Technical guidance for the AEIC 2019 aircraft emissions inventory

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Document purpose

This document provides a technical overview, and summary of, the inventory of aircraft emissions produced for 2019 using the Aircraft Emissions Inventory Code (AEIC) developed at MIT (Simone et al., 2013).

Please contact Sebastian Eastham (MIT, seastham@mit.edu) with additional questions regarding the production or use of this inventory.

Purpose, scope, and limitations of the AEIC 2019 inventory

This inventory provides an estimate of the total fuel burn, distance flown, and pollutant emissions associated with both landing and take-off (LTO) and non-LTO flight, including cruise.

AEIC uses great circles to describe the path of aircraft from their origin to their destination and does not perform wind-optimal routing or account for air space restrictions. Flights are simulated based on schedule data from OAG (www.oag.com), such that flight cancellations or larger disruptions to the network will not be captured. Aircraft are represented based on their model name only, to the level of specificity provided by OAG (e.g. 777-200). Performance data for each model are estimated based on the EUROCONTROL Base of Aircraft Data (BADA) v3. Data is aggregated to an approximate resolution of 60 km (horizontally), and provided on a daily-average basis.

For these reasons, this inventory is intended for use in regional and global simulations of the atmosphere which aim to include a realistic representation of the aggregate effect of aviation. The contributions of individual flights, aircraft, or carriers cannot be discerned from this inventory, and analyses at such scales are not appropriate when using this data.

Data format and grid description

All data are provided in NetCDF files, with one file for each day. Each file contains the estimated, gridded, daily average of the quantities shown in Table 1. All quantities are provided per unit area to facilitate remapping of the inventory to different horizontal grids and resolutions.

Table 1. Gridded quantities and totals for the 2019 inventory. All values are given to three significant figures.
**NO_x emissions are speciated within each file, but a total is provided here for ease of reference. This total uses an NO_2 mass basis.*
***Unburned hydrocarbons are given assuming a CH_4 mass basis.*

Quantity	Name in file	Unit in file	Total in 2019
Fuel burn	FUELBURN	$kg/m^2/s$	258 Tg
Carbon monoxide emissions	CO	$kg/m^2/s$	1,290 Gg
Nitrogen oxide (NO_x) emissions*	-	-	4,510 Gg
...NO_x as NO	NO	kg $NO/m^2/s$	2,520 Gg
...NO_x as NO_2	NO2	kg $NO_2/m^2/s$	530 Gg
...NO_x as HONO	HONO	kg $HONO/m^2/s$	114 Gg
Unburned hydrocarbon emissions**	HC	$kg/m^2/s$	134 Gg
Black carbon aerosol emissions	BC	kg $C/m^2/s$	18.1 Gg C
Organic carbon aerosol emissions	OC	kg $C/m^2/s$	7.60 Gg C
Distance flown	DISTANCE	$km/m^2/s$	52.0 bn km

Data are provided on a rectilinear latitude-longitude grid at a resolution of 0.5° latitude by 0.625° longitude (colloquially 0.5x0.625). The grid is half-polar, such that the first/last grid cells are “centered” on the poles, with their upper/lower edge at 89.75°S/N respectively. It is also dateline-centered, such that the first meridional band of grid cells is centered on 180°W with edges at 180.25°W and 179.75°W.

Vertically, there are 36 layers of varying thickness. The data orientation is “positive”, such that the first layer is adjacent to the Earth’s surface and increasing number corresponds to increasing altitude. The layers are defined identically to the first 36 layers used in the NASA Global Modeling and Assimilation Office (GMAO) Modern Era Retrospective for Research and Analysis version 2 (MERRA-2). The Goddard

Earth Observation System (GEOS) which produces MERRA-2 uses a hybrid vertical coordinate. The pressure at the lower edge of the grid cell at latitude index *j*, longitude index *i*, and layer *k* is defined as

$$p(i,j,k) = A(k) + B(k) \times p_{\mathrm{sfc}}(i,j)$$

where $A(k)$ and $B(k)$ are layer-specific constants given in Appendix A, and p_{sfc} is the surface pressure at the base of the column. Since there are 36 layers and the pressure must also be defined at the top of the uppermost layer, we provide the first 37 values for *A* and *B*.

