in the vertical grid cell number corresponding to 1 kft above the ground with a sea level surface pressure (1013.25 hPa).

Files

The gridded data in ASCII format consists of files named as:

AEIC_2005_#x#_r1_MM.txt

Where "#x#" refers to the grid size and "MM" denotes the number of the month the emissions take place. There are a total of 12 ASCII files for each grid size. Each file contains 8 columns of data in the following order:

iLat, iLon, btmLim, topLim, FB, CO, HC, NOx

The above variables are defined as:

iLat	**Latitude index of grid cell (specific to grid)**
iLon	**Longitude index of grid cell (specific to grid)**
btmLim	**Nominal altitude of bottom of emission release (meters)**
topLim	**Nominal altitude of top of emission release (meters)**
FB	**Average monthly fuel burn rate in cell (kg/s)**
CO	**Average monthly CO emission rate in cell (g/s)**
HC	**Average monthly HC emission rate in cell (g/s, on CH_4 mass basis)**
NOx	**Average monthly NOx emission rate in cell (g/s, on NO_2 mass basis)**

The latitude/longitudinal indices are defined by the Generic 1x1, GMAO 2x2.5, and GMAO 4x5 horizontal grid coordinates available at the following link under Appendix 2 (Horizontal Grids): http://acmg.seas.harvard.edu/geos/doc/man/. Only grid locations that have fuel burn are included. Those with no fuel burn are omitted from the files.

Derived Emissions

Adapted from Barrett et al. (2010)

This section describes how to calculate emissions not included in the emissions files. It has been adapted from [*Barrett et al.,* 2010].

CO_2 emissions as g of CO_2 = 3159 × **FUEL**. The uncertainty range for this number is 3148 to 3173 based on the C:H ratios for JP-8 fuel as inferred from the Defense Energy Support Center/Petroleum Quality Information System [*Hileman et al.,* 2010].

H_2O emissions as g of H_2O = 1231 × **FUEL**. The range is 1197-1258 [*Hileman et al.,* 2010].

NO_x emissions are given on an NO_2 mass basis. Recommended partitioning at cruise at the engine exit plane by mole fraction is: 90% NO, 9% NO_2, 1% HONO for non-LTO emissions, or 76% NO, 23% NO_2, 1% HONO for LTO emissions.

CO emissions as CO in g = **CO**.

HC emissions are in CH_4 equivalent, which is converted to total organic gases (TOG) as TOG = **HC** × 1.16 [*FAA/EPA,* 2009]. Speciation of the TOG mass is given in Barrett et al. [2010], Appendix A. Inclusion of the different TOG species depends on the chemistry scheme being used.

SO_2 and S^{VI} emissions are scaled from **FUELBURN** assuming a fuel sulfur concentration **FSC** = 600 [400-800] in mg/kg-fuel [*Hileman et al.,* 2010]. For low sulfur fuels, **FSC** = 15. A mole fraction **E** = 2 [0.5-6] in % of the fuel sulfur is emitted as S^{VI}, with the remaining (100-***E***) % being emitted as SO_2. Therefore emissions of SO_2 in g = (**FSC**/1000) × [(100-**E**)/100] × **FUELBURN** × (64/32), where it should be recalled that **FUELBURN** is in kg. Emissions of S^{VI} as SO_4 in g = (***FSC***/1000) × (***E***/100) × **FUELBURN** × (96/32).

The emission species for S^{VI} is at the discretion of the modeler. Guidelines are to emit S^{VI} as:

- SO_3 if the model explicitly treats the aircraft exhaust plume from the engine exit plane, i.e. emissions of S^{VI} as SO_3 in g = (**FSC**/1000) × (**E**/100) × **FUELBURN** × (80/32).
- H_2SO_4(g) if the model treats the aircraft exhaust plume from a point downstream of the engine exit plane, i.e. emissions of S^{VI} as H_2SO_4(g) in g = (**FSC**/1000) × (**E**/100) × **FUELBURN** × (98/32).
- Sulfate aerosol if the model treats emissions at the grid scale, i.e. emissions of S^{VI} as SO_4 in g = (**FSC**/1000) × (**E**/100) × **FUELBURN** × (96/32).

Below 3000 ft AGL, a number EI for sulfates plus organic carbon of 1×10^{16} [0.2×10^{16}-2×10^{16}] particles/kg-fuel can be assumed with a geometric standard deviation of 1.5 [1.4-1.6]. Above

3000 ft AGL, a number EI for sulfates plus organic carbon of 2×10^{16} [1×10^{16}-5×10^{16}] particles/kg-fuel can be assumed with a geometric standard deviation of 1.5 [1.4-1.6]. Based on *Lukachko et al.* [2010]. Appendix B in Barrett et al. [2010] provides practical suggestions for calculating aerosol parameters.

Checksums for AEIC emissions are given in Table 2.

Variable		**Sum**
FUEL	Fuel burn (kg)	1.80576E+11
CO	CO (g)	7.49257E+11
HC	HC as CH_4 (g)	2.00827E+11
NOX	NO_x as NO_2 (g)	2.68932E+12

Table 2. Checksums for AEIC data set of Year 2005 emissions.