Since only the average emissions rate is provided for each day, the dimensions of the data in each file are 1×36×361×576 (time × level × latitude × longitude).

Usage of data in global models

Derived emissions

Emissions of sulfur species, carbon dioxide (CO_2), and water vapor (H_2O) can be calculated from the estimated fuel burn rates using fixed emissions factors and uncertainty ranges estimated by Hileman, Stratton, and Donohoo (2010).

For sulfur, we assume that the fuel is 600 ppm sulfur by mass. 2% of this sulfur is expected to be oxidized in the plume from S^{IV} to S^{VI}, meaning it will be present as sulfate aerosol (SO_4) rather than sulfur dioxide (SO_2) (Stettler et al., 2011). This corresponds to an emissions index of 1.176 g SO_2 per kg of fuel, and 0.0036 g SO_4 per kg of fuel. For 2019, we therefore calculate 304 Gg of SO_2 emissions (SO_2 mass basis) and 9.31 Gg of emissions of sulfate aerosol (SO_4 mass basis).

Water vapor emissions can be estimated using a fixed emissions index of 1.231 kg of water vapor per kg of fuel burned (uncertainty range 1.197 – 1.258 kg_{H2O}/kg_{fuel}). Emissions of CO_2 can be estimated using a fixed emissions index of 3.159 kg CO_2 per kg of fuel (uncertainty range 3.148 – 3.173 kg_{CO2}/kg_{fuel}).

Carbonaceous aerosol emissions

Black carbon emissions are calculated based on the FOX model (Stettler et al., 2013). The emissions listed in the file correspond to the mass of pure carbon. We do not calculate a number emissions index for aerosols. A constant emission index of 20 mg/kg_{fuel} is used for organic carbon. The mass provided corresponds only to the carbonaceous fraction of the aerosol. If used in a global model, users may need to convert to total organic matter.

NO_x speciation

NO_x emissions are calculated as described in Simone, Stettler, and Barrett (2013). Total NO_x is divided into NO, NO_2, and HONO (HNO_2) emissions assuming a nitrogen partitioning of 91.75, 7.5 and 0.75%, for NO, NO2, and HONO respectively.

Unburned hydrocarbon speciation

The unburned hydrocarbons in the inventory represent a mix of organic compounds, provided on a CH_4 mass basis. This can be converted to the estimated emissions of total organic gases (TOG) by multiplying the estimate by 1.16. We recommend that the estimated TOG are then speciated following FAA/EPA guidelines (US FAA/EPA, 2009), although the exact speciation will vary depending on what chemical species are represented in a given chemical mechanism. Appendix B provides suggested emissions

factors for use in the “full chemistry” mechanism used by GEOS-Chem v13.0.0 release candidate 2 (The International GEOS-Chem User Community, 2021).

Distance flown

The “distance flown” metric is provided to facilitate the use of this inventory for contrail modeling. This includes only "cruise” segments, meaning flight above 1 km altitude. The total cruise distance flown for 2019 is estimated at 52 billion kilometers.

Global distributions of fuel burn in 2019

Figures 1 and 2 show the global distribution of aviation fuel burn for 2019, as estimated by AEIC.