References

Baughcum, S.L., Tritz, T.G., Henderson, S.C., Pickett, D.C. Scheduled Civil Aircraft Emission Inventories for 1992: Database Development and Analysis, Appendix D. NASA. **1996.**

Barrett, S., Prather, M., Penner, J., Selkirk, H., Dopelheuer, A., Fleming, G., Gupta, M., et al. Guidance on the use of AEDT Gridded Aircraft Emissions in Atmospheric Models Federal Aviation Administration, Version 2.0. August, **2010.** Available from http://lae.mit.edu/uploads/LAE_report_series/2010/LAE-2010-008-N.pdf.

CAA. Aircraft Engine Emissions. Available from http://www.caa.co.uk/default.aspx?catid=1437&pagetype=90&pageid=13449. **2009.**

Eurocontrol Experimental Centre, User Manual for The Base Of Aircraft Data (BADA) Revision 3.9. EEC Technical/Scientific Report No. 11/03/08-08, **2011**.

FAA/EPA. Recommended Best Practice for Quantifying Speciated Organic Gas Emissions From Aircraft Equipped with Tubofan, Turbojet and Turboprop Engines. Version 1.0, May **2009**. Available from http://www.faa.gov/regulations_policies/policy_guidance/envir_policy/media/FAA-EPA_RBP_Speciated%20OG_Aircraft_052709.pdf.

Hileman, J. I.; Stratton, R.W.; Donohoo, P.E., Energy Content and Alternative Jet Fuel Viability. To appear in *Journal of Propulsion and Power*. **2010**.

Kim, B., Fleming, G., Lee, J., Waitz, I., Clarke, J., Balasubramanian, S., Holsclaw, C., et al. System for assessing Aviation's Global Emissions (SAGE), Part 1: Model description and inventory results. Transportation Research Part D: Transport and Environment, 12(5), 325–346. doi:10.1016/j.trd.2007.03.007. **2007**.

Lukachko, S.; Waitz, I.; Petzold, A.; Schumann, U.; Miake-Lye, R.; Barrett, S. ACCRI PM Specification. Technical Report (contact iaw@mit.edu for access), April, **2010**.

Hileman, J. I.; Stratton, R.W.; Donohoo, P.E., Energy Content and Alternative Jet Fuel Viability. To appear in *Journal of Propulsion and Power*. **2010**.

Reynolds, T. G. Analysis of Lateral Flight Inefficiency in Global Air Traffic Management. 8th AIAA Aviation Technology, Integration & Operations Conference, Anchorage, AK, Sep (pp. 2008–11). Retrieved from http://www.arct.cam.ac.uk/aim/Documents/ATIO2008_FlightInefficiency_presentation.pdf. **2008**.

Reynolds, T. G. Development of flight inefficiency metrics for environmental performance assessment of ATM. Eighth USA/Europe Air Traffic Management Research and Development Seminar (ATM2009). Retrieved from http://www.atmseminarus.org/seminarContent/seminar8/presentations/pr_122_EI.pdf. **2009**.

Stettler, M. E. J., Eastham, S., & Barrett, S. R. H. Air quality and public health impacts of UK airports. Part I: Emissions. Atmospheric Environment, 45(31), 5415–5424. doi:10.1016/j.atmosenv.2011.07.012. **2011**.

Wilkerson, J. T., Jacobson, M. Z., Malwitz, a., Balasubramanian, S., Wayson, R., Fleming, G., Naiman, a. D., et al. Analysis of emission data from global commercial aviation: 2004 and 2006. Atmospheric Chemistry and Physics, 2010. 10(13), 6391–6408. doi:10.5194/acp-10-6391-2010. **2010.**

Appendix A (List of Acronyms)

ACCRI	Aviation Climate Change Research Initiative
AEIC	Airport Emissions Inventory Code
AEDT	Aviation Environmental Design Tool
AGL	Above Ground Level
BC, OC	Black Carbon; Organic Carbon
BFFM2	Boeing Fuel Flow Method 2
CO, HC, CH_4	Carbon monoxide, hydrocarbon, methane
EI, nEI	Mass emission index, number emission index.
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FSC	Fuel Sulfur Concentration (or Content)
GS	Ground Speed
g	Grams
GB	Gigabyte
hPa	Hecto-pascal = 100 pascals
kft	kilofeet (thousands of feet)
Lat	Latitude
Lon	Longitude
LTO	Landing and Takeoff
NO, NO_2	Nitric oxide, nitrogen dioxide
NO_x	Oxides of nitrogen (NO+NO_2 by definition, but assumed to include HONO mass in reporting)
OAG	Official Airline Guide
PM	Particulate Matter
PMSO	Sulfur particulate matter reported as SO_4 (note that raw AEDT inventory values of PMSO should be discarded)
SO_2, S, H_2SO_4	Sulfur dioxide, elemental sulfur, sulfuric acid
TAS	True Air Speed
TOG	Total organic gases
UTC	Coordinated Universal Time