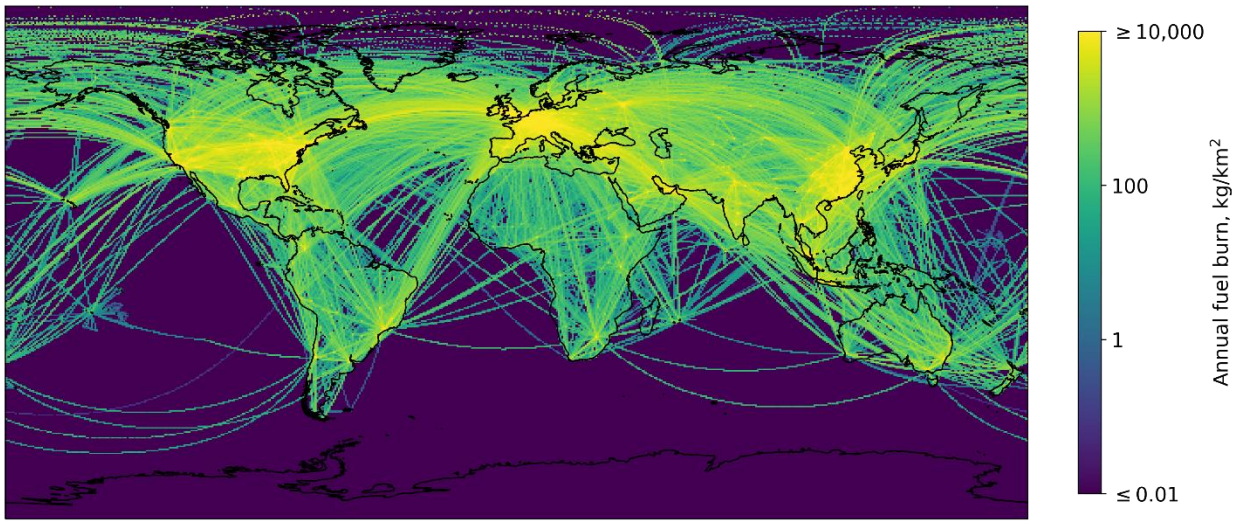

Figure 1. Global distribution of fuel burn for 2019. Each location shows the estimated total fuel burn summed across all vertical levels, in units of kg of fuel burned per square kilometer of horizontal space. Data are discretized to a regular 1°×1° grid as described above.

Based on these results, 91% of all aviation fuel burn occurs in the Northern Hemisphere, with 80% between 15°N and 60°N specifically. Figure 2 shows the vertical distribution of global aviation fuel burn, in Tg burned each year per kilometer of altitude.

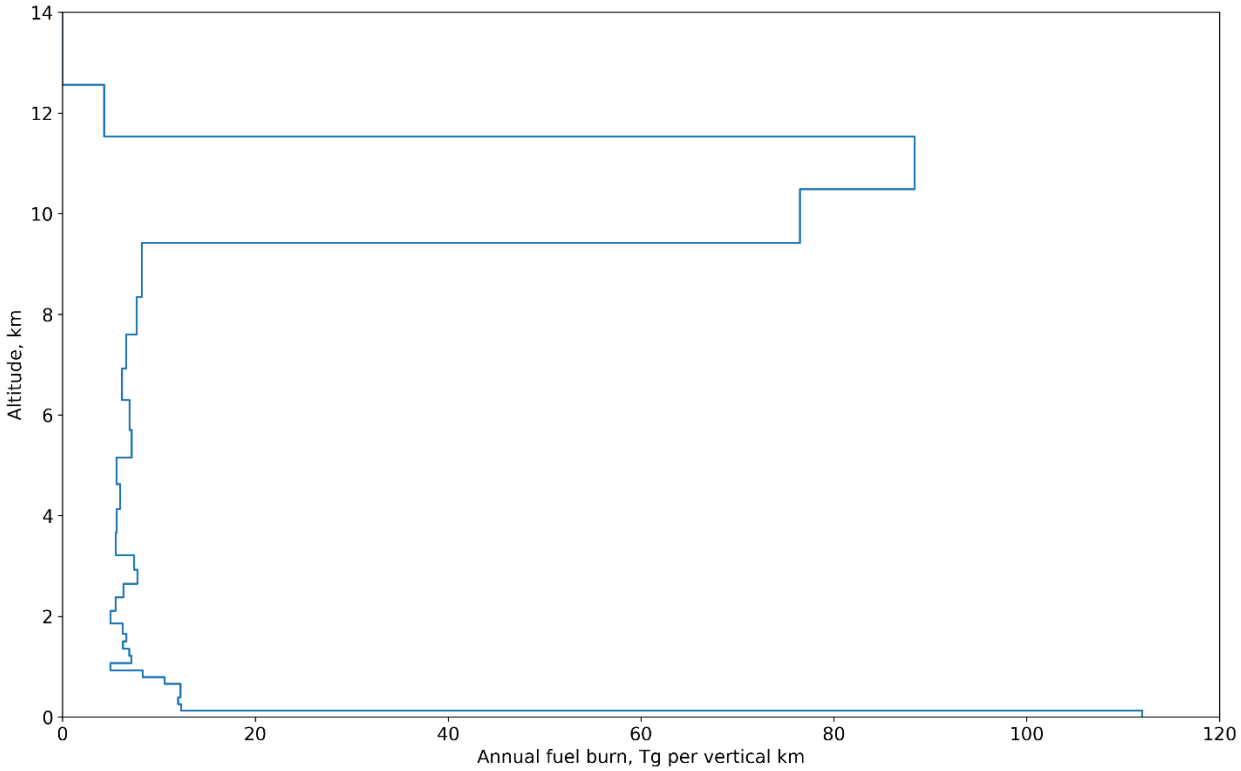

Figure 2. Vertical distribution of fuel burn for 2019. Fuel burn is discretized onto the vertical layer structure used by the NASA GEOS model, as described above. Total fuel burn is represented by the integrated area between the blue line and the vertical axis.

Based on analysis of the data after discretization and assuming uniform distribution within each layer, 9.2% of total fuel burn occurs below 1 km altitude. 81% of total fuel burn occurs above 5 km altitude, with 73% above 8 km. Finally, Figure 3 shows the total global estimated fuel burned for each day in 2019. Peak fuel burn by season occurs during Northern hemispheric summer (27%), with the minimum during Northern hemispheric winter (24%). Variation by day of the week is smaller. The greatest difference is between Tuesdays and Fridays, with the fuel burn on Tuesdays around 5% lower (on average) than the following Friday.

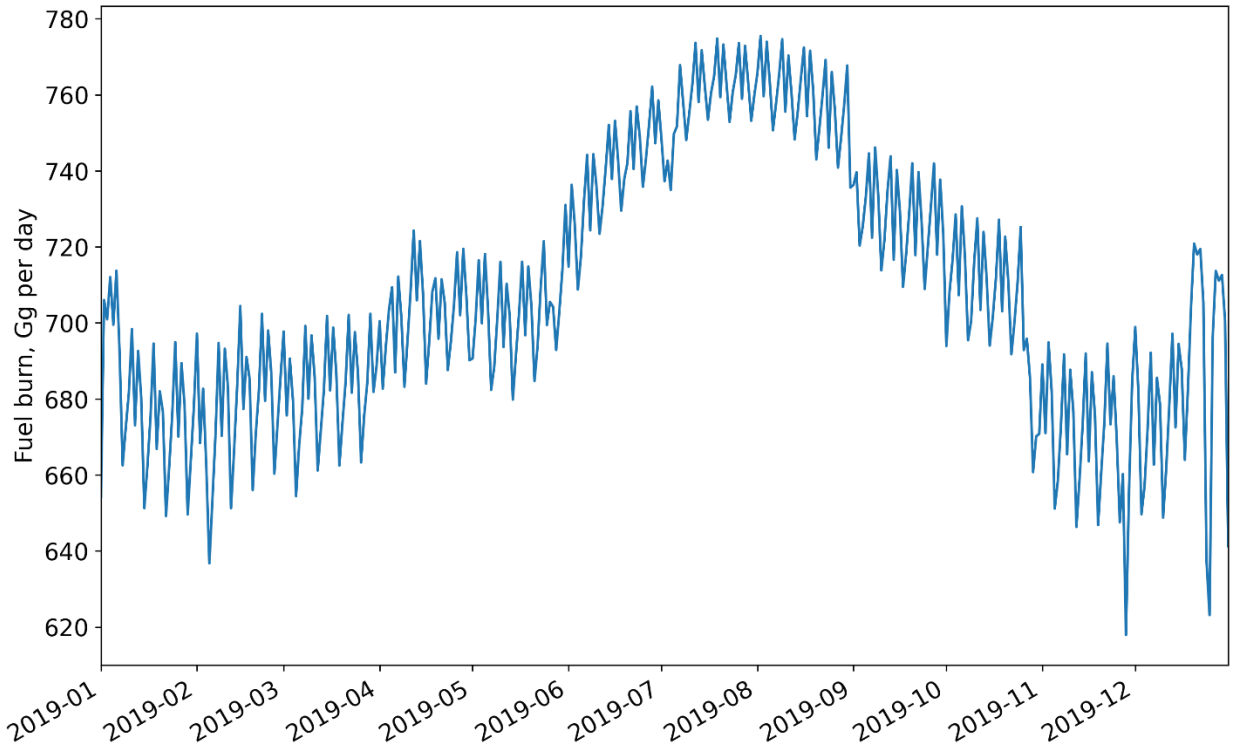

Figure 3. Total, global fuel burn for each day in 2019 as estimated by AEIC. Dates show the start of each month.

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Appendix A: Vertical grid definition

As discussed in the main text, the vertical grid is defined with 36 layers. The pressure at the lowermost edge of each layer is calculated as a function of the local surface pressure and two layer-specific constants, *A* and *B*. Table 2 shows the value of these constants for the 37 layer edges used in this dataset. Example pressures and altitudes are also provided for a case where the surface pressure is 1013.25 hPa, to assist in verification that the values are being used correctly. The uppermost layers have zero emissions.

Table 2. Vertical grid definition for the emissions dataset. The "typical" pressures and altitudes are calculated for a surface pressure of 1013.25 hPa. The altitude is estimated using the 1976 Committee on Extension to the Standard Atmosphere (COESA) standard lower atmospheric data (United States. National Aeronautics and Space Administration, 1976).

Layer number *k*	*A*(*k*), hPa	*B*(*k*), unitless	Typical *p*(*k*), hPa	Typical altitude, km
1	0.000	1.000	1013.250	0.000
2	0.048	0.985	998.051	0.127
3	6.594	0.963	982.765	0.257
4	13.135	0.942	967.480	0.388
5	19.613	0.920	952.195	0.521
6	26.092	0.899	936.911	0.656
7	32.571	0.877	921.626	0.792
8	38.982	0.856	906.342	0.931
9	45.339	0.835	891.059	1.071
10	51.696	0.813	875.776	1.213
11	58.053	0.792	860.493	1.357
12	64.363	0.771	845.211	1.503
13	70.622	0.749	829.929	1.652
14	78.834	0.721	809.556	1.853
15	89.100	0.686	784.088	2.111
16	99.365	0.651	758.621	2.375
17	109.182	0.616	733.160	2.647
18	118.959	0.581	707.699	2.926
19	128.696	0.546	682.239	3.214
20	142.910	0.495	644.054	3.662
21	156.260	0.444	605.880	4.132
22	169.609	0.393	567.706	4.627
23	181.619	0.343	529.550	5.149
24	193.097	0.294	491.401	5.702
25	203.259	0.247	453.269	6.291
26	212.150	0.200	415.155	6.922
27	218.776	0.156	377.070	7.600
28	223.898	0.114	339.005	8.337
29	224.363	0.064	288.927	9.415
30	216.865	0.028	245.246	10.487
31	201.192	0.007	208.244	11.528
32	176.930	0.000	176.930	12.561
33	150.393	0.000	150.393	13.592
34	127.837	0.000	127.837	14.622
35	108.663	0.000	108.663	15.653
36	92.366	0.000	92.366	16.684
37	78.512	0.000	78.512	17.714

Appendix B: Speciation of unburned hydrocarbons for GEOS-Chem v13

Table 3 provides a suggested set of emissions factors for use in the chemical transport model GEOS-Chem, which can simulate both tropospheric and stratospheric chemistry (Bey et al., 2001; Eastham et al., 2014). These factors are estimated based on both FAA/EPA guidance regarding speciation for aircraft engines (US FAA/EPA, 2009) and the available species in the GEOS-Chem v13 chemical mechanism. Emissions of an individual species are calculated relative to the total organic gas (TOG) emissions which are themselves calculated as being 1.16 times the emissions rate of unburned hydrocarbons (UHC). The data should therefore be used as

$$\text{Emissions of species X} = (\text{Emissions of UHC} \times 1.16) \times EI_{spc}$$

where emissions of UHC are provided in the NetCDF data files and the emissions index for each species (EI_{spc}) are provided in Table 3.

Chemical species	Name in GEOS-Chem v13	Emissions index (EI_{spc}), $kg_{species}/kg_{TOG}$
Acetone	ACET	3.693477×10^{-3}
Acetaldehyde	ALD2	4.271822×10^{-2}
Lumped alkanes (4 or more carbons)	ALK4	2.137911×10^{-1}
Ethane	C2H6	5.214505×10^{-3}
Propane	C3H8	7.808710×10^{-4}
Formaldehyde	CH2O	1.230811×10^{-1}
Lumped alkenes (3 or more carbons)	PRPE	1.780418×10^{-1}
Methacrolein	MACR	5.362609×10^{-2}
Lumped aldehydes (3 or more carbons)	RCHO	3.676944×10^{-2